

SOME PROTON CAPTURE REACTIONS

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A thesis submitted for the degree of Doctor of Philosophy
in the University of Dacca



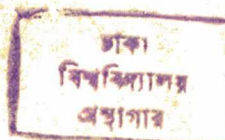
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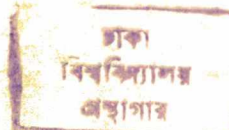
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ABSTRACT

The proton capture reactions through (p,γ) and (p,n) in ^{51}V and ^{55}Mn and (p,γ) in ^{54}Fe and ^{27}Al up to 3 MeV are studied and a number of analogue resonances have been located.

Properties of resonant states including analogue resonances through (p,γ) and (p,p) reactions in ^{27}Al have been obtained. The spin-parity of resonating states in ^{28}Si due to 2.198, 2.482, 2.511 and 2.735 MeV proton resonances are assigned as $13.707\text{---}2^-$, 3^- , $13.980\text{---}4^+$, $14.007\text{---}4^+$ and $14.223\text{---}3^+, (2)^+$ by measurement of angular distribution of gamma rays. These are analogue states corresponding to the excitation energy 4.383, 4.685, 4.741 and 4.928 MeV of ^{28}Al . A small multipolarity mixing is observed. A strong transition occurs between 14.007 and 4.620 MeV levels of ^{28}Si each with $J^\pi = 4^+$. This is possibly a case of analogue to antianalogue M1 transition. Eleven isolated resonances in the energy range $E_p = 0.85$ to 3.0 MeV have been studied through elastic scattering of protons on ^{27}Al at the centre of mass angles 90° , 125° and 141° ; various properties of the resonances have been obtained. They, in general, are in good agreement with previous results. Of these, four resonances are located above 2 MeV where no previous measurement is available. The resonances at $E_p = 1.117$ and 1.793 MeV were identified as analogues, the former being in agreement with Awaya. The (p,p) transition strengths obtained from the present work show poor agreement with the corresponding (d,p) spectroscopic transition strengths.

The Coulomb displacement energies have been obtained from the present work for four isobaric pairs of nuclei e.g. ^{28}Al - ^{28}Si .

^{52}V - ^{52}Cr , ^{55}Fe - ^{55}Co and ^{56}Mn - ^{56}Fe and they are in excellent agreement with available measurements. A semi-empirical relation similar to that of Anderson et al. has been obtained using a large number of data with better accuracy available in the mass region $A=27-238$ since the above work. T_z -dependence of Coulomb displacement energy is found to be very small.

Fine structures enveloping gross structures are displayed by some analogue resonances in ^{52}Cr and ^{56}Fe . They have been analysed using Robson's formalism.

ACKNOWLEDGEMENTS

I express my deep sense of gratitude to Professor H.M. Sen Gupta for his kind supervision, constant help and guidance and encouragement althrough the progress of this work. I am thankful to Professor A.K.M. Siddique and Dr. S. Ali for their interest in the work. I also gratefully acknowledge the help of Dr. N. Ahmed in the beginning of this work. Thanks are due to Mr. M. Rahman and Mr. M. A. Awal for their invaluable help. The help of Mr. Hanifuddin Mia and Mr. Musa of Computer Division, A.E.C. Dacca are highly appreciated. I am also thankful to Dr. D. Hossain for friendly discussions during the time of analysis of angular distribution of gamma rays.

I am grateful to the Department of Atomic Energy, Government of India for the hospitality and facility during my stay at BARC, Bombay, India which made the measurement of gamma rays angular distributions possible. The indispensable help of Dr. M.K. Mehta, Dr. S.K. Gupta and Dr. C.V.K. Baba during the measurements are warmly and gratefully acknowledged. I am very much grateful to Professor. W.J. Thomson who kindly calculated the proton penetration factor for ^{27}Al and sent to us.

I am also thankful to Mr. H. Reza for preparing targets and crew of Van de Graaff Accelerator at A.E.C., Dacca for running the machine efficiently.

CHAPTER-1

I N T R O D U C T I O N

Isobaric spin quantum number T is introduced from the concept of the charge independence of nuclear forces. In general a nucleon is considered as a single entity having two states such as the proton and the neutron. A nucleon is assigned to have an isobaric spin t . The $t = +\frac{1}{2}$ means that the nucleon is in a proton state and $t = -\frac{1}{2}$ means it is in a neutron state. The total isobaric spin of a nucleus is defined as

$$T = \sum_{i=1}^A t_i$$

where t_i is the isobaric spin vector of the i th nucleon. T_z , the Z - component of T for any nuclear state is $T_z = (N-Z)/2$. In analogy with ordinary spin S having been associated with $(2S+1)$ independent states to same S , there are $(2T+1)$ independent nuclear states associated with the isobaric spin number T . Each state belongs to different values of T_z , where $T_z = T, T-1, \dots, -T$. If the forces are the same for neutron and proton these states should have the same energy apart from their Coulomb displacement energy and neutron-proton mass difference and are said to form a T -multiplet. The different members of the T -multiplet correspond to states in a set of isobars. Any one of these states, in whichever nuclei it occurs, is known as the analogue of the corresponding state in $T=T_z=(N-Z)/2$ nuclei. In practice Coulomb displacement energy and neutron-proton mass difference give different energy for different T_z . This produces

a shift in the position of the level of one isobar with respect to another such that the excitation energy of these analogue states increases with the decrease in $(N-Z)$.

As an example, we consider three light nuclei, ^{12}B , ^{12}C and ^{12}N ; these are isobars, all having the same mass number A but differing in the proton and neutron number Z and N . The value of Z -component of T is $T_z=1, 0, -1$ for ^{12}B , ^{12}C and ^{12}N . In this example for ^{12}B there exists a vacancy in a proton level while a neutron occupies a level of considerably higher energy and for ^{12}N there is a vacancy in upper neutron level and a proton occupies a higher energy state. These two nuclei are transformed into the stable ^{12}C nucleus by β^- and β^+ -decay respectively.

As stated in the beginning since the nuclear forces are charge independent, it is expected that in any pair of isobaric nuclei at least the low lying excited energy states should have the same value. The Coulomb force acts between protons and the difference in the proton number in parent nucleus and analogue nucleus gives rise to Coulomb displacement energy. It is then expected that in any isobaric pair of nuclei the energy states may differ almost by a constant value of energy. Even some of the energy states of the same isobaric pair of nuclei may be very well equal to each other and these energy states are known as isobaric analogue states.

In order to obtain information about the compound nucleus by studying the spectrum of evaporated neutrons in the (p,n) reaction Anderson et al.¹⁾ in 1961, performed a series of experiments on a

- number of nuclei with masses ranging from 48 to 93. The time of flight technique was used to obtain the neutron energy spectrum. Targets were bombarded with 15 MeV protons. In the first experiment with ^{51}V as a target they were disturbed to find a very strong neutron group which corresponds to a rather high excitation energy in the residual nucleus. After checking out the electronics they concluded that the peak was due to the isobaric analogue state from light element contaminant. The existence of sharp analogue states only in light nuclei was known at that time. They then calculated the charge from the energy of strong neutron group. This energy is simply the Coulomb energy of the added proton together with the neutron-proton mass difference. They found that the contaminant was ^{51}V , the target nucleus itself.

Isobaric analogue resonances were first observed in the (p,n) reaction on ^{89}Y as compound nuclear states by Fox et al.²⁾ in 1964 by using the proton beam from Tandem Van de Graaff having an energy spread of about 3 keV. The neutron spectrum displayed strong resonances and these resonances were interpreted as isobaric analogue states in the compound nucleus ^{90}Zr corresponding to the low-lying excited states of its isobaric nucleus ^{90}Y . It is to be noted that analogue states observed by Fox et al.²⁾ were interpreted as compound nucleus resonances, whereas the analogue states investigated by Anderson et al.¹⁾ were observed as states in the residual nucleus in direct reaction.

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Following the discovery of isobaric analogue states as compound nucleus resonances a new tool has become available in the field of nuclear spectroscopy. Since then a large number of experiments (refs. 3-6) and many others) on the study of isobaric analogue states in medium weight nuclei have been performed by different proton induced reactions namely through (p,p), (p, γ) and (p,n) and it has thereby been possible to locate and study the properties of isobaric analogue states.

Isobaric analogue states in ^{52}Cr have been studied by a few authors 7-9). There appears some discrepancies among these measurements and a few well established levels in ^{52}V (ref. 10) do not seem to have any analogues in ^{52}Cr . The present investigation in ^{51}V by (p, γ) and (p, n) reactions has been undertaken in an attempt to resolve these discrepancies.

The analogue states in ^{55}Co have been investigated by some authors 11-13). Information on analogue states in this nucleus is scanty. The present (p, γ) experiment on ^{54}Fe ranges between $E_p = 0.85-3.00$ MeV.

Information on analogue states in ^{56}Fe is not sufficient. A few analogue states have been identified by Otto et al. 14,15), Friedrich et al. 16) and Sakai et al. 17). The present work by (p, γ) and (p, n) reactions on ^{55}Mn target has been undertaken with a view to study the analogue states in the energy range $E_p = 0.85-3.05$ MeV.

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Information on analogue states in ^{28}Si is also inadequate. The only measurements are in refs. 18 and 19. Two analogue states in ^{28}Si by (p, γ) reaction in ^{27}Al in the energy range $E_p = 1.20-2.50$ MeV have been reported by Jaffe and Harchol¹⁸⁾. Awaya¹⁹⁾ reported three analogue states by $^{27}\text{Al} (p, p)$ resonance reaction in the energy range $E_p = 0.77-1.390$ MeV.

In chapter 3 results on identification of analogue states through gamma-emission and where possible neutron emission following proton capture reactions in ^{51}V , ^{54}Fe , ^{55}Mn and ^{27}Al are discussed.

The Coulomb displacement energies for pairs of isobaric nuclei namely $^{52}\text{V}-^{52}\text{Cr}$, $^{55}\text{Fe}-^{55}\text{Co}$, $^{56}\text{Mn}-^{56}\text{Fe}$ and $^{28}\text{Al}-^{28}\text{Si}$ were obtained from the present experiments. The systematics of available Coulomb displacement energy for isobaric pairs of nuclei in the mass region $A=27$ to 238 have been surveyed in an attempt to obtain a semi-empirical relation similar to that of Anderson et al.²⁰⁾; this was felt necessary as a large amount of data has accumulated since the above work. The results are discussed in chapter 4. An attempt has also been made to look for any T_z -dependence of Coulomb displacement energy starting from experimental data.

Fine structures enveloping gross structures are sometimes exhibited in proton induced reactions. Fine structures were observed in the present work in (p, γ) and (p, n) reactions in ^{51}V and ^{55}Mn , but no such structure was found in ^{27}Al and ^{54}Fe . The results are discussed in chapter 5.

Properties of resonance levels including analogue resonances in ^{28}Si obtained from proton capture reaction in ^{27}Al have been summarized by Endt and Van der Leun (21). Information above $E_p = 2$ MeV are lacking. Angular distribution of gamma rays de-exciting the resonance levels at $E_p = 2.198$, 2.482, 2.511 and 2.735 MeV have been studied and the results are discussed in chapter 6.

Finally in chapter 7 we consider the ^{27}Al (p,p) resonance measurements in the energy range $E_p = 0.85-3$ MeV. Eleven isolated resonances were studied including two analogues and properties of the resonance levels in ^{28}Si have been given.

CHAPTER - 2

EXPERIMENTAL PROCEDURE2.1 Experimental set up

The experiments were performed with protons from the 3 MeV Van de Graaff accelerator at the Atomic Energy Centre, Dacca. (Data on gamma decay were collected at the Bhaba Atomic Research Centre, Bombay, India). A 25° beam deflection was achieved with an analysing magnet, the field of which was measured with a proton-spin resonance device. An electronic stabilizing system kept the proton energy spread below 1 keV.

The block diagram of the experimental set up for the measurement of gamma-ray excitation function is shown in fig.2:1. The detector pulses were amplified with a preamplifier and RIDL amplifier. The pulses from the amplifier led to a RIDL single channel analyser followed by a scaler through a common control unit. This controls all the scalers used in the experiment with the help of flipflop circuits, i.e. it can start and stop simultaneously all the system connected to it. For checking the count rates the N.E. timer was employed. This has 10 c/s oscillator and a transistorized binary system for count oscillator pulse. This was also connected to common control unit. The proton beam after passing through the target material was stopped in the target backing which is in contact with the target holder. The target holder is insulated from the beam tube. The beam current collected by the target holder was integrated by means of a current integrator which is based on the one described by Smulders and Smith²²).

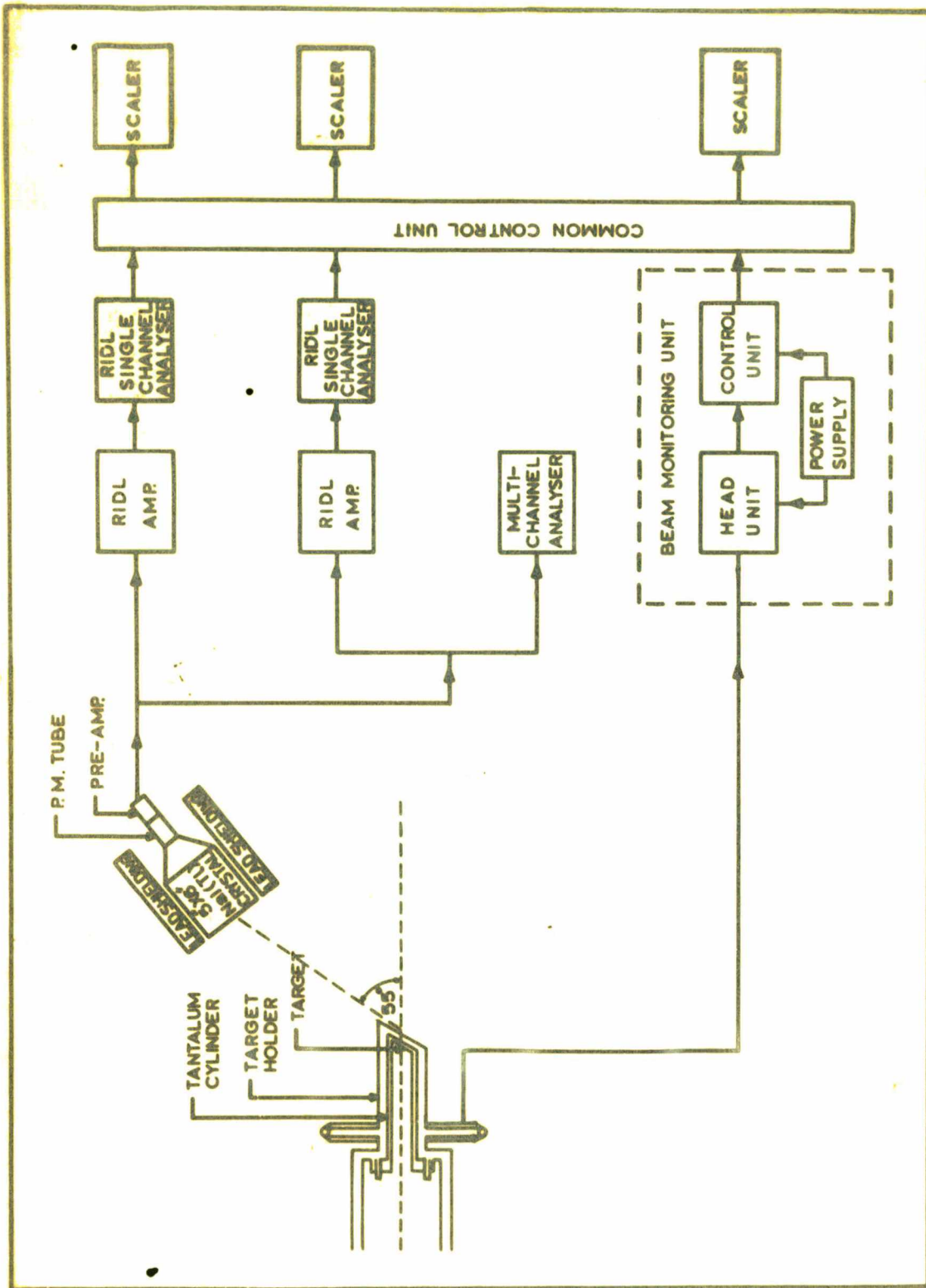


Fig.2.1 Block diagram of experimental set up of (p, γ) excitation function.

The scintillation spectrometer consists of a 5" x 6" NaI (Tl) crystal mounted on a EMI photomultiplier tube 9578. The detector was shielded by a cylindrical lead shielding of 10 cm thickness around the crystal. The detector was kept at a distance of 9 cm from the target making an angle of 55° with the direction of the bombarding proton beam to ensure that the measured intensities are averaged for possible angular distributions. The gamma ray excitation function was measured simultaneously with two differential discriminators and scalars. Two channels were set to accept pulses of 1.5 and 3.0 MeV arbitrarily, corresponding to gamma rays deexciting the product nuclei resonance levels.

2.2 Principle of scintillation counters

When an incident charged particle impinges on the phosphor it dissipates its energy in the ionization and excitation of the molecules. A fraction of this energy is converted into photons which are radiated in all directions. Some of these photons fall on the photo-cathode of the photomultiplier tube and eject a number of photo-electrons. These photo-electrons are accelerated by the potential applied between the cathode and the first dynode of the tube. On striking the first dynode each photo-electron ejects several further electrons by secondary emission. This electron multiplication process is repeated at subsequent dynodes, each of which is at a higher potential than the preceding one. Finally after a multiplication of about 10^6 to 10^9 the electron avalanche arrives at the collector plate. It produces a voltage pulse in the output condenser which is applied to an external pulse recording circuit. Thus the initial

- energy of a single ionizing particle is transformed into a single voltage pulse, which is used for detection and measurement.

2.3 Interaction of gamma radiation with matter

The mode of absorption of nuclear radiation and production of scintillation is different for charged, uncharged particles and photons. In case of gamma ray detection, the photons interact with phosphor in three distinct processes, namely, photoelectric effect, Compton effect and pair production. They are discussed in chapter 6.

2.4 Stilbene Scintillator

A $1\frac{1}{2}$ " x 1" stilbene crystal mounted on a RCA 8575 photomultiplier tube with ORTEC equipment was used for the detection of neutrons. Both neutrons and gamma rays being uncharged are detected by secondary processes. In the scintillation method they interact with the material of the scintillators to give recoil protons and electrons respectively which subsequently deexcite to give quanta of light. A photosensitive cathode of a photomultiplier tube collects these quanta of light and are transformed into electrical pulses by the tube. Consequently the separation of neutrons and gammas are difficult. Bonner²³⁾ devised methods to reduce the gamma backgrounds to a large extent using pulse height discrimination method. Hornyak²⁴⁾ used ZnS embedded in Lucite and obtained good particle discrimination but the detection has poor energy resolution. In the past few years a number of methods have been suggested to obtain an effective separation between neutrons and gamma rays using the decay time property of the recoil proton and electron pulses in certain fast scintillators.

• 2.5 n- γ discrimination by zero cross-over technique

One recent ingenious method first suggested by Alexander et al.²⁵⁾ is the zero cross-over technique. An effective separation of neutrons against gamma rays has been obtained by this method by different authors using fast scintillators like stilbene NE218 and NE213. In the present measurement the zero cross-over technique was used for n- γ separation and particle identification. In phosphor used in zero cross-over technique for particle identification the signal pulse is constituted of a component with a short decay time constant plus a component with a long decay time constant. If signals due to the long lived states as amplified by the photomultiplier tube are integrated and then subjected to double differentiation, shift in the zero cross-over of the resulting bipolar pulses will take place depending on the decay times of the initial signals. The neutron pulses, for example, having a large decay time than the gamma pulses will have its zero cross-over point shifted further off from the same due to a gamma ray. A measure of the time differences between the points of initiation and the zero cross-over of the pulses will, therefore, identify the different ionizing agents.

For stilbene the long lived states for proton and electron deexcitation are ~ 67 and ~ 49 nanoseconds respectively while the corresponding values for short lived states are 6.0 and 5.6 nanoseconds. The somewhat large difference of the long lived decay states enable it to bring about excellent n- γ discrimination using the zero cross-over pulse shape discrimination method.

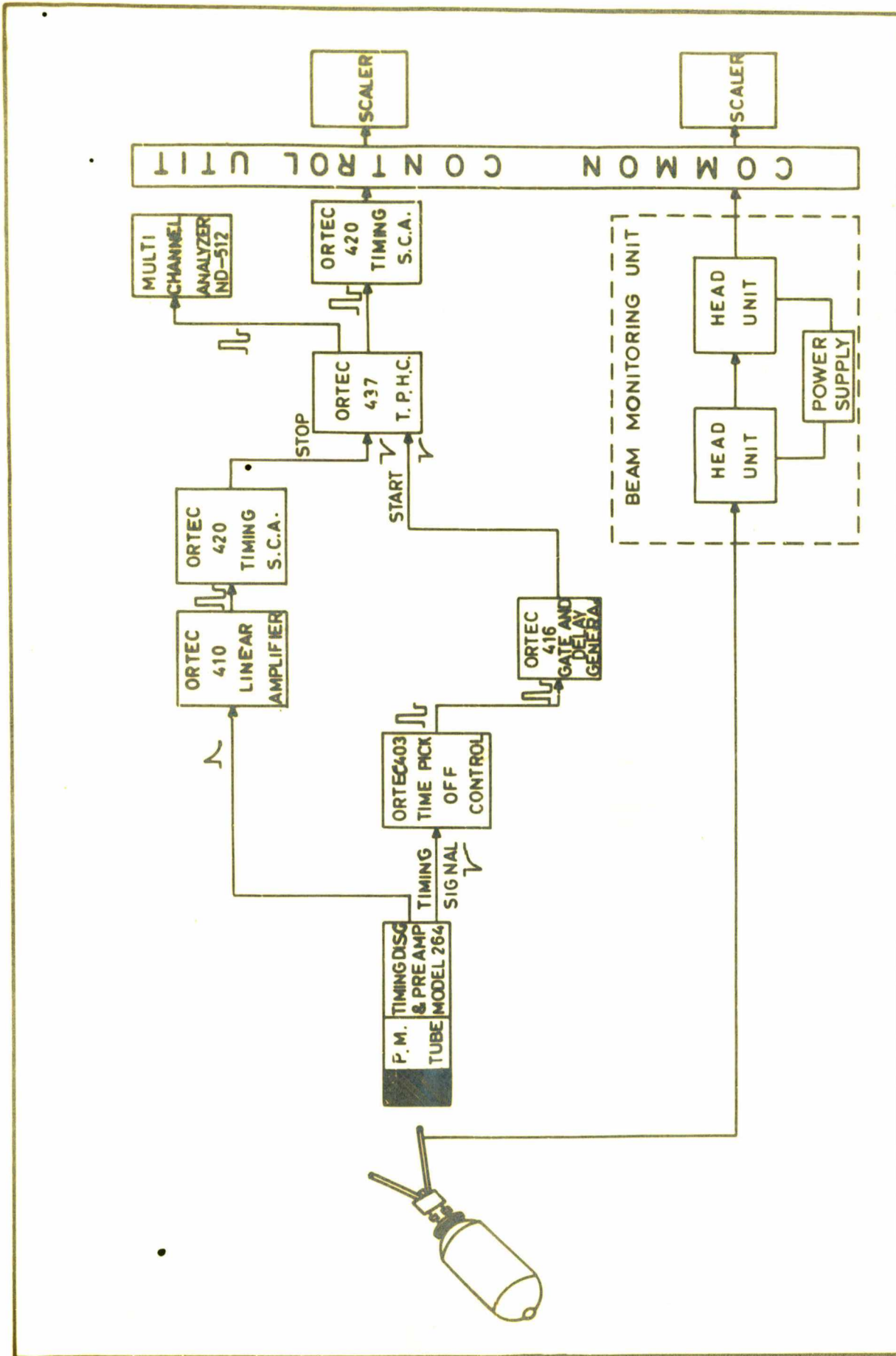


Fig.2.2 Block diagram of experimental set up of (p,n) excitation function.

2.6 (p,n) experimental set up

The neutron yields were measured with a $1\frac{1}{2}$ " x 1" Stilbene scintillation detector incorporated with ORTEC n- γ discrimination system (fig.2.2). The current signal derived from the 9th dynode of PM tube and shaped in a fast preamplifier model ORTEC 264 is fed to the input of a linear amplifier (ORTEC 410). The bipolar pulses obtained from the linear amplifier are fed into a timing single channel analyzer (ORTEC 420) that provides an output at the time the input pulse goes through zero. The negative fast spike appearing at the output of the single channel analyzer constitutes what is called the 'stop' signal of a time-to-pulse-height converter (ORTEC 437). The 'Start' signal of the TPHC is obtained from the anode of the PM tube through a walkfree time derivation unit. This is a fast negative timing signal. The time derivation unit is controlled by an ORTEC 403 time pick off control unit and the output passing through a gate and delay generator (ORTEC 416) actuates the 'start' input of the TPHC. The anode pulses are arranged to arrive in time coincidence or to be slightly delayed with respect to the bipolar dynode pulses, which have components of different zero cross-over times, so that a STOP pulse occurs with every START pulse. The TPHC on receiving the 'start' and 'stop' signals converts the time difference between the two into a voltage signal which appears at its output. Thus the spectra of the output pulses from the TPHC shows two peaks corresponding to the neutron and gamma rays when analyzed in a multichannel analyzer. A typical n- γ spectrum showing the separation of neutron from gamma rays in ^{55}Mn (p,n) ^{56}Fe reaction is shown in fig. 2.3. The discriminator

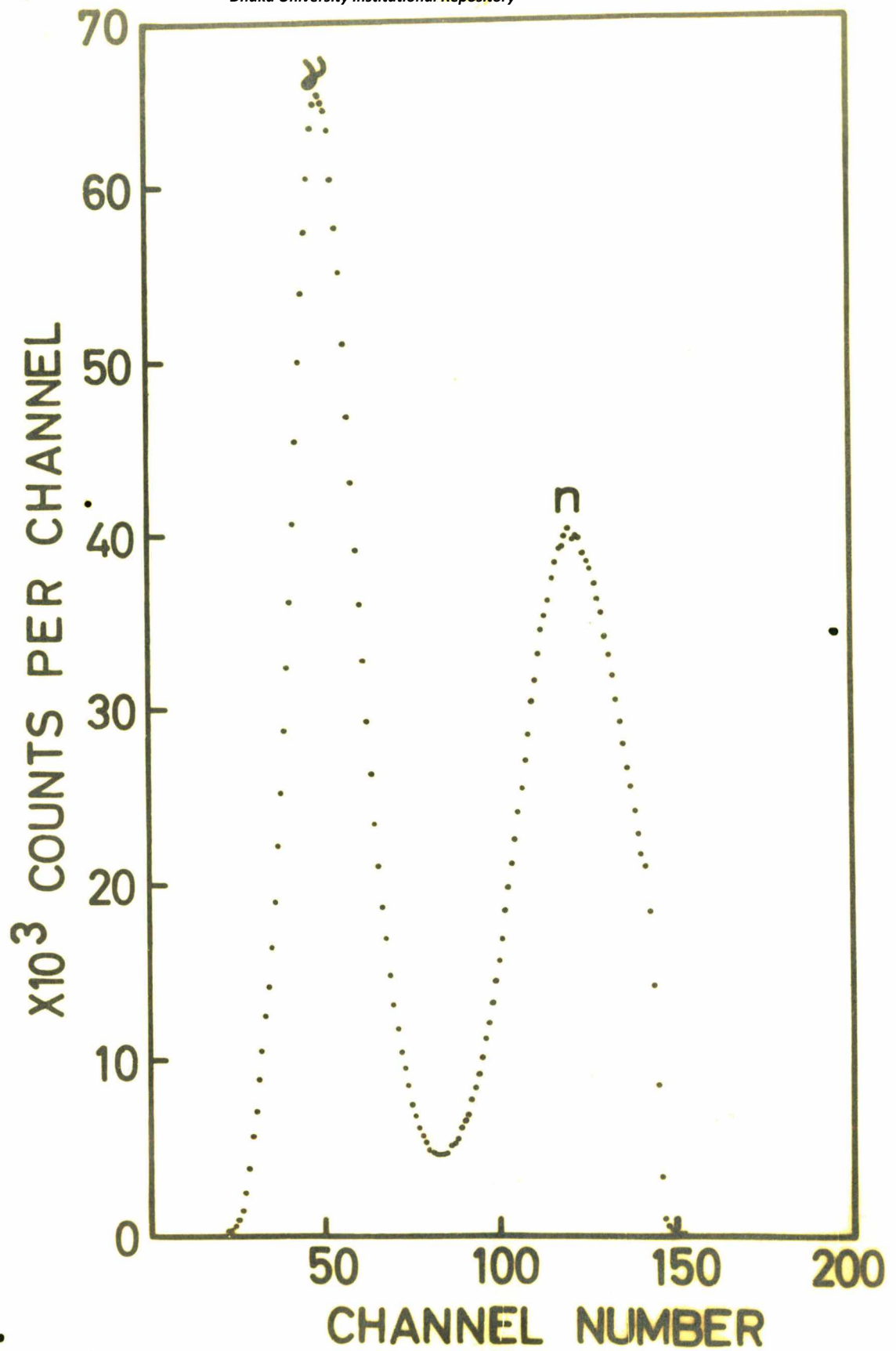


Fig.2.3 A typical n- γ discrimination spectrum.

level of the single channel analyzer (ORTEC 420) is then adjusted so that the gamma pulses are rejected and the neutron output pulses are recorded in a scaler.

2.7 Beam alignment

The size of the beam spot is defined and regulated by the slit and the collimator used in the beam path. In the present measurement the beam was aligned by horizontal slits used before the magnet to get a 3mm beam spot which was viewed through viewer used there. The beam after analysing by a 25° analysing magnet was aligned by the horizontal slits and two tantalum collimators. The beam was narrowed to 2mm by the horizontal slits before it passes through the first 5mm tantalum collimator. The beam finally passes through a 2mm tantalum collimator which is placed concentric in cold copper tube of the cold trap. The cold trap is hanged with a clamp which is connected to a L-shaped stand. The clamp has an arrangement for horizontal and vertical adjustment of cold tube. Once the beam is properly aligned it will only hit the target area.

2.8 Target holder

The target holder is made up of two hollow copper cylinders. They are joined by silver soldering. Chilled water circulates through the area in between the outer and the inner cylinders. The front face of the target holder is cut at 45° for better heat dissipation from the backing material of target. A hollow tantalum cylinder is used to push the target into the target holder.

2.9 Suppression of backgrounds by cold trap:

Since the resonance in the (p, γ) reactions of medium weight nuclei are of low intensity, the detection system needs the most effective suppression of background signals. The intensity of the background signals were almost equal to those of the reactions to be studied. There are three main sources of background, stated below.

- (i) When the projectile hits the dirt deposited on the target and the neighbouring collimator the light elements in the dirt produces $(p, p'\gamma)$, $(p, \alpha\gamma)$ and $(p, n\gamma)$ reactions. The cross-sections of these reactions are high and consequently γ -yield was comparable to that of the reactions studied. The dirt is due to mercury vapour coming out of the diffusion pump and other gaseous vapours such as carbon etc.
- (ii) Deuterons leaking from the deuteron container through the palladium foil of the palladium heater get accelerated along with the protons and due to higher mass cannot reach the target and are deposited on the slits and on the magnet chamber etc. The next incoming deuteron hitting the deposited one produces neutron through ${}^2\text{H}({}^2\text{H}, n){}^3\text{He}$ reaction. The neutrons in turn produce gamma rays from the thick lead shielding through $\text{Pb}(n, \gamma)$ reaction.
- (iii) Gamma rays from cosmic rays and other sources.

The first type of background was reduced by the use of cold trap. All foreign particles are trapped on the cold surface such as liquid air cooled copper tube and 2mm tantalum collimator which are placed in front of the target holder.

Neutron background was reduced by disconnecting the deuteron container and the palladium leak from the ion source. The deuteron contaminated ion source was replaced by a fresh one.

A concrete wall was built in between the accelerator and the target area to minimise the machine background gammas. The detector was also shielded by thick cylindrical lead shielding to minimize gamma backgrounds.

2.10 Targets

The ^{27}Al , ^{51}V and ^{55}Mn targets were prepared in the Atomic Energy Centre, Dacca. The backing material used was tantalum. The thickness of tantalum was about 0.2mm. The tantalum backing was cleaned by glowing it in a speedivac coating unit (Model 12E6/1222) and then target material was evaporated on it.

The ^{27}Al , ^{51}V and ^{55}Mn targets were prepared from natural aluminium, vanadium and manganese which were procured from British Drug House. The ^{54}Fe targets (different thickness) were procured from Harwell, England. Table 2.1 shows the various targets of different thicknesses used in present measurements.

Table 2.1

Target thickness and isotopic abundance

Target	Thickness of target ($\mu\text{g}/\text{cm}^2$)	Abundance %	Reactions
$^{27}\text{Al}(\text{natural})$	20	^{27}Al — 100	(p, γ)
$^{51}\text{V}(\text{natural})$	20	^{51}V — 99.76 ^{50}V — 0.24	(p, γ) and (p, n)
$^{54}\text{Fe}(\text{isotopic})$	20	^{54}Fe — 98.63 ^{56}Fe — 1.20 ^{57}Fe — 0.26 ^{58}Fe — 0.007	(p, γ)
$^{55}\text{Mn}(\text{natural})$	16 and 45	^{55}Mn — 100	(p, γ) and (p, n)

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Tantalum was chosen as backing material since the gamma rays from Coulomb excitation of tantalum are lower in energy ($E_\gamma \leq 301$ keV) (ref. 26) than those of other available backing material except tungsten²⁷⁾. Because commercially available tantalum is heavily contaminated with sodium, sodium free tantalum was selected. The metal was much less contaminated with light elements than other available materials, e.g. silver and tungsten. Moreover the surface smoothness of tantalum is an advantage for the preparation of targets of uniform thickness. Disadvantages of tantalum are its low heat conductivity and its high absorption coefficient for low energy gamma rays.

2.11 Beam energy resolution

The beam energy resolution depends on the stability of the analysing magnet current and finite width of the slit. This spread is assumed to be Gaussian and is determined from the steps of the thick target yield of $^{27}\text{Al} (p, \gamma) ^{28}\text{Si}$ reaction at 992 keV resonance. The spread in beam was found to be 850 eV. The proton energy E_p is related to the measured frequency 'f' of nuclear resonance probe by

$$E_p = Kf^2 \quad \text{..... (2.1)}$$

where K is constant depending on the effective radius of the analysing magnet. The K -value of the analysing magnet was measured from 992 keV resonance in $^{27}\text{Al} (p, \gamma) ^{28}\text{Si}$ reaction which has been used as a primary calibration energy.

CHAPTER -3

Isobaric Analogue Resonances from (p, γ) and (p,n) reactions in ^{51}V , ^{54}Fe , ^{55}Mn , and ^{27}Al 3.1 Introduction

A new tool in the field of nuclear spectroscopy has become available following the observation of the isobaric analogue states as compound nuclear resonances at high excitation energy by Fox et al.²⁾. A large number of experiments have been performed to study the isobaric analogue resonances in different proton induced reactions. The reactions that are commonly used are the elastic and inelastic proton scattering, (p, γ) and (p,n) reactions. These studies serve to identify analogue states as standing well above the background of numerous fine resonances in medium and heavy nuclei at an excitation where the density of normal states ($T = T_z$) is high and as such cannot be studied by other methods. Such measurements are expected to provide useful information on the isobaric spin dependence of the nuclear forces and Coulomb displacement energy in nuclei throughout the periodic table of elements.

There has been a very limited measurement on analogue resonances in ^{52}Cr . The analogue states in ^{52}Cr corresponding to the ground and low-lying levels in ^{52}V (ref. 10) have been studied from (p, γ) and (p,n) reactions in ^{51}V upto $E_p = 2.70$ MeV (refs. 7,8, 10). A few analogue resonances has also been located in the energy range of $E_p = 2.10-3.10$ MeV by Coleman et al.⁹⁾. There appears some discrepancies among these measurements. Analogue resonances observed by some workers have not been observed in other measurements for

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example, analogues corresponding to levels 0.875, 1.490, 1.759 and 1.795 MeV in ^{52}V . A few well established levels in ^{52}V do not seem to have any analogues in ^{52}Cr . The present work in ^{51}V by (p, γ) and (p, n) reactions was, therefore, undertaken in an attempt to study the analogue resonances in ^{52}Cr .

There is a little information on isobaric analogue states in ^{55}Co . From (p, γ) reaction in ^{54}Fe Maripuu ¹¹⁾ has reported two analogue states arising as strong resonances in the energy range of $E_p = 1 - 2$ MeV. In the elastic proton scattering on ^{54}Fe four analogue states ¹²⁾ have been observed in the energy range $E_p = 1.70 - 2.00$ MeV and $2.30 - 3.20$ MeV. Three analogue states namely at $E_p = 1.802, 2.243$ and 2.750 MeV by ^{54}Fe (p, p) were observed by Lindstrom et al. ¹³⁾ in the energy range $E_p = 1.75 - 3.30$ MeV. Moreover a few levels have been identified as analogues to ^{55}Fe from $(^3\text{He}, d)$ and (α, t) reactions at low excitation ²⁸⁻³²⁾. The present work on (p, γ) reaction in ^{54}Fe was undertaken with the intention to study analogue states using a proton beam upto 3 MeV.

Sufficient measurements on analogue resonances in ^{56}Fe are not available. Otto et al. ¹⁴⁾ measured the excitation curves of (p, γ) and (p, n) reactions in ^{55}Mn in the energy range $E_p = 1.30 - 1.85$ MeV and observed a number of analogue resonances corresponding to the ground and low-lying states in ^{56}Mn upto 0.486 MeV. A later paper ¹⁶⁾ was concerned with the decay properties of some of these (p, γ) resonances. The only other measurements available is of Sakai et al. ¹⁷⁾ who in their ^{55}Mn (p, γ)

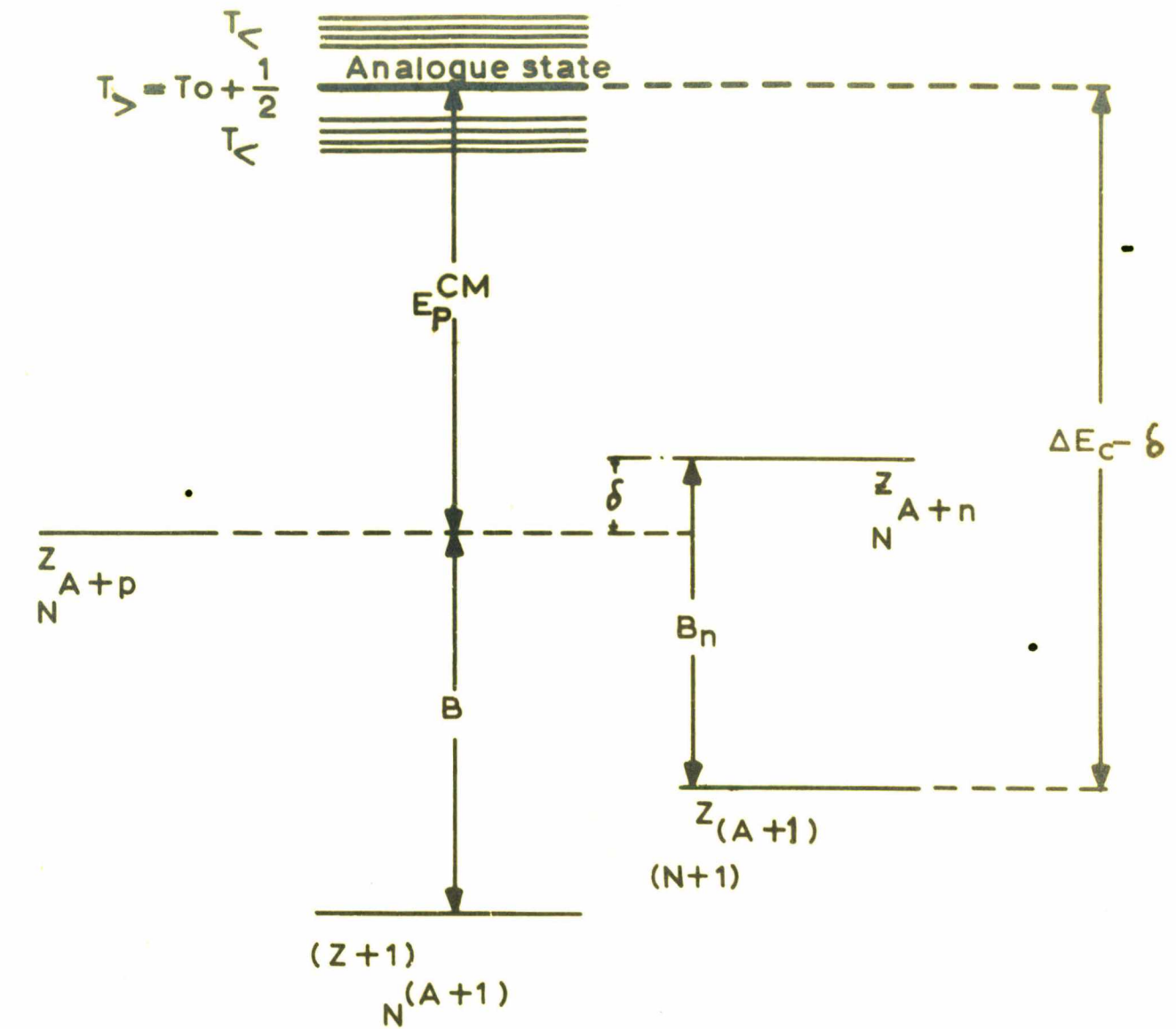
^{56}Fe reaction observed three analogue resonances at $E_p = 1.349$, 1.439 and 1.537 MeV. The present work was undertaken with a view to study the analogue states in ^{56}Fe from (p, γ) and (p, n) reactions in ^{55}Mn using the proton beam of energy upto 3.05 MeV.

Many workers have studied the (p, γ) reaction in ^{27}Al and properties associated with resonances. These have been summarized by Ednt and Van der Leun ²¹⁾. Information on analogue states is, however, inadequate. The elastic scattering of protons on ^{27}Al was measured by Awaya ¹⁹⁾ in the energy range $E_p = 0.77-1.39$ MeV; a few resonances were observed, some of which were identified as analogues of low-lying states of ^{28}Al (ref. 21). Jaffe and Harchol ¹⁸⁾ compiled (p, γ) data from previous measurements and reported three analogue resonances in the energy range $1.20 - 2.50$ MeV. No other measurement has yet been performed. This motivated to undertake the present measurement.

This chapter is concerned with the identification of isobaric analogue resonances from (p, γ) reaction in ^{27}Al in the energy range $E_p = 0.85-3$ MeV. Properties of resonance levels in ^{28}Si , including analogue resonances, by (p, γ) and (p, p) measurements will be discussed in chapters 6 and 7 respectively.

3.2 Formation of Analogue Resonances

The formation of analogue resonances as compound nuclear states in medium weight nuclei were first interpreted in the (p, p) and (p, n) reactions on ^{89}Y by Fox et al. ²⁾. A reaction of this type is pictorially presented in fig. 3.1 When one adds a proton and a neutron to a target nucleus ${}^Z_N A$ one can obtain the analogue states in the analogue nucleus ${}^{(Z+1)}_{N+1}(A+1)$ and the parent state in the parent nucleus ${}^Z_{N+1}(A+1)$. The mass number for the analogue nucleus and the parent nucleus are same but their total isobaric spin are different. The ground state isobaric spin of the target nucleus is $T_0 = T_Z = (N-Z)/2$. The total isobaric spin of the analogue nucleus and the parent nucleus are $T = T_Z = T_0 - 1/2$ and $T = T_Z = T_0 + 1/2$ respectively. A target nucleus ${}^Z_N A$ is bombarded with protons to form a state in the compound system ($Z + 1$ protons, N neutrons) with total isobaric spin $T = T_0 + 1/2$, the analogue of a state in the parent system (Z protons, $N+1$ neutrons) which has the same total isobaric spin $T = T_0 + 1/2$. The energy of analogue state in a compound system does not correspond to the same energy in the parent system. This inequality in energy is accounted for by the Coulomb displacement energy and the neutron-proton mass difference as shown in fig. 3.1; the Coulomb interaction causes the energy to increase and the neutron-proton mass difference causes a decrease in energy. The difference is given by $\Delta E_c - \delta$; where ΔE_c is the Coulomb displacement energy between the nuclei ${}^{Z+1}_N(A+1)$ and ${}^Z_{N+1}(A+1)$ and δ is the neutron-



Target Nucleus

Analogue Nucleus

Parent Nucleus

Fig.3.1 Schematic level diagram showing energy relation between analogue states.

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proton mass difference. One can write from fig. 3.1

$$\Delta E_c - \delta = E_p^{CM} + B_n - \delta$$

$$\text{or, } \Delta E_c = E_p^{CM} + B_n \dots\dots\dots (3.1)$$

where, E_p^{CM} is the incident proton energy in the centre of mass system and B_n is the neutron separation energy in the parent nucleus.

The ground state energy of analogue in the compound system analogue nucleus ${}^{Z+1}_{N(A+1)}$ comes to be

$$E(g.s.a.) = E_p^{CM} + B_p = \Delta E_c - B_n + B_p \dots\dots\dots (3.2)$$

where B_p is the proton separation energy in the compound system.

The energy of analogue states corresponding to the low-lying excited states in parent nucleus is obtained by

$$E(g.s.a.) = \Delta E_c - B_n + B_p + e_x \dots\dots\dots (3.3)$$

where e_x is the energy of low-lying excited states in the parent nucleus.

3.3 Analogue states in ${}^{52}\text{Cr}$ Measurements

Isobaric analogue states from ${}^{51}(\text{p}, \gamma) {}^{52}\text{Cr}$ and ${}^{51}\text{V}(\text{n}, \text{n}) {}^{51}\text{Cr}$ reactions in the energy region $E_p = 0.70-2.98$ MeV and $E_p = 2.14 - 3.12$ MeV respectively were measured. The analogue

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resonances at $E_p = 0.760$ and 0.783 MeV corresponding to ground state and first excited state 0.0172 MeV in ^{52}V (ref. 10) were observed by (p, γ) reaction in ^{51}V by mass two beam. The target used was nominally $16 \mu\text{g}/\text{cm}^2$ thick and they were prepared in A.E.C., Dacca. The thickness of tantalum backing was about 0.2 mm. The beam intensity was $1-3 \mu\text{A}$. Throughout the experiments the backings were water cooled to avoid evaporation under exposure to the proton beam. The gamma-ray and neutron yields were obtained in 1 KeV steps for a fixed number of beam charges. The yields were then plotted as a function of proton energy to obtain the excitation function. The excitation function thus obtained is independent of the complex decay scheme of the capturing levels and was therefore free from any ambiguities arising due to the arbitrary setting of discriminator bias in measuring the (p, γ) yield. The detection of neutron below proton energy 2.14 MeV was not possible because of the high neutron threshold and detector threshold (Q -value of (p, n) reaction in ^{51}V is -1.530 MeV (ref.33) and the detector threshold -0.6 MeV).

The identification of analogue states depends on many factors such as the density of T_z states, the strength function of the T_z states and the spectroscopic factor of the state. In favourable cases the analogue resonances can be identified by inspection of resonance intensity. In the γ -ray yield curve (fig.3.2) the γ -ray intensity shows maxima at proton energies which may be interpreted as analogue states of ^{52}V in ^{52}Cr . The excitation energy $E_x(\text{Obs})$ was obtained from the incident proton energy E_p , the

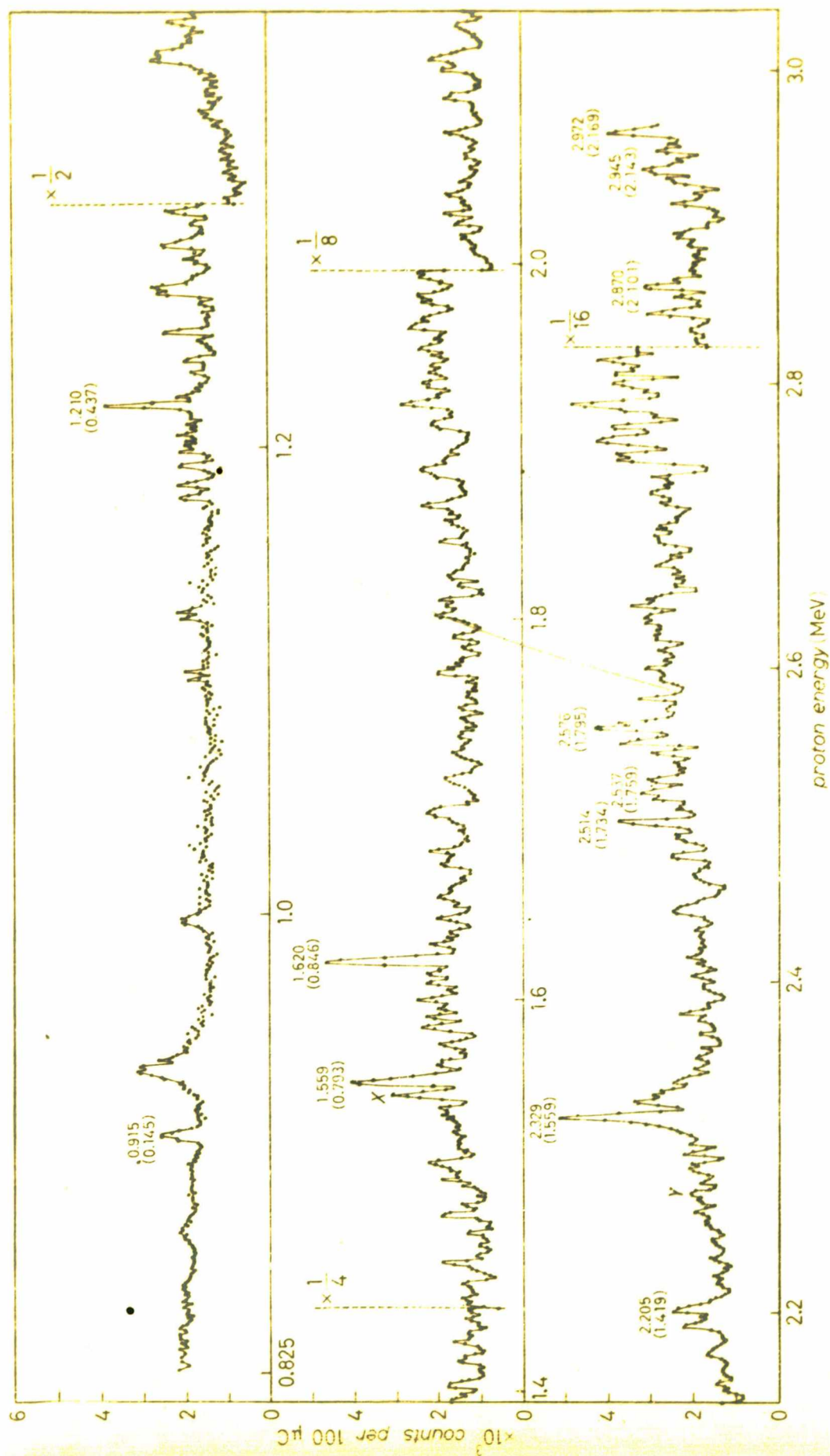


Fig.3.2 Measured gamma ray yield as a function of proton energy from the $^{51}\text{V}(p, \gamma)^{52}\text{Cr}$ reaction at $E_p \gg 1.5$ MeV and the proton analogue resonances are labelled and the corresponding low-lying states in ^{52}V are shown in parenthesis.

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known Q-value of the (p, γ) reaction given by

$$E_x(\text{Obs}) = Q(p, \gamma) + \frac{A}{A+1} E_p \quad \dots\dots (3.4)$$

The excitation energy $E_x(\text{cal})$ of the compound nuclear system ^{52}Cr can be obtained from a knowledge of the Coulomb displacement energy ΔE_c of the isobaric pair of nuclei $^{52}\text{V} - ^{52}\text{Cr}$, low-lying excited states of ^{52}V (ref. 10) and Q-value of $^{52}\text{V} (p, n) ^{52}\text{Cr}$ reaction namely through the relation

$$E_x(\text{Cal}) = Q(p, n) + \Delta E_c + e_x \quad \dots\dots (3.5).$$

The Coulomb displacement energy ΔE_c can be obtained experimentally from (p, γ) , (p, n) , β -decay, (p, d) and many other reactions. The values of ΔE_c , as measured by various workers, have been subjected to a systematic analysis by Anderson et al. ²⁰).

The variation of ΔE_c with target mass and charges shows the following empirical least squares relation

$$\Delta E_c = (1.444 \pm 0.005) \frac{\bar{Z}}{A^{1/3}} - (1.13 \pm 0.04) \quad \dots\dots (3.6)$$

where $\bar{Z}$ = average charge of the compound nucleus and its isobar and A = mass number of the isobar. The value ΔE_c for the pair $^{52}\text{V} - ^{52}\text{V}$ as calculated from the relation comes to be (7.961 ± 0.071) MeV. It may be noted that we have made a similar least squares analysis of Coulomb displacement energy and obtained the relation given by $\Delta E_c = (1.437 \pm 0.003) \bar{Z}/A^{1/3} - (1.081 \pm 0.02) \quad \dots\dots (3.7)$ as discussed in details in the following chapter. The ΔE_c -value as calculated from above relation comes to be (7.966 ± 0.038) MeV.

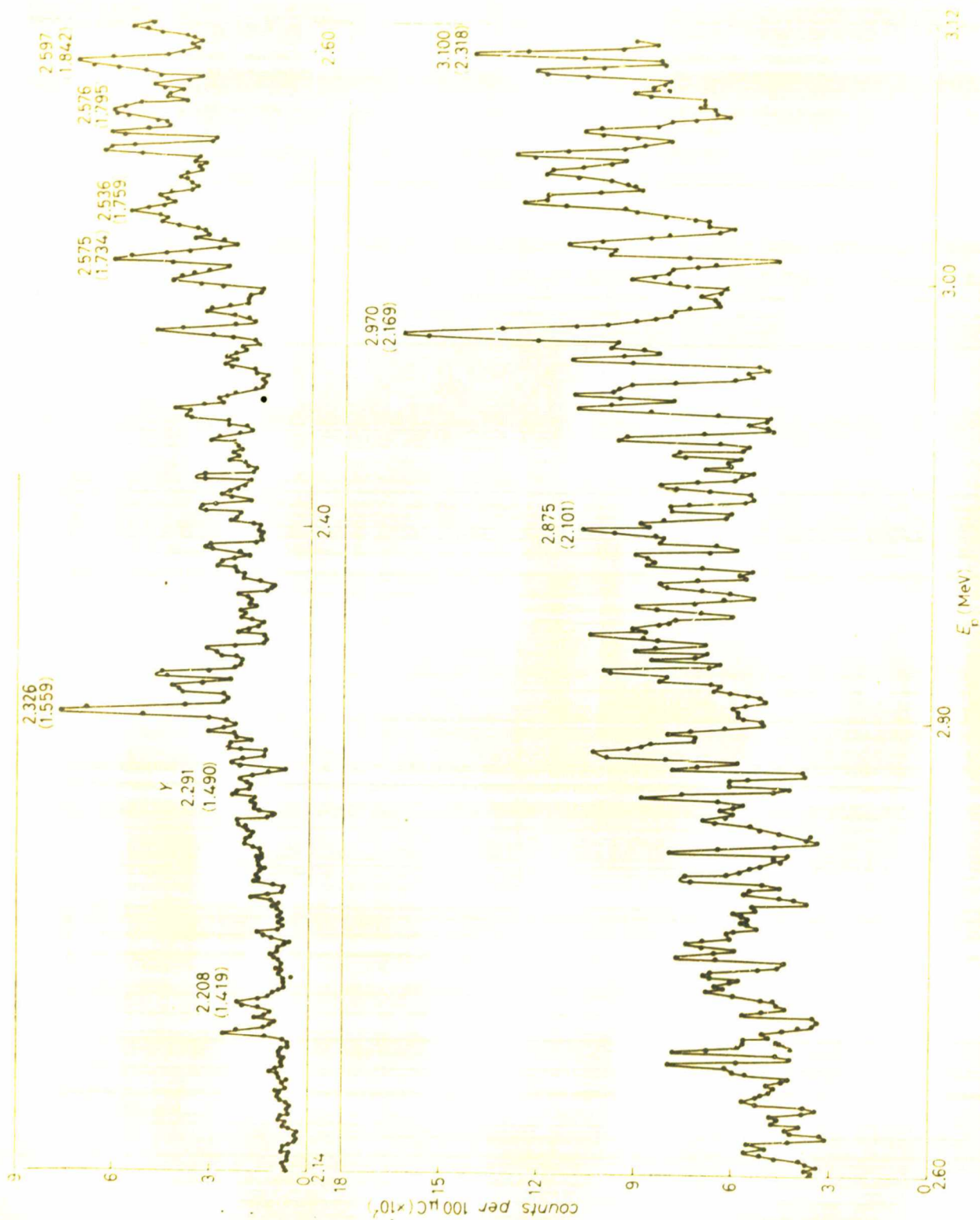


Fig.3.3 Neutron yield curve from the $^{51}\text{V}(p,n)^{52}\text{Cr}$ reaction, the analogue resonances are labelled and the corresponding levels in ^{52}V are shown in parenthesis.

Result and discussion

The γ -ray yield curve shown in fig. 3.2 exhibits a number of strong resonances that stand prominently above the background of fine resonances. These strong resonances are identified as analogues of the ground and the low-lying levels in ^{52}V . The (p,n) spectrum shown in fig. 3.3 is almost identical with the (p, γ) excitation curve. It is seen that the resonances appear at about the same proton energy agreeing to within a few keV. It is thus possible to check the consistency of the measurement. The (p, γ) yield curve covering the energy range from 0.700-0.930 MeV using mass 2 beam is given in fig. 3.4.

It is seen from the fig. 3.3 that the compound nucleus ^{52}Cr corresponding to the low-lying states in ^{52}V below 1.419 MeV were not observed in ^{51}V (p,n) ^{51}Cr reaction for reason stated earlier. These analogue states have been observed by (p, γ) reaction in ^{51}V .

In the present experiment on ^{51}V , sixteen analogue states have been observed. The results of present work and other available measurements are summarized in table 3.1 for comparison. It is seen from the table that a resonance at $E_p = 1.558$ MeV has been suspected to be analogue of the possible 0.768 MeV state in ^{52}V by some authors ^{7,10)} while it has not been observed by others ⁸⁾. The present work shows a resonance at correct proton energy (marked "x" in fig. 3.2), but there is no positive evidence for the existence of 0.768 MeV states in ^{52}V and we believe it to be a component of the structure exhibited by the adjacent resonance

TABLE 3.1
Isobaric Analogue States in ^{52}Cr

States in ^{52}V (MeV)	Observed Proton Resonances E_p (Lab)(MeV)						Excitation Energy (MeV)		$E_x(\text{Obs}) - E_x(\text{Cal})$ (keV)						
	(p, γ)		(p,n)	(p, γ)	(p,n)	(p, γ)	(p,n ℓ)	$E_x(\text{Obs})$	$E_x(\text{Cal})$	$E_x(\text{Cal})$					
	b)	b)	c)	c)	d)	d)	f)		h)	(b-g)	(b-h)	(c-g)	(d-g)	(e-g)	(f-g)
a)															
0	0.760		0.763		0.781		0.769	11.213	11.090	11.095	123	118	126	144	132
0.0172															
0.0228	0.783		0.781		0.795		0.785	11.236	11.110	11.115	126	121	124	138	128
0.142		0.915	0.910		0.915		0.912	11.365	11.235	11.240	130	125	125	130	127
0.148															
0.437	1.210		1.210		1.202		1.208	11.655	11.527	11.532	128	123	128	120	126
			(1.558)				(1.558)								
0.793	1.559		1.565		1.562		1.592	11.997	11.883	11.888	114	109	120	117	146
0.846	1.620		1.629		1.626		1.629	12.057	11.936	11.941	121	116	129	127	130
0.875							1.658		11.965	11.970					129
1.262									12.372	12.377					
1.419	2.205	2.208	2.203	2.203		2.213	2.203	12.632	12.059	12.514	123	118	119	129	119
1.490			2.273	2.273		2.309(2.273)			12.580	12.585			117	152	117
1.559	2.329	2.326	2.333	2.333		2.346	2.346	12.751	12.649	12.654	102	97	107	120	109
1.578									12.668	12.673					

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Table 3.1 (Contd.)

States in ^{52}V (MeV)	Observed proton Resonances E_p (Lab) (MeV)						Excitation Energy (MeV)		E_x (Obs) - E_x (Cal) (keV)							
	(p, γ)		(p, n)	(p, γ)	(p, n)	(p, γ)	(p, n)	E_x (Obs)	E_x (Cal)	E_x (Cal)	(b-g)	(b-h)	(c-g)	(d-g)	(e-g)	(f-g)
	b)	b)	b)	c)	c)	e)	f)	b)	g)	h)						
a)																
1.660									12.750	12.755						
1.734	2.514	2.515	2.521	2.521		2.517	2.538	2.515	12.824	12.829	110	105	116	112	133	110
1.759	2.537	2.536	2.538	2.538		2.539		2.545	12.849	12.854	106	101	108	109		111
1.795	2.576	2.576	2.583	2.583			2.583	2.580	12.885	12.890	109	104	116		116	111
1.842		2.595						2.617	12.932	12.937	83	78				109
2.101	2.870	2.875						2.875	13.191	13.196	94	89				99
2.143	2.945								13.233	13.238	123	118				136
2.169	2.972	2.972						2.985	13.259	13.264	124	119				
2.318		3.100						3.085	13.408	13.413	100	95				85

a) Ref. 10
b) Present work
c) Ref. 7
d) Ref. 8

e) Summarized in Data Sheets 10).

f) Ref. 9

g) Expected from $Q(p, n)$ for ^{52}V - ^{52}Cr pair, levels of ^{52}V and ΔE_c value as obtained from equation (3.6)

h) Expected from $Q(p, n)$ for ^{52}V - ^{52}Cr pair, levels of ^{52}V and ΔE_c value as obtained from equation (3.7)

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at $E_p = 1.559$ MeV. A resonance analogue to the 0.875 MeV has previously been reported ¹⁰⁾ but not observed by others ^{7,8)}.

In the present measurement no strong resonance has been observed corresponding to this states; this is in agreement with the latter authors.

The resonance marked "Y" in fig. 3.3 at 2.2 MeV might correspond to the analogue of 1.490 MeV states, but it is hardly distinguishable from the adjacent normal states. This has been suspected to be analogue ¹⁰⁾ and is weakly excited in refs.(7,8). It is thus concluded that the 1.490 MeV state has no analogue in ^{52}Cr . We have observed strong resonances at $E_p = 2.54$ and 2.58 MeV, (figs. 3.2 and 3.3) where an inconsistency exists.

The only measurement available at higher excitation energy is of Coleman et al. ⁹⁾ from $(p, n\gamma)$ experiments and there is a good agreement between their results and those of the present work. The only exception is the resonance at $E_p = 2.945$ MeV, which is observed in our (p, γ) reaction. The analogue of the 1.842 and 2.318 MeV have been observed by Coleman et al. ⁹⁾ and our (p, n) reaction measurement. The former is also weak in the (p, γ) yield curve of Arai et al. ⁸⁾ and while the latter is not covered in their energy range.

It will be seen from the table 3.1 that the difference between $E_x(\text{Obs})$ and $E_x(\text{Cal})$ comes to be on the average 114 keV and 109 keV using relations (3.6) and (3.7) respectively while a

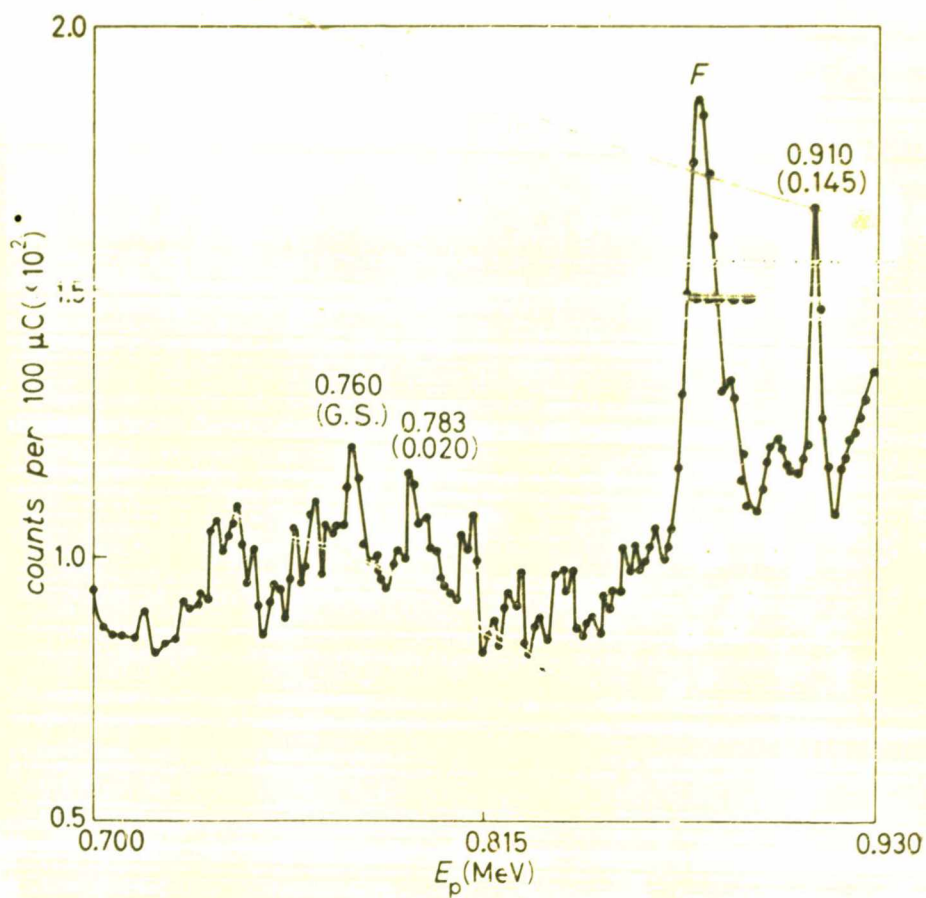
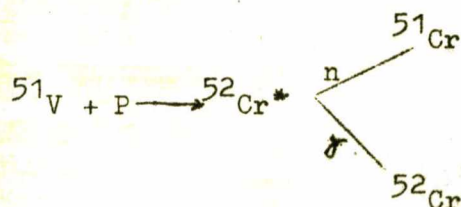


Fig.3.4 Gamma ray yield curve from the $^{51}\text{V}(p,\gamma)^{51}\text{Cr}$ reaction in the energy range $E_p = 0.700\text{--}0.930$ MeV. F stands for fluorine.

variation of the individual cases lies within a reasonable limit. This confirms the identification of strong resonances as analogue resonances. The Coulomb displacement energy from the present measurement comes to be (8.075 ± 0.043) MeV. This value is in excellent agreement with the value (8.075 ± 0.020) MeV of Teranishi et al.⁷⁾

The energy level diagram for the isobaric pair $^{52}\text{V} - ^{52}\text{Cr}$ is shown in fig. 3.5. The low-lying energy levels of ^{52}V are shifted by the Coulomb energy difference and the neutron-proton mass difference. The first column of fig. 3.5 gives the low-lying levels in ^{52}V , second column and third column represent predicated excitation energy level $E_x(\text{Obs})$ in ^{52}Cr respectively.

Therefore even though the (p, γ) and (p, n) reactions lead to different final nuclei, the reactions give information about the resonance levels in the compound nucleus ^{52}Cr . The process may be represented by



The nucleus ^{51}V , in its ground state, has eight neutrons and three protons in $1f_{7/2}$ shell outside the closed $N=Z=20$ core. The incoming proton interacts with the five excess neutrons leaving other neutrons practically undisturbed, thus forming ^{52}Cr . Some of the levels of ^{52}Cr will have the same spin, parity and isotopic spin as the low-lying levels of the isobaric nucleus ^{52}V . The

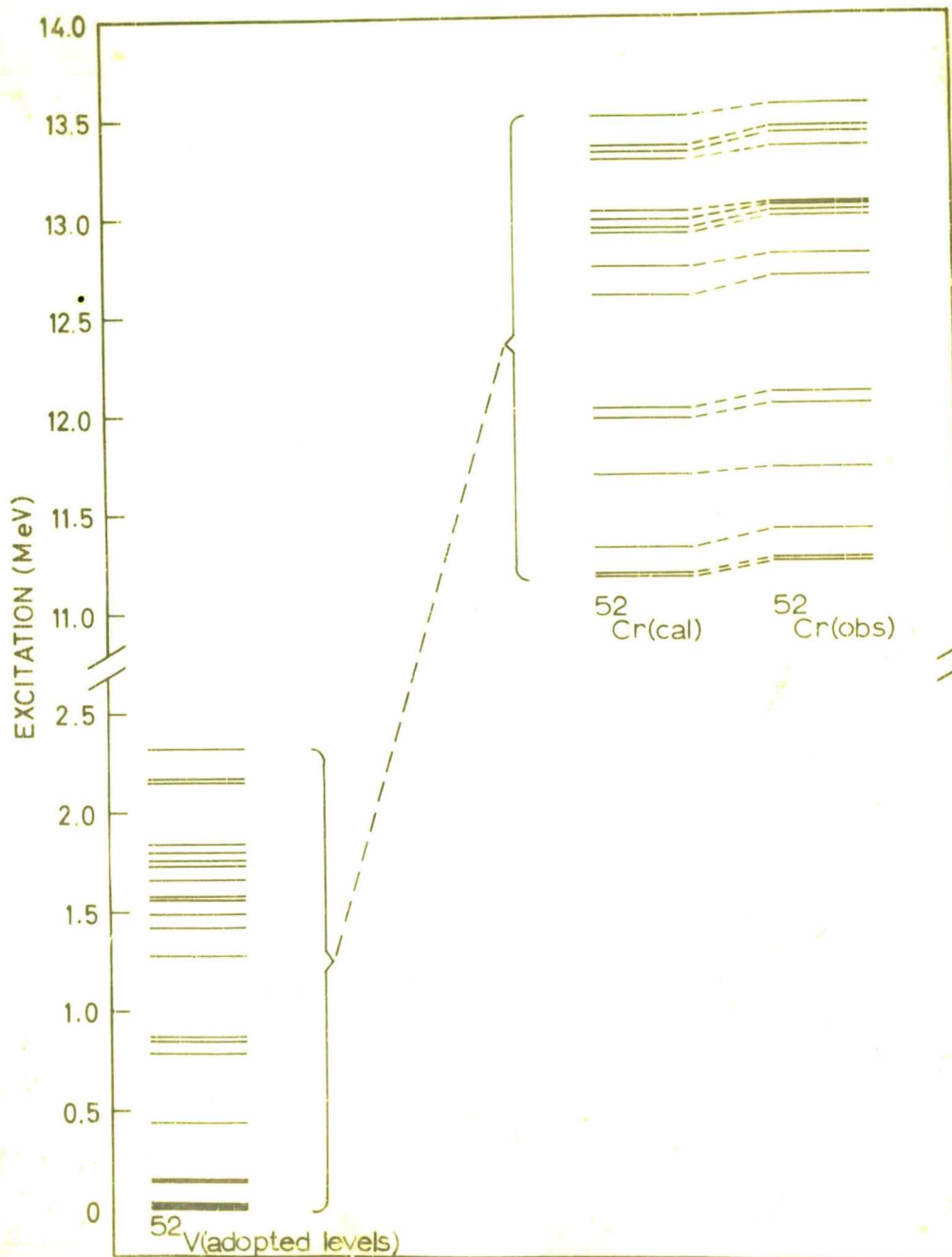


Fig.3.5 The energy level diagram for the isobaric pair ^{52}V - ^{52}Cr . The low-lying energy levels of ^{52}V are shifted by the Coulomb energy difference and the neutron-proton mass difference.



Fig.3.6 Measured gamma ray yield as a function of proton energy from the $^{54}\text{Fe}(p, \gamma)^{55}\text{Co}$ reaction at $E_p \geq 1.5$ MeV. The proton analogue resonances are labelled and the corresponding states in ^{55}Fe are shown in parenthesis.

excitation energies of analogue states can, therefore, be estimated from the level scheme of the low lying energy levels e_x in ^{52}V (ref. 10) and the Coulomb displacement energy ΔE_c , as stated earlier.

3.4 Analogue states in ^{55}Co

Measurement

The target isotopically enriched and nominally $20\text{ }\mu\text{g/cm}^2$ thick on tantalum backing was procured from A.E.R.E., Harwell, England. The beam current used was between $1.5\text{ }\mu\text{A}$ and $3\text{ }\mu\text{A}$. The (p,n) reaction in ^{54}Fe is not possible in our 3 MeV Van de Graaff accelerator because of its neutron threshold. Q-value of (p, n) reaction in ^{54}Fe is - 9.0039 MeV (ref. 33). Analogues corresponding to the ground and lowest four states below 1.918 MeV cannot be reached by proton capture reaction, because Q-value $^{54}\text{Fe} (p, \gamma) ^{55}\text{Co}$ reaction is 5.068 MeV as against $\Delta E_c + Q (p, n)$ in $^{55}\text{Fe} - ^{55}\text{Co}$ pair = 4.613 MeV.

Results and discussion

Isobaric analogue states from $^{54}\text{Fe} (p, \gamma) ^{55}\text{Co}$ reaction have been measured in the proton energy range 0.854 - 2.980 MeV. The γ -ray yield curve is shown in fig. 3.6 which displays a number of strong resonances clearly distinguishable from the adjacent ones. They were identified as analogues to the well known low-lying levels in ^{55}Fe (ref. 34).

The results of the present measurement along with previous ones¹¹⁻¹³⁾ are summarized in table 3.2. Eleven resonances were identified in this work to be analogues of the low lying levels

TABLE - 3.2
Isobaric Analogue States in ⁵⁵Co.

States in ⁵⁵ Fe (MeV) a)	Observed Proton Resonances E _p (Lab) (MeV)				Excitation energy (MeV)		E _x (Obs) - E _x (Cal) (keV)					
	(p, γ) b)	(p, γ) c)	(p, p) d)	(p, p) e)	E _x (Obs) b)	E _x (Cal) f)	E _x (Cal) g)	(b-f)	(b-g)	(c-f)	(d-f)	(e-f)
1.916	1.730				6.766	6.531	6.531	235	235			
2.050	1.809	1.803		1.802	6.844	6.663	6.663	181	181	175		144
2.153	1.894	1.886			6.928	6.766	6.766	162	162	153		
2.470	2.216				7.244	7.083	7.083	161	161			.
2.545	2.253			2.243	7.280	7.158	7.158	122	122			112
2.589	2.277				7.304	7.202	7.202	102	102			
2.948	2.699				7.718	7.561	7.561	157	157			
3.029	2.764		2.758	2.750	7.782	7.642	7.642	140	140		134	126
			2.773									
3.076	2.813				7.830	7.689	7.689	141	141			
3.117	2.875				7.891	7.730	7.730	161	161			
3.311	2.968		2.961		7.982	7.924	7.924	58	58		51	
3.431			3.125			8.044	8.044				92	

a) Ref. 34 d) Ref. 12 f) Expected from Q(p,n) for ²⁸Al-²⁸Si pair, levels in ²⁸Al and ΔE_c value
b) Present work e) Ref. 13 as predicted by equation (3.6).
c) Ref. 11 f) Expected from Q(p,n) for ²⁸Al-²⁸Si pair, levels in ²⁸Al and ΔE_c value as predicted by equation (3.7).

in ^{55}Fe , while previous authors ¹¹⁻¹³⁾, observed two, four and three analogue states by (p, γ) and (p, p) reactions. Two strong resonances at $E_p = 1.803$ and 1.886 MeV observed by Maripuu ¹¹⁾ from (p, γ) reaction were also excited strongly in the present measurement. In (p, p) measurement on ^{54}Fe by Ahlgren et al. ¹²⁾ four resonance at $E_p = 2.758, 2.773, 2.961$ and 3.125 MeV were observed as analogues; out of these, the 3.125 MeV is beyond our energy range and the 2.773 MeV analogue resonance was weakly excited in the present experiment. This is shown as marked 'x' in fig. 3.6 at $E_p = 2.779$ MeV. It is also seen that there does not seem to have any state in ^{55}Fe to which it may be a possible analogue. Three analogue states at $E_p = 1.802, 2.243$ and 2.750 MeV by (p, p) reported by Lindstrom et al. ¹³⁾ were observed in the present experiment. It is to be noted that the analogue states observed in ^{54}Fe ($^3\text{He}, d$) reaction ^{29,30)} at excitation energies 6.850 and 6.982 MeV were also observed in the present (p, γ) experiment. The analogue states in $(^3\text{He}, d)$ and (α, t) measurements occur at lower excitation energy ²⁸⁻³²⁾.

It is seen from the table 3.2 that the difference between $E_x(\text{Obs})$ and $E_x(\text{Cal})$ comes to be on the average 147 keV and a systematic variation of the individual cases exists within a reasonable limit. The Coulomb displacement energy for the present measurement comes to be (9.079 ± 0.054) MeV. This is in good agreement with the value (8.832 ± 0.074) MeV given by the semi-empirical relation (3.6) of Anderson et al. ²⁰⁾. The energy

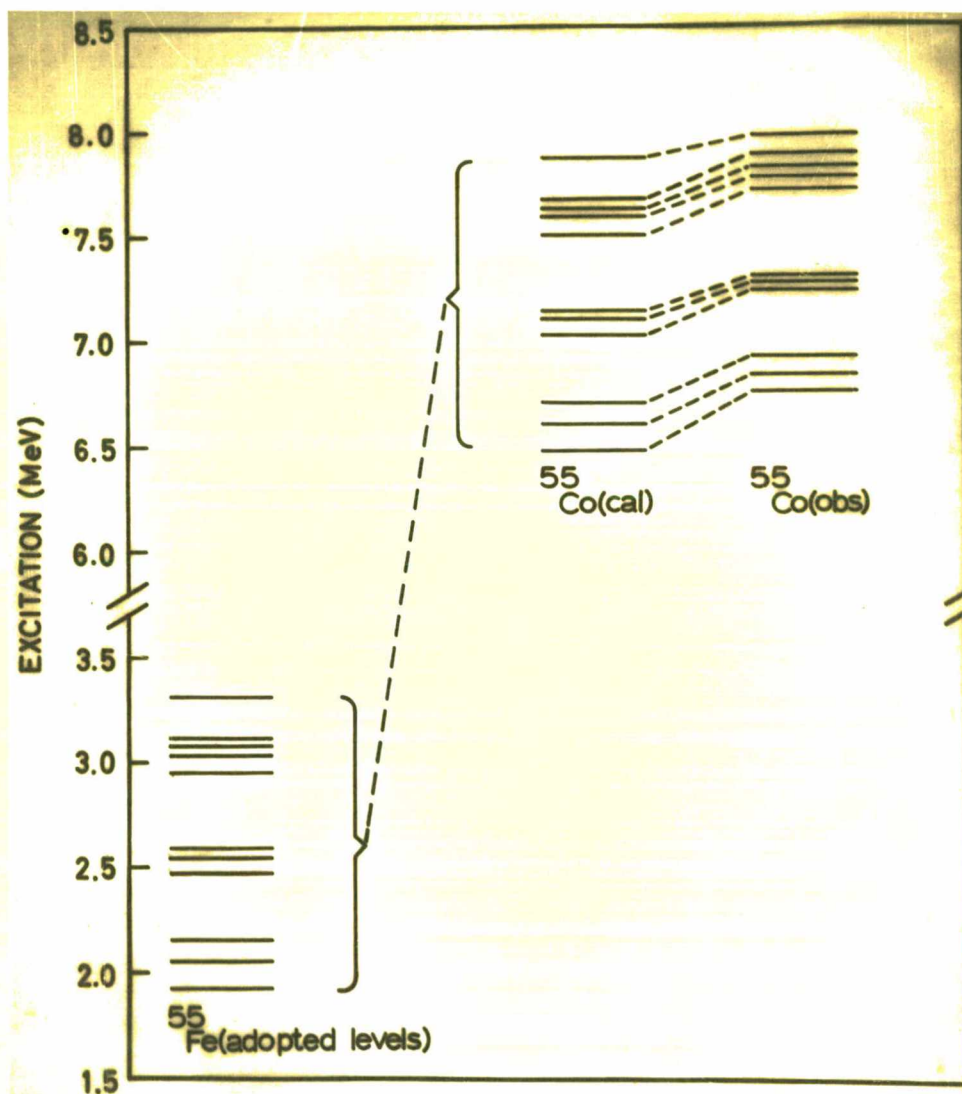


Fig.3.7 The energy level diagram for the isobaric pair ^{55}Fe - ^{55}Co . The low-lying energy levels of ^{55}Fe are shifted by the Coulomb energy difference and the neutron proton mass difference.

level diagram for the pair $^{55}\text{Fe} - ^{55}\text{Co}$ is given in fig. 3.7. The low lying energy levels of ^{55}Fe (ref.34) are shifted by the Coulomb energy difference and neutron-proton mass difference. The systematic difference in energies are almost maintained between the low lying levels in ^{55}Fe and observed excited states in the compound nucleus ^{55}Co when the former is shifted by a constant amount.

The strong resonances observed in (p, γ) reaction in ^{54}Fe correspond to the low lying energy levels in ^{55}Fe . Because of this agreement with the corresponding level scheme in ^{55}Fe and the correct value of the Coulomb displacement energy it is concluded that the corresponding resonances in the ^{55}Co nucleus represent the isobaric analogue states of the ^{55}Fe nucleus. The nucleus ^{54}Fe has eight neutrons and six protons in $1f_{7/2}$ shell in its ground state and the incident proton interacts with the two excess neutrons. The other neutrons remain practically undisturbed and the compound nucleus ^{55}Co is thus formed.

3.5 Analogue states in ^{56}Fe Measurements

In order to study the isobaric analogue states in ^{56}Fe corresponding to the low lying states in ^{56}Mn (ref. 34) the experimental set up and technique to obtain the (p, γ) and (p, n) yields from ^{55}Mn was identical with that of the measurement of analogue states in ^{52}Cr by (p, γ) and (p, n) reactions in ^{51}V . The targets used in the present work were fabricated by vacuum

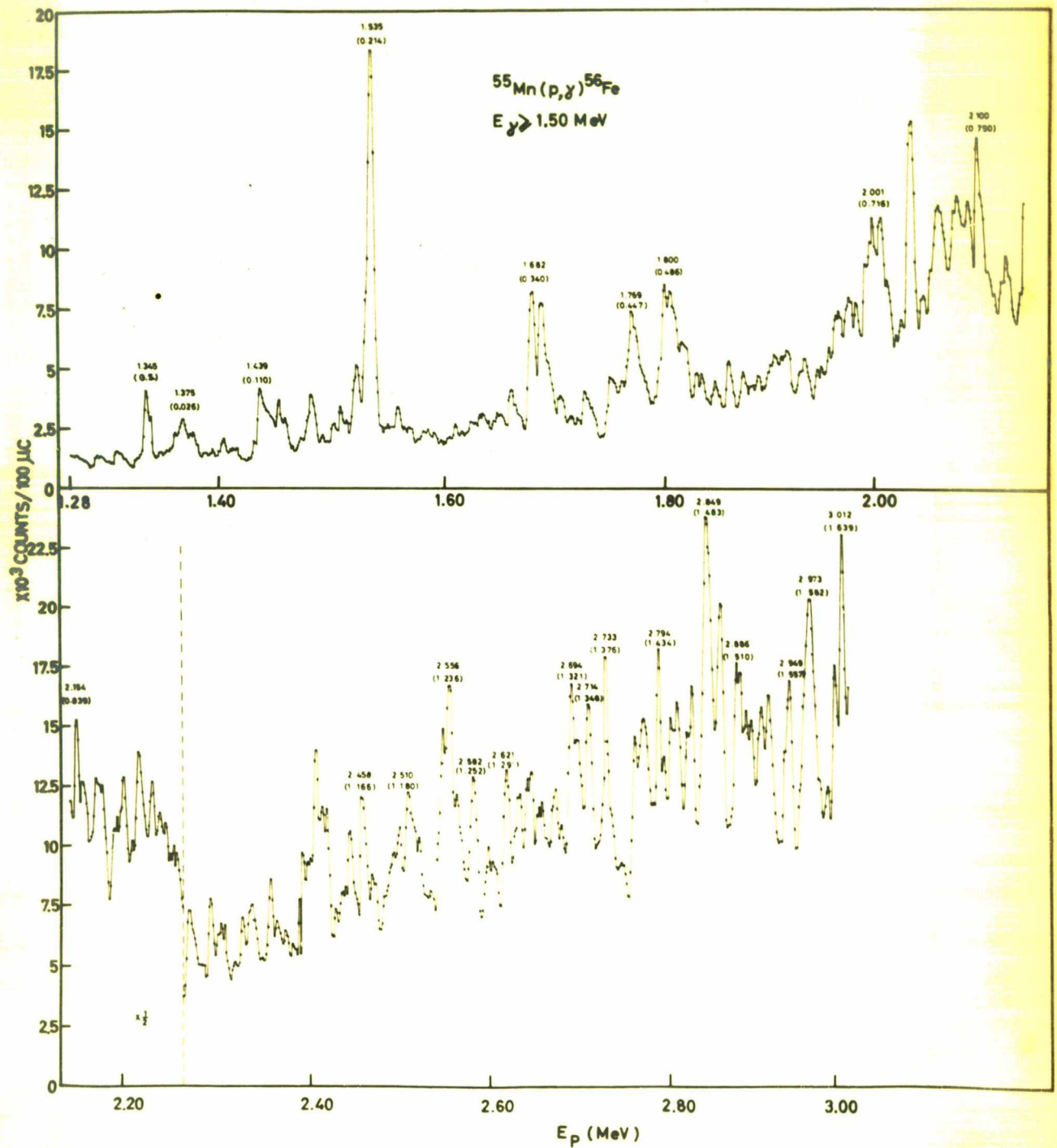


Fig.3.8 Measured gamma ray yield as a function of proton energy from the $^{55}\text{Mn}(p,\gamma)^{56}\text{Fe}$ reaction. The proton analogue resonances are labelled and the corresponding states in ^{56}Fe are shown in the parenthesis.

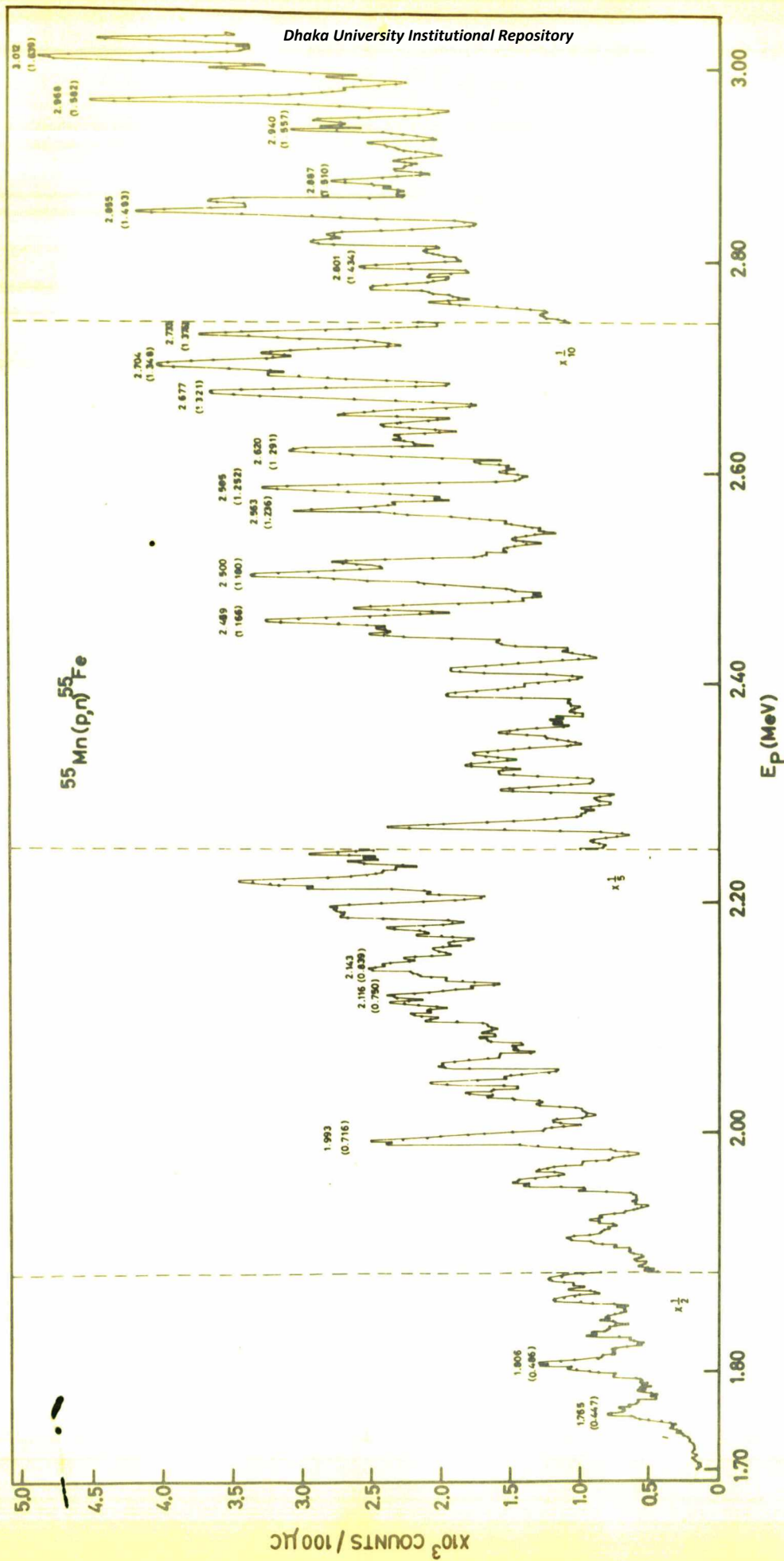


Fig.3.9 Neutron yield curve from $^{55}\text{Mn}(p,n)^{55}\text{Fe}$ reaction, the analogue resonances are labelled and the corresponding states in ^{56}Mn are shown in the parenthesis.

evaporation of natural Manganese ($\sim 100\%$ abundance of ^{55}Mn) onto 0.2 mm tantalum backings in A.E.C., Dacca.

The beam intensities were $3-6 \mu\text{A}$. For the measurement of (p, γ) and (p, n) yield curves the target thickness was nominally $16 \mu\text{g}/\text{cm}^2$ and $45 \mu\text{g}/\text{cm}^2$ respectively.

Results and discussion

Isobaric analogue states in ^{56}Fe from (p, γ) and (p, n) reactions in ^{55}Mn have been studied in the energy range $E_p = 1.28-3.05$ MeV and $1.50-3.05$ MeV respectively. The (p, γ) excitation curve shown in fig. 3.8 displays a number of strong resonances and they are clearly distinguishable from the neighbouring resonances. The neutron yield curve shown in fig. 3.9, also exhibits a number of strong resonances. The strong resonances appear almost at the same proton energy as that of (p, γ) yield curve agreeing to within a few keV. But the shape of a few resonances is somewhat different and this was also reported by Otto et al.¹⁴⁾. It is seen on comparison that neutron yield curve supplements the information derived from the gamma yield curve. These strong resonances were identified as analogues to the ground and low-lying levels in ^{56}Mn (ref. 34). The present results together with those of previous workers^{14, 17)} are listed in table 3.3. Twenty four analogue states in the compound nucleus ^{56}Fe from (p, γ) and (p, n) reactions in ^{55}Mn corresponding to the low-lying states in ^{56}Mn were observed

TABLE 3.3
Isobaric analogue States ^{56}Fe

States in ^{56}Mn (MeV)	Observed Proton Resonances E_p (Lab) (MeV)			Excitation Energy (MeV)		$E_x(\text{Obs}) - E_x(\text{Cal})$ (keV)		
	(p, γ) b)	(p, n) b)	(p, γ) c)	$E_x(\text{Obs})$ b)	$E_x(\text{Cal})$ d)	$E_x(\text{Obs}) - E_x(\text{Cal})$ (b-d)	$E_x(\text{Obs}) - E_x(\text{Cal})$ (b-e)	$E_x(\text{Obs}) - E_x(\text{Cal})$ (c-d)
a)								
0	1.345		1.348	11.509	11.343	166	163	99
0.026	1.375		1.381	11.539	11.369	170	167	105
0.110	1.439		1.441	11.602	11.453	149	146	79
0.214	1.535	1.536	1.536	11.697	11.557	140	137	69
0.340	1.682	1.683	1.678	11.841	11.683	158	155	71
0.447	1.769	1.765	1.764	11.924	11.790	134	131	57
0.436	1.800	1.806	1.799	11.960	11.829	131	128	59
0.716	(2.001)	1.993		12.150	12.059	91	88	
0.750	2.100	2.116		12.259	12.093	166	163	
0.839	2.154	2.143		12.299	12.182	117	114	
1.166	2.458	2.459		12.603	12.509	94	91	
1.180	2.510	2.500		12.649	12.523	126	123	
1.236	2.556	2.563		12.703	12.579	124	121	
1.252	2.582	2.585		12.726	12.595	131	128	
1.291	(2.621)	2.620		12.763	12.634	129	126	
1.321	2.694	2.677		12.826	12.664	162	159	
1.348	2.714	2.704		12.849	12.691	158	155	
1.376	2.733	2.733		12.873	12.719	154	151	
1.434	2.794	2.801		12.936	12.777	159	156	

Table 3.3 (Continued)

States in $^{56}\text{Mn}(\text{MeV})$	Observed Proton Resonances $E_p(\text{Lab}) (\text{MeV})$				Excitation Energy (MeV)			$E_x(\text{Obs}) - E_x(\text{Cal})$ (keV)	
	(p, γ)		(p, n)	(p, γ)	$E_x(\text{Obs})$	$E_x(\text{Cal})$	$E_x(\text{Cal})$	$(b-d)$	$(b-e)$
	b)	c)	b)	c)	b)	d)	e)		
a)									(C-d)
1.483	2.849		2.855		12.990	12.829	12.829	164	161
1.510	2.886		2.887		13.024	12.853	12.856	171	168
1.557	2.949		2.940		13.081	12.900	12.903	181	178
1.582	2.973		2.968		13.106	12.925	12.928	181	178
1.639	3.012		3.012		13.147	12.982	12.985	165	162

(a) Ref. 34

(b) Present work

(c) Ref. 14

(d) Expected from $Q(p, n)$ for ^{56}Mn - ^{56}Fe pair, levels in ^{56}Mn and ΔE_c -value as predicted by equation(3.6)

(e) Expected from $Q(p, n)$ for ^{56}Mn - ^{56}Fe pair, levels in ^{56}Mn and ΔE_c -value as predicted by equation(3.7)

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in the present measurement. Otto et al.¹⁴⁾ observed seven analogue resonances corresponding to the ground and low lying states in ^{56}Mn up to 0.486 MeV. The results of the present measurements are in excellent agreement with those of Otto et al.¹⁴⁾ and moreover seventeen new analogue resonances were observed.

Below 1.70 MeV the 1" x 1½" stilbene detector could not be used for the detection of neutrons because the sum of the Q-value for the (p,n) reaction and neutron detector threshold was $-1.0145 - 0.6 = -1.62$ MeV. Therefore, two analogue resonances at $E_p = 1.536$ and 1.683 MeV were identified by ZnS crystal in (p,n) reaction. The nucleus ^{55}Mn , in its ground state, has five protons in $1f_{7/2}$ shell and ten neutrons distributed in $1f-2p$ shells. The incoming proton interacts with five unpaired neutrons. The other neutrons remain practically undisturbed and the compound nucleus ^{56}Fe is formed.

A comparison of the observed excitation energy as compound nuclear resonances in ^{56}Fe with those expected from known levels in ^{56}Mn shows that they differ on the average by 147 keV. The Coulomb displacement energy as obtained from the present work comes to be (8.641 ± 0.047) MeV for $^{56}\text{Mn} - ^{56}\text{Fe}$ pair using the relation (3.6) as given by Anderson et al.²⁰⁾. Excitation energies obtained by relation (3.7) given in this work are also presented in the table 3.3. It is seen that the difference between the observed and expected excitation energy, i.e., $E_x(\text{Obs}) - E_x(\text{Cal})$ on the average comes to be 144 keV using the present semi-empirical relation for Coulomb displacement energy ΔE_c . The energy level diagram for the isobaric pair $^{56}\text{Mn} - ^{56}\text{Fe}$

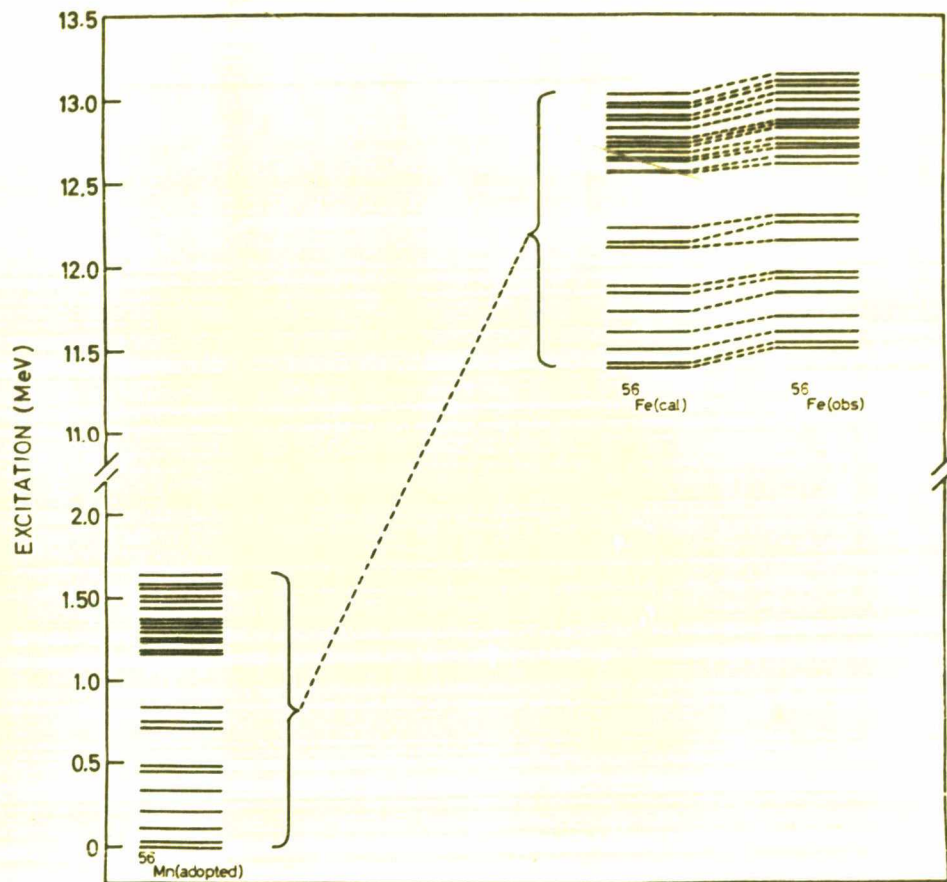


Fig.3.10 The energy level diagram for the isobaric pair ^{56}Mn - ^{56}Fe . The low-lying energy levels of ^{56}Mn are shifted by the Coulomb energy difference and the neutron proton mass difference.

is shown in fig. 3.10. The low-lying energy levels of ^{56}Mn are pushed up by the Coulomb energy difference and the neutron-proton mass differences. The first column gives the low-lying levels of ^{56}Mn , the second and third Columns represent the predicted and observed excitation energy in ^{56}Fe respectively. The systematic appearance of strong resonances differing in energy from one another by approximately the same spacing as in the levels of ^{56}Mn suggest that these resonances are analogue resonances.

3.6 Analogue states in ^{28}Si

Measurements

The experimental set up and technique for the study of isobaric analogue states in ^{28}Si from (p, γ) reaction in ^{27}Al are given in chapter 2. The targets used were prepared by vacuum evaporation of natural Aluminium (100% abundance of ^{27}Al) on to 0.2mm tantalum backing using a tantalum boat in Atomic Energy Centre, Dacca. The target thickness was nominally $20 \mu\text{g}/\text{cm}^2$. The beam current was 1-3 μA . The (p, n) reaction in ^{27}Al is not possible in our 3 MeV Van de Graaff Accelerator because of its high neutron threshold. The Q-value of (p, n) reaction in ^{27}Al is -5.5925 MeV (ref. 33).

Results and discussion

An attempt was made to study the isobaric analogue states in ^{28}Si from (p, γ) reaction in ^{27}Al corresponding to the low lying levels in ^{28}Al (ref. 21). The proton energy range was 0.85-3.0 MeV. The (p, γ) yield curve thus obtained as a function of proton energy is shown in fig. 3.11. The yield curve exhibits

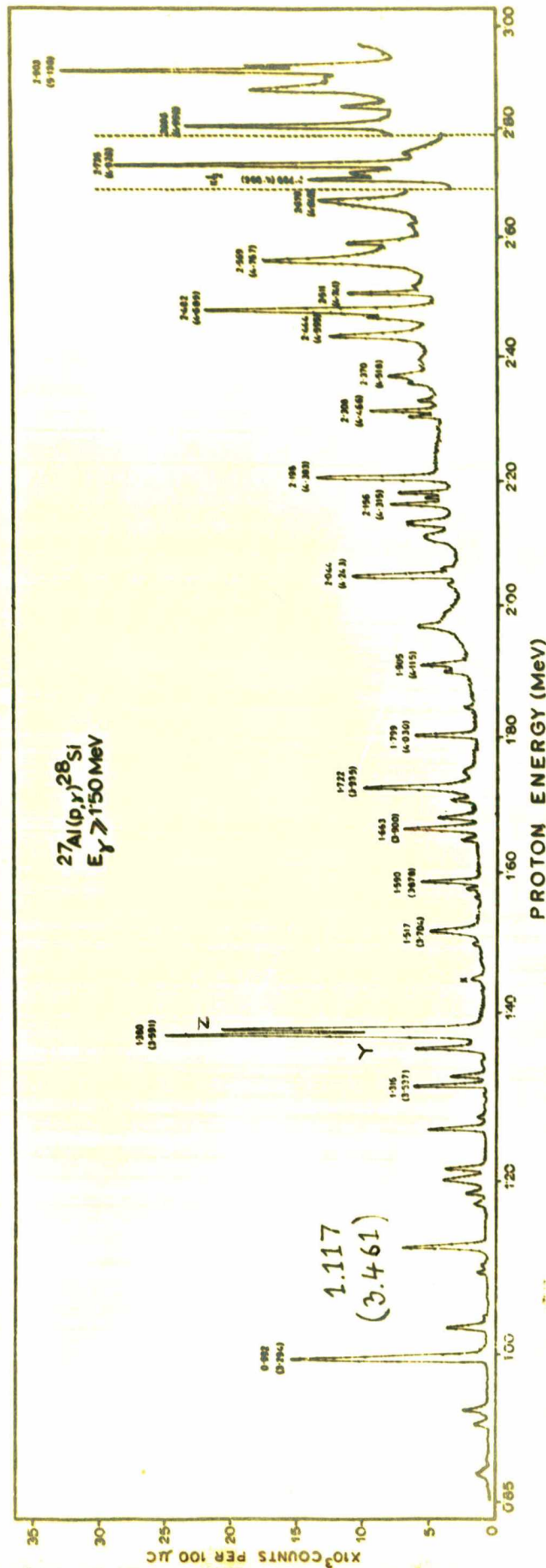


Fig. 3.11 The measured gamma ray yield as a function of proton energy from the $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ reaction. The proton analogue resonances are labelled and the corresponding states in ^{28}Al are shown in the parenthesis.

a number of strong resonances that stand prominently above the background of many fine resonances. These resonances were identified as analogues of the low lying levels in ^{28}Al . The analogue resonances corresponding to the ground and low lying states in ^{28}Al below 3.294 MeV can not be reached by proton capture reaction, because Q-value of $^{27}\text{Al} (p, \gamma) ^{28}\text{Si}$ reaction is 11.585 MeV as against $\Delta E_c + Q(p, n)$ in $^{28}\text{Al}-^{28}\text{Si}$ pair = 9.154 MeV.

The results of the present measurement along with those of Awaya ¹⁹⁾ and the compilation of Jaffe and Harchol ¹⁸⁾ are presented in table 3.4 for comparison. It is seen that there is a good agreement between the present measurement and that of Awaya (ref. 19). But there exists a contradiction in assignment to proton resonances at $E_p = 1.117$ and 1.198 MeV between the two measurements ^{18,19)}.

Proton resonances at $E_p = 1.905$, 2.308 and 2.370 MeV were tentatively identified to be analogues to 4.115, 4.466 and 4.518 MeV states in ^{28}Al . These analogue resonances are not strong enough and they are shown in parenthesis in table 3.4. The 3.669 MeV state in ^{28}Al does not seem to have any analogue in ^{28}Si . The present work, however, shows a weak resonance marked 'X' in fig. 3.11 at the correct proton energy $E_p = 1.454$ MeV.

The analogue resonances at 2.530 MeV reported by Jaffe and Harchol ¹⁸⁾ does not seem to have states in ^{28}Al . No such resonance was observed in the present measurement. Resonances at $E_p = 1.364$ and 1.388 MeV marked "Y" and "Z" respectively in

TABLE 3.4
Isobaric Analogue States in ^{28}Si

States in ^{28}Al (MeV)	Observed Proton Resonances E_p (Lab) (MeV)			Excitation Energy (MeV)		E_x (Obs)- E_x (Cal) (keV)			
				E_x (Obs) b)	E_x (Cal) e)	E_x (Cal) f)	(b-e)	(b-f)	(c-e)
	(p, γ) b)	(p,p) c)	(p, γ) d)						
3.294	0.992	0.991		12.542	12.449	12.467	93	111	92
3.451	1.117	1.117	1.198	12.662	12.616	12.634	46	28	46
3.537	1.316			12.854	12.692	12.710	162	180	
3.591	1.380	1.198	1.380	12.916	12.746	12.764	170	188	-6
3.669					12.824	12.842			
3.704	1.517			13.048	12.859	12.877	189	207	
3.878	1.590			13.118	13.033	13.051	85	103	
3.900	1.663			13.189	13.055	13.073	134	152	
3.935	1.724			13.246	13.090	13.108	156	174	
4.030	1.799			13.320	13.185	13.203	135	153	
4.115	(1.905)			13.422	13.270	13.288	171	189	
4.243	2.044			13.556	13.398	13.416	158	176	
4.315	2.156			13.664	13.470	13.488	167	185	

Table 3.4 (Contd.)

States in 28 Al	Observed Proton Resonances E _p (Lab) (MeV)				Excitation Energy (MeV)		E _x (Obs) - E _x (Cal) (keV)				
	b)	c)	d)		b)	e)	f)	(b-e)	(b-f)	(c-e)	(d-e)
4.383	2.198				13.705	13.538	13.556	167	185		
4.466	(2.308)				(13.811)	13.621	13.639	190	208		
4.518	(2.370)				(13.811)	13.673	13.691	197	215		
4.595	2.444				13.942	13.750	13.768	192	210		
4.685	2.482		2.530		13.978	13.840	13.858	138	156		185
4.741	2.511				14.006	13.896	13.914	110	128		
4.767	2.569				14.062	13.922	13.940	140	158		
4.845	2.670				14.160	14.000	14.018	160	178		
4.906	2.709				14.197	14.061	14.079	136	154		
4.928	2.735				14.222	14.083	14.101	139	157		
4.999	2.806				14.291	14.154	14.172	137	155		
5.138	2.903				14.384	14.293	14.311	91	109		

a) Ref. 21
b) Present work
c) Ref. 19
d) Ref. 18
e) Expected from Q(p,n) for ²⁸Al-²⁸Si pair, levels in ²⁸Al and ΔE_c value as predicted by equation (3.6.)
f) Expected from Q(p,n) for ²⁸Al-²⁸Si pair, levels in ²⁸Al and ΔE_c value as predicted by equation (3.7.)

fig. 3.11 do not correspond to any states in ^{28}Al and they are not analogues. We believe them to be components of some slight structure exhibited by the resonance 1.380 MeV corresponding to 3.591 MeV states in ^{28}Al . This resonance was studied with thinner targets, but does not display the Robson's asymmetry ³⁵⁾, usually observed in the analogue resonances.

The ^{27}Al nucleus has, in its ground state, five protons and six neutrons in $1d_{5/2}$ shell. The incident proton interacts with one unpaired neutron in $1d_{5/2}$ shell. The other neutrons remain undisturbed and the compound nucleus ^{28}Si is formed.

The excitation energy $E_x(\text{Cal})$ of the analogue states in ^{28}Si are deduced from a knowledge of the energy levels of ^{28}Al (ref. 21), the Coulomb displacement energy ΔE_c and the Q-value for the (p,n) reactions of the isobaric pair of nuclei $^{28}\text{Al} - ^{28}\text{Si}$. The expected excitation energy $E_x(\text{Cal})$ along with the observed excitation energy given by the (p, γ) compound nucleus resonances are shown in table 3.4. It will be seen from the table that they differ on the average by 149 keV and 131 keV respectively using semi-empirical relations (3.6) and (3.7) thus confirming the identification of the strong resonances as analogues. The Coulomb displacement energy from the present experiment comes to be (5.439 ± 0.051) MeV which is in close agreement with the value (5.467 ± 0.007) MeV given by Hardy et al. ³⁶⁾. The value of ΔE_c for the isobaric pair of nuclei $^{28}\text{Al} - ^{28}\text{Si}$ is found to be (5.290 ± 0.062) and (5.308 ± 0.033) MeV

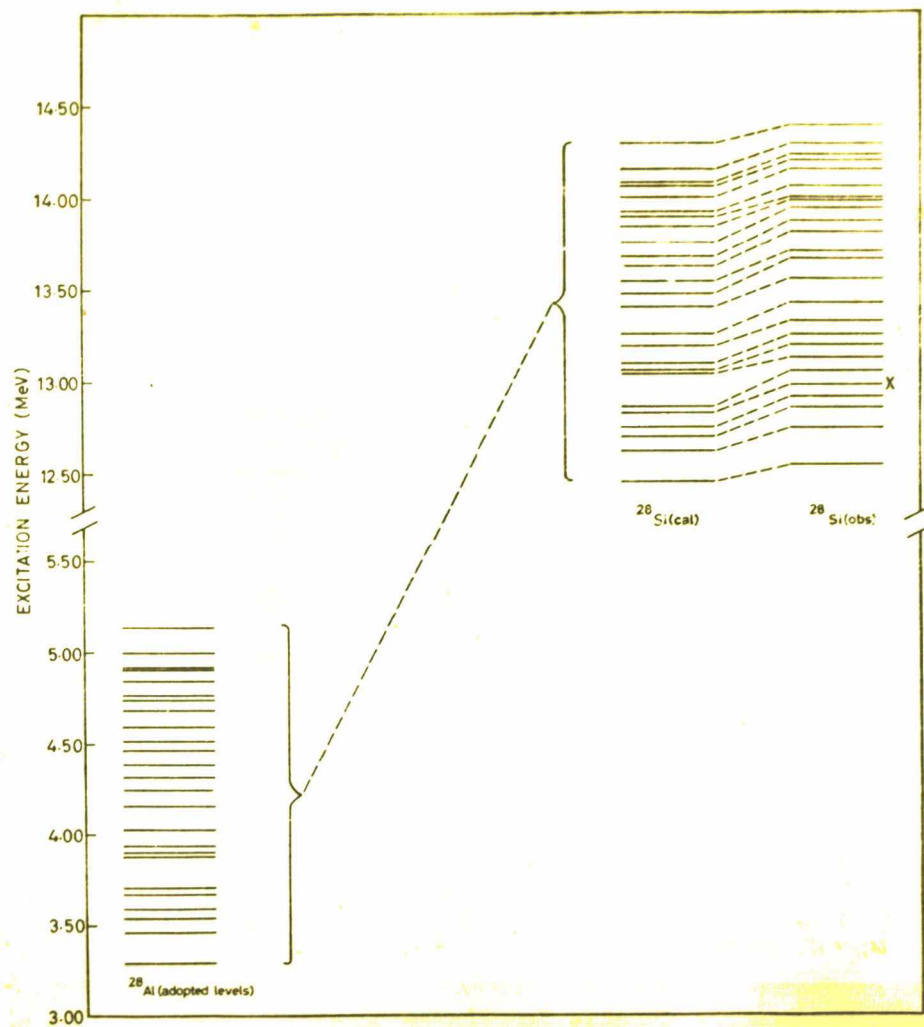


Fig.3.12 The energy level diagram for the isobaric pair ^{28}Al - ^{28}Si . The low-lying energy levels of ^{28}Al are shifted by the Coulomb energy difference and the neutron-proton mass difference. Mark X indicates the levels corresponding to $E_p = 1.454$ MeV resonance in $^{27}\text{Al}(p, \gamma)^{28}\text{Si}$ reaction

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using relations (3.6) and (3.7) of Anderson et al.²⁰⁾ and the present work respectively.

The energy level diagram for the pair $^{28}\text{Al} - ^{28}\text{Si}$ is given in fig. 3.12. The low lying energy levels of ^{28}Al are shifted by the Coulomb energy difference minus the neutron-proton mass difference. The appearance of strong resonances and their correspondence with the low lying levels in ^{28}Al gives evidence that they are analogues. There is an excellent agreement if one displaces the analogue resonances through a constant amount.

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CHAPTER - 4

COULOMB DISPLACEMENT ENERGY4.1 Introduction

The measurement of Coulomb displacement energy by experimental observations began with the discovery of mirror nuclei by Fowler et al.³⁷⁾. They noted that if the nuclear forces were charge symmetric the difference in binding energy could be accounted for by the electrostatic interaction between the protons. Since then the systematic variation of the Coulomb displacement energy have been studied by many authors³⁸⁻⁴⁰⁾. They have shown that the Coulomb displacement energy depends on pairing and T-value effect and have discontinuities at shell closures.

Recent observations of analogue states in heavier nuclei, first in the (p,n) reactions¹⁾ and then in other processes²⁾, have made it possible to extend the measurements of Coulomb displacement energy in that region of nuclei which usually have ground states with T greater than unity. The following information can be obtained from the study of Coulomb displacement energy:

(i) an understanding of the dependence of the Coulomb energy on Z and A (or on A and T_z) for a larger group of nuclei or an understanding of the dependence on the detailed nuclear structure for a smaller group of nuclei or even a single isobaric pair.

(ii) the charge distribution and the charge radii of atomic nuclei

(iii) the charge dependent effects such as charge dependence of nuclear forces.

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In practice every single measurement yields a numerical value for a Coulomb displacement energy. In recent years there has been a large amount of data on Coulomb displacement energy which includes the heavier nuclei through various processes, such as (p,n), (p,d) (d,n), (^3He , d), (^3He , t), (^3He , p), (p, γ) and β -decay measurements. In fact this has prompted several theoretical and semi-empirical studies of Coulomb displacement energy. Anderson et al.^{20,41,42)} have used the analogue state group in (p,n) reactions for a wide range of nuclei from mass 40 to 165. They plotted ΔE_c against $Z/A^{1/3}$ using data available upto 1965 and found that a straight line fitted data quite well. There appeared to be pairing effects and possible shell effects superimposed on the straight line even with experimental uncertainties of about ± 100 keV. Batty et al.⁴³⁾ studied the Coulomb displacement energies of nuclei upto mass 238 at higher proton energy with the same reaction. But the uncertainties in the values of ΔE_c were greater.

The use of isobaric analogue resonance technique is very helpful in the sense that the Coulomb displacement energy can be measured very accurately. The present measurements report results on ΔE_c for four pairs of isobaric nuclei in the mass region 28 to 58. Many experiments with a better accuracy and better energy resolution have been performed since the work of

Anderson et al.²⁰⁾ and an attempt has therefore been made to fit the Coulomb displacement energy ΔE_c with a linear least squares relation similar to that of Anderson et al.²⁰⁾. We have used all available measurements for the purpose in the region of the periodic table $A = 27 - 238$. An attempt has also been made to study any possible T_z dependence of ΔE_c .

4.2 Coulomb displacement energy

The values of Coulomb displacement energy obtained in the present experiments are presented in table 4.1; also included in the table are the values from previous measurements (refs. 14, 44-49). It will be seen that there is a good agreement between these measurements.

4.3 Phenomenological Approach to Coulomb displacement energy

There have been several theoretical approaches to derive Coulomb energy of a nucleus from liquid drop model, shell model and others. The simplest model starts with a uniform spherical charge distribution of constant density and gives

$$\Delta E_c = \frac{3}{5} \frac{e^2}{r_0 A^{1/3}} Z(Z+1) \quad \dots (4.1)$$

Corrections arising from diffuseness of nuclear surface, exchange energy, shell effect, T_z -dependence of nuclear radius etc. have been incorporated. A review of all such works has been made by Jänecke⁵⁰⁾.

TABLE 4.1

Coulomb displacement energy, ΔE_c .

Isobaric pair	$\bar{Z}/A^{1/3}$	ΔE_c (Cal) from (MeV)		ΔE_c (Obs) (MeV)	References
		equation (3.6)	equation (3.7)		
$^{28}_{Al}-^{28}_{Si}$	4.446	5.290 ± 0.062	5.308 ± 0.033	5.439 ± 0.051	P.W.
"	"	"	"	5.467 ± 0.007	36
$^{52}_{V}-^{52}_{Cr}$	6.296	7.961 ± 0.071	7.966 ± 0.038	8.075 ± 0.043	P.W.
"	"	"	"	8.060 ± 0.030	47
"	"	"	"	8.075 ± 0.020	7
"	"	"	"	8.406 ± 0.020	47
"	"	"	"	8.290 ± 0.030	44
"	"	"	"	8.050 ± 0.020	88
$^{55}_{Fe}-^{55}_{Co}$	6.968	8.932 ± 0.074	8.932 ± 0.074	9.079 ± 0.054	P.W.
"	"	"	"	8.950 ± 0.070	49
"	"	"	"	8.993 ± 0.028	49
$^{56}_{Mn}-^{56}_{Fe}$	6.665	8.494 ± 0.073	8.497 ± 0.039	8.641 ± 0.047	P.W.
"	"	"	"	8.593 ± 0.015	14
"	"	"	"	8.590 ± 0.010	15

P.W. Present work.

The following empirical forms are used to analyse experimental data (50-53)

$$\Delta E_c = a_1 \bar{Z}/A^{1/3} + a_2 (\bar{Z}/A)^{1/3}, \quad \dots (4.2)$$

$$\Delta E_c = b_1 \bar{Z}/A^{1/3} + b_2, \quad \dots (4.3)$$

$$\Delta E_c = (c_1 Z_c + c_2)/A^{1/3} \quad \dots (4.4)$$

Clearly, the first term in above expressions is a direct consequence of relation (4.1) and gives the major contribution to ΔE_c .

The second term in (4.2) is a consequence of exclusion principle and arises from antisymmetrization of the wave functions, and it has been argued that $a_2/a_1 \approx -0.5$.

The expression (4.3) follows from (4.2) if one assumes $(\bar{Z}/A)^{1/3} \approx \text{constant}$, as is true in heavier nuclei and the ratio b_2/b_1 is predicted to be approximately - 0.4.

The expression (4.4) follows if we assume that the matrix elements for $1/r_{ij}$ appearing in the Coulomb energy operator

$$H_c = e^2 \sum_{i < j} \left(\frac{1}{2} - t_z^i \right) \left(\frac{1}{2} - t_z^j \right) / r_{ij}, \quad \dots (4.5)$$

are the same for all pairs of protons in a nucleus and is proportional to $A^{1/3}$; it is then expected that $c_2/c_1 \approx 0$.

Relation (4.3) has been used by Anderson et al.²⁰⁾, as mentioned earlier, to analyse experimental data on ΔE_c and the following least squares values are obtained

$$b_1 = (1.444 \pm 0.005) \text{ and } b_2 = - (1.13 \pm 0.04).$$

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With the availability of further data, a similar analysis has been made and we obtained $b_1 = (1.437 \pm 0.003) \text{ MeV}$ and $b_2 = -(1.081 \pm 0.020) \text{ MeV}$. The chi-square values in the present case as well as in the case of Anderson et al. ²⁰⁾ have been found to be 0.016 and 0.017 respectively.

4.4 Results and discussion

The relations (4.2) - (4.4) have been used in the present case and the results of least squares analyses are shown in table 4.1; also included for comparison^{are} the values given by Jänecke ⁵⁰⁾ and Anderson et al. ²⁰⁾.

TABLE - 4.1

Summary of least squares analyses using relations (4.2) - (4.4)

Coefficients (MeV)				
Relation (4.2)	Relation (4.3)	Relation (4.4)	No. of data points	References
a_1 a_2	b_1 b_2	c_1 c_2		
1.415 -1.136	1.437 -1.081	1.384 -1.852	245	(j)
1.424 -1.237	1.430 -0.992	1.389 -2.041	149	(k)
	1.444 -1.130			(l)

(j) Present work.

(k) Ref. ⁵⁰⁾

(l) Ref. ²⁰⁾

Fig. 4.1 shows a plot of experimental values of Coulomb displacement energy ΔE_c in the mass region $A = 27$ to 238 as a

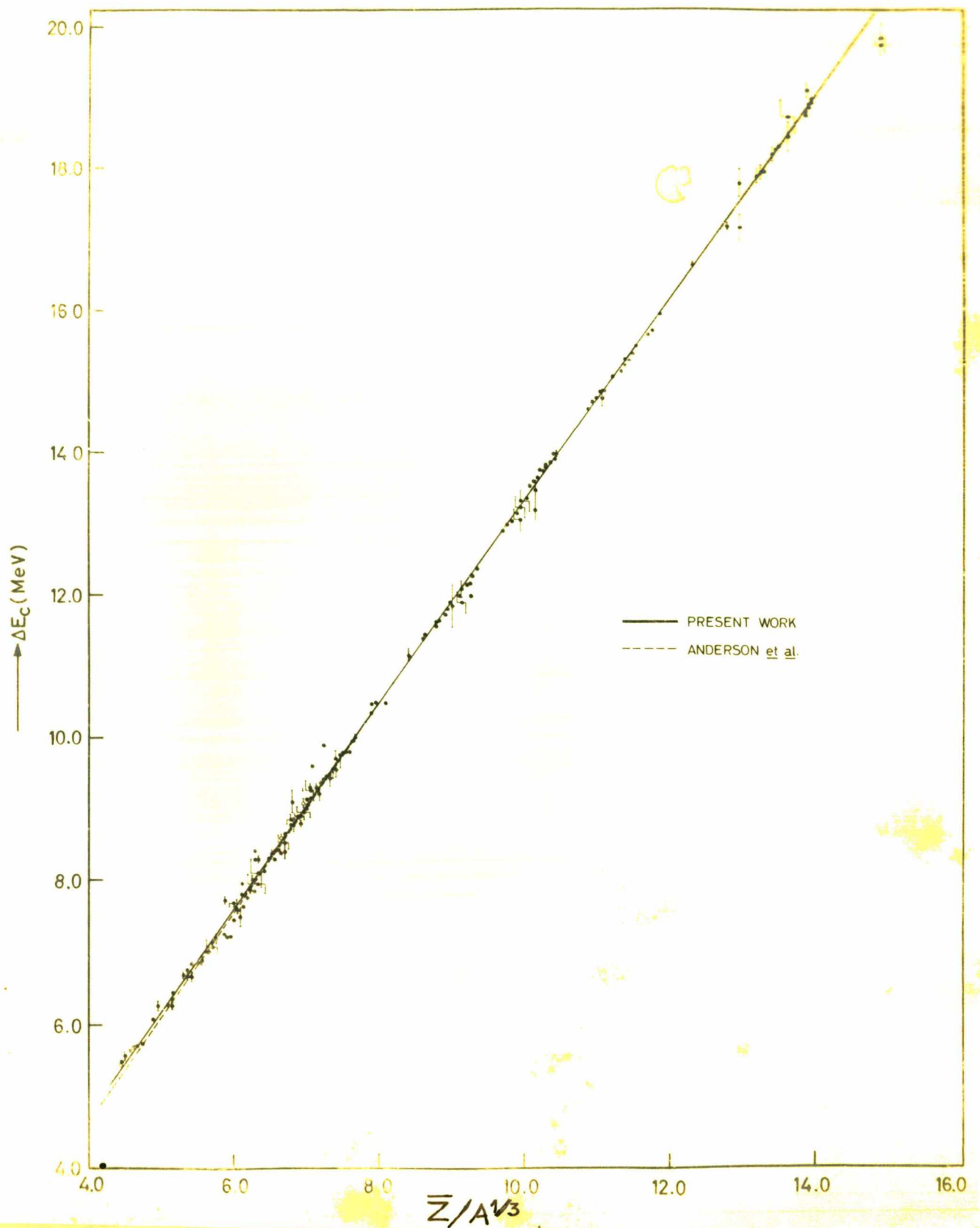


Fig.4.1 Coulomb displacement energies plotted against $\bar{Z}/A^{1/3}$ for all available isobaric pairs of nuclei in the mass region $A=27-238$. The broken and solid lines represent least squares fit using relations (3.6) and (3.7) respectively.

function of $\bar{Z}/A^{1/3}$ compared with the semi-empirical relation;

solid line is from present work, that is

$$\Delta E_c = (1.437 \pm 0.003) \bar{Z}/A^{1/3} - (1.081 \pm 0.020)$$

and broken line is from Anderson et al.²⁰⁾ given below

$$\Delta E_c = (1.444 \pm 0.005) \bar{Z}/A^{1/3} - (1.13 \pm 0.040) \dots (4.6)$$

A number of data points in the region $\bar{Z}/A^{1/3} \sim 6-7$ are not shown in the figure for clarity; but included in the analysis. Errors ≤ 30 keV are not shown in the figure. The experimental data for ΔE_c in the mass region $A = 27$ to 238 plotted in fig. 4.1 are also presented in table A-1 in appendix. It is seen that values of ΔE_c as predicted by the present relation lie very close to the observed values.

Fig. 4.1 shows that the observed values of ΔE_c from the present work on four pairs of isobaric nuclei namely $^{52}\text{V}-^{52}\text{Cr}$, $^{55}\text{Fe}-^{55}\text{Co}$, $^{56}\text{Mn}-^{56}\text{Fe}$ and $^{28}\text{Al}-^{28}\text{Si}$ are in good agreement with the values of ΔE_c in this region of periodic table as stated earlier and most of values of ΔE_c lie on or near to this straight line. Henceforth the present relation can be used in predicting Coulomb displacement energy in many relevant experiments.

Improvements to relations (4.3-4.4) were made by Seeger⁵⁴⁾ and Lindner⁵⁵⁾ by considering surface diffuseness and T_z -dependence of charge radius. This can be seen, if the quantities $\Delta E_c (\text{Expt}) - \Delta E_c (\text{Cal})$ be plotted for different isotones against Z_A and for

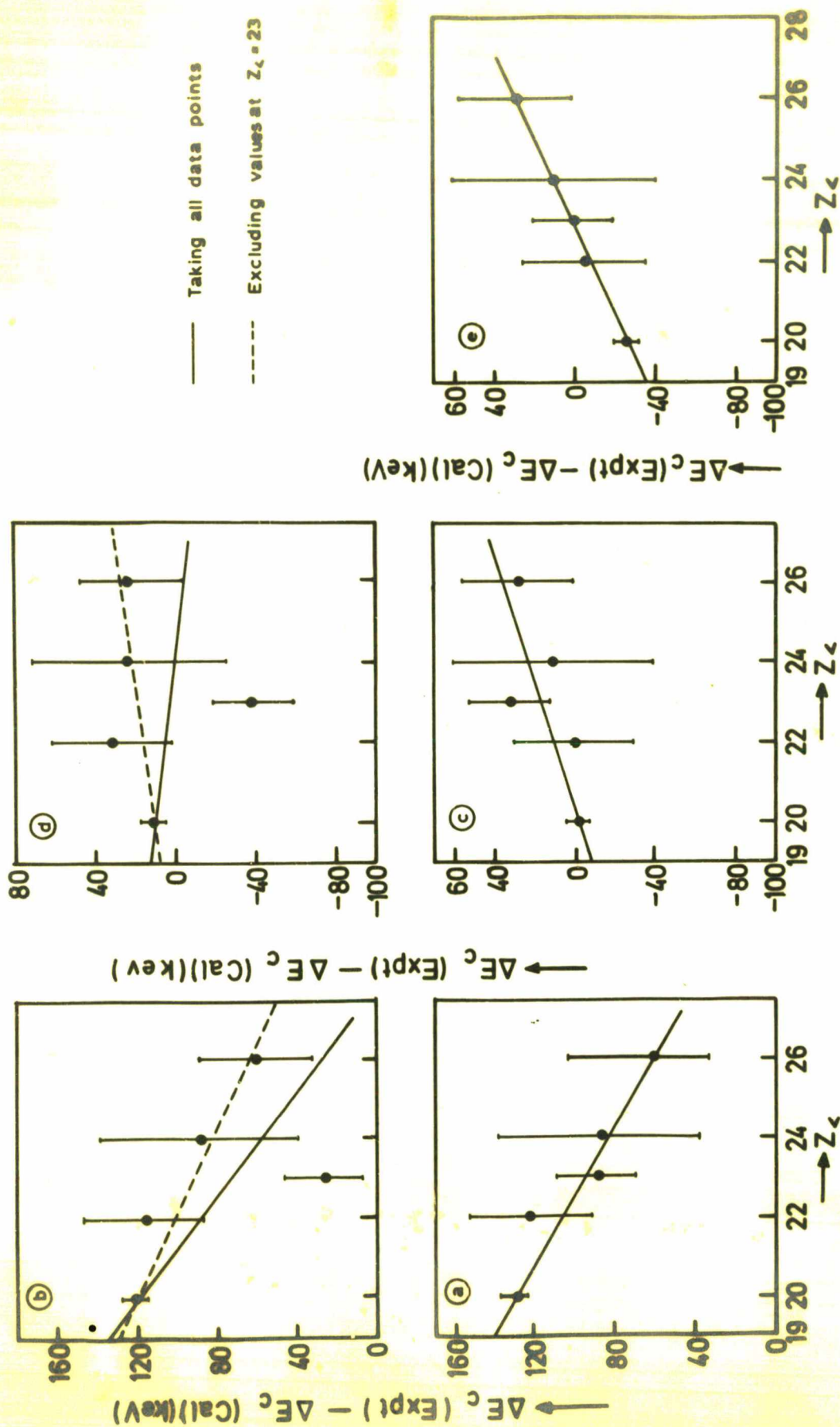


Fig. 4.2 A plot of $\Delta E_c (\text{Expt}) - \Delta E_c (\text{Cal})$, as a function of Z_c for $N_c = 29$.
 (a) Anderson et al. relation (4.3), (b) Present work, relation (4.3),
 (c) Present work relation (4.3), with values of $\Delta E_c (\text{Cal})$ obtained for
 respective Tz-groups. (d) Present work, relation (4.2), (e) Present work,
 same as (c), but using relation (4.2).

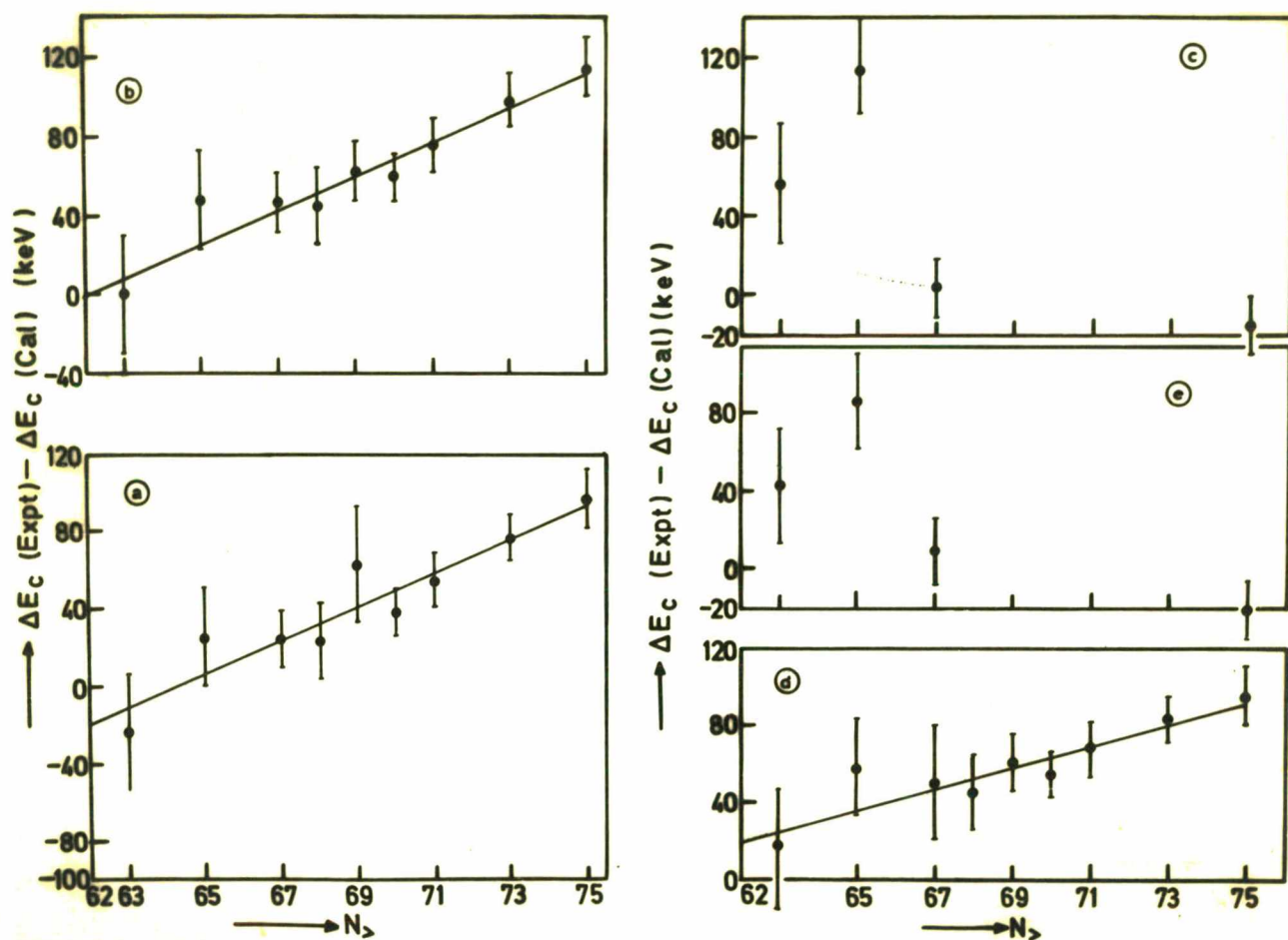


Fig.4.3 A plot of $\Delta E_c (\text{Expt}) - \Delta E_c (\text{Cal})$, as a function of N_2 for $Z_L = 50$. (a) - (e) same as fig.4.2.

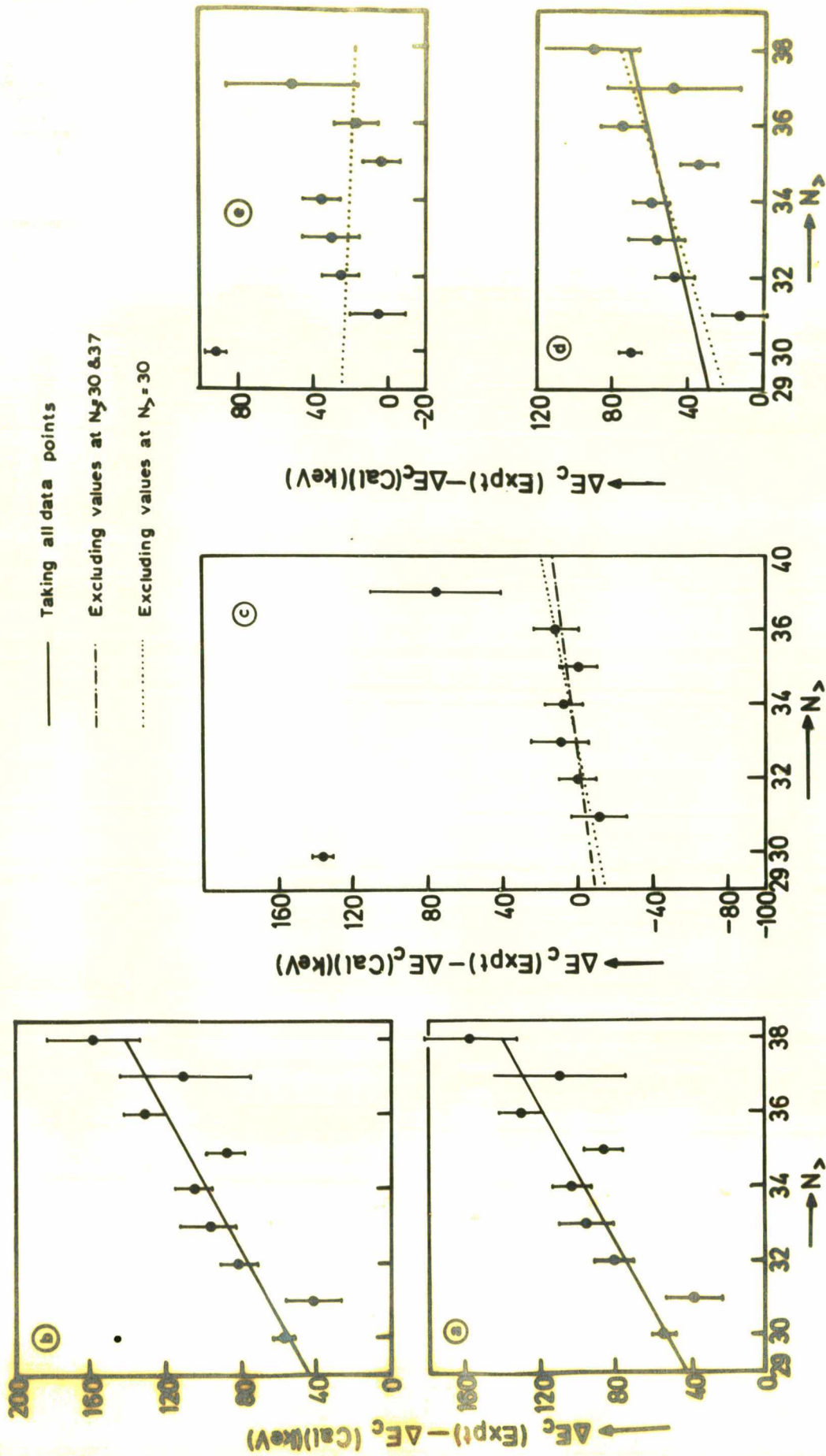


Fig.4.4 A plot of $\Delta E_c (\text{Expt}) - \Delta E_c (\text{Cal})$, as a function of N_γ for $Z_c = 28$. (a) - (e), same as fig.4.2.

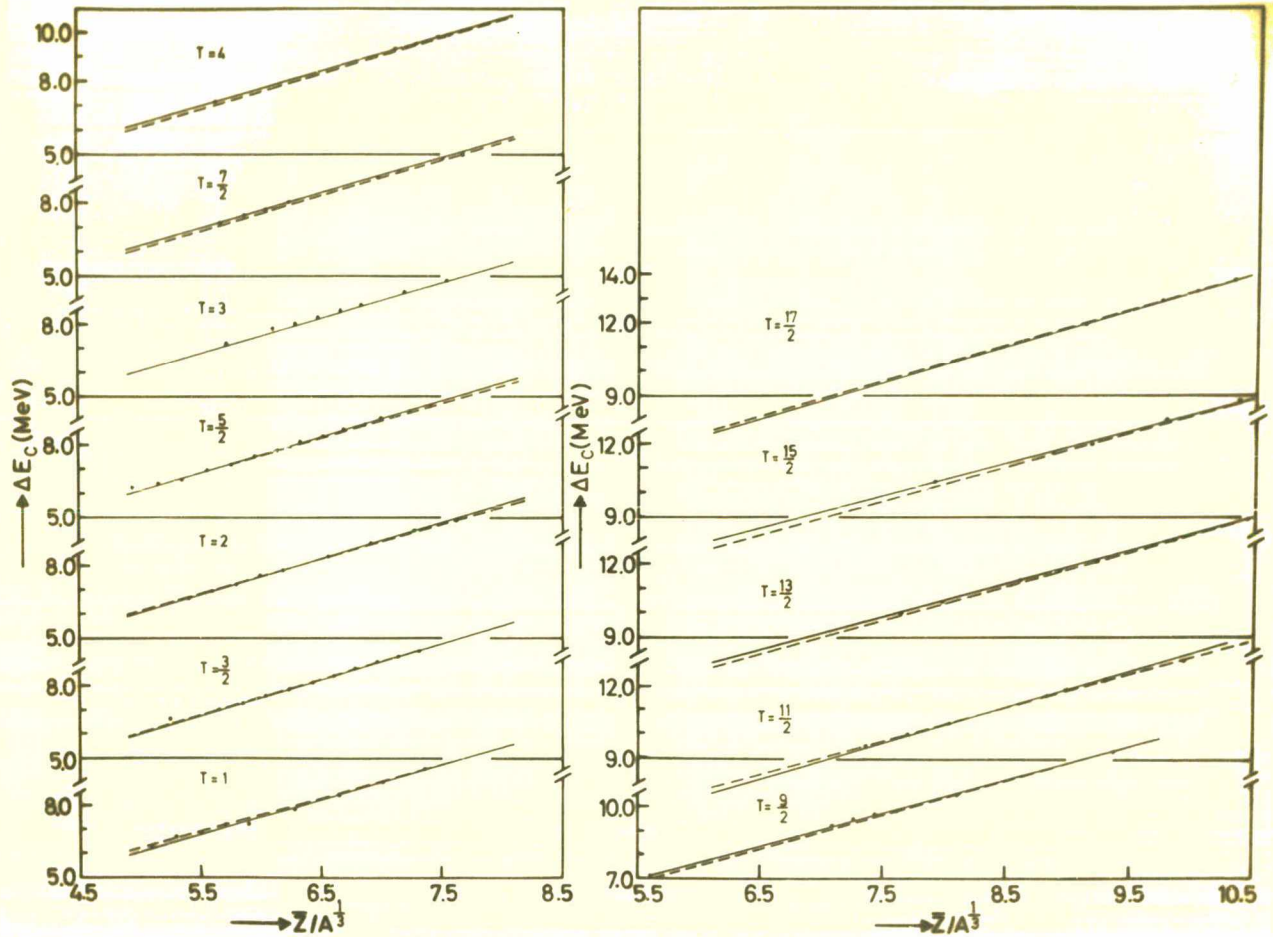


Fig.4.5 A plot of ΔE_C as a function of $Z/A^{1/3}$ for different T_Z -values, Solid line is from relation (4.3), using b_1 and b_2 separate groups and broken line is same as solid line but using b_1 and b_2 assuming a single group.

different isotopes against N_z . They represent an approximately linear relationship with scatter about the mean line, having a negative slope in the former case and a positive slope in the latter (curve-a in figs. 4.2—4.4 for example). These relations after necessary corrections for theoretical T_z -dependence of ΔE_c however, shows respectively a positive and a negative slope. The introduction of T_z -dependence⁵⁵⁾ thus rotates the curves in right direction, but more than what is necessary, showing that T_z -effect have been over estimated. We, therefore, proceed as follows.

Data on Coulomb displacement energy ΔE_c were arranged into several groups according to T_z -values and we made a least squares analysis using relations (4.2) and (4.3) in each group separately, as well as for the entire population treated as a single group. Groups of T_z , for which data were insufficient or the range of $Z/A^{1/3}$ was small, were excluded from the analyses. Results are summarized in table 4.2 and are displayed in fig. 4.5; for clarity, results for relation 4.2 are not shown. It appears from these figures that T_z -effect on ΔE_c is small.

We wanted to make a quantitative study in order to see if the same regression equation can be used for different groups; the results were, therefore, subjected to the F-test, as summarized in tables 4.3—4.5. We arrive at the following conclusions:

TABLE - 4.2

Least squares analyses of ΔE_c using relations 4.2-4.4 for separate groups of T_z as well as assuming them to belong to a single group.

T_z	No. of data points	Values of Coefficients of relation (4.2) (MeV)		Values of Coefficients of relation (4.3) (MeV)		Values of Coefficients of relation (4.4) (MeV)	
		a_1	a_2	b_1	b_2	c_1	c_2
1	9	1.420	-1.241	1.439	-1.175	1.365	-1.602
3/2	11	1.454	-1.489	1.492	-1.433	1.391	-2.082
2	9	1.473	-1.647	1.502	-1.472	1.408	-2.468
5/2	14	1.435	-1.288	1.459	-1.157	1.376	-1.613
3	8	1.429	-1.236	1.455	-1.117	1.382	-1.730
7/2	9	1.411	-1.051	1.412	-0.815	1.371	-1.379
4	4	1.419	-1.099	1.414	-0.800	1.376	-1.448
9/2	7	1.385	-0.862	1.378	-0.625	1.356	-1.096
11/2	7	1.419	-1.203	1.410	-0.840	1.384	-1.996
13/2	7	1.399	-0.962	1.371	-0.451	1.372	-1.486
15/2	5	1.395	-0.897	1.344	-0.187	1.368	-1.309
17/2	5	1.514	-2.434	1.505	-1.742	1.450	-5.052
S.G. ⁺	95	1.418	-1.174	1.464	-1.295	1.378	-1.718

⁺ Assuming all data points of above groups of T_z as a single group.

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TABLE 4.3

Analysis of variance using relation (4.2)

Residual due to	Sum of squares	Degrass of freedom	F ⁺		
			Calculated	5% value	10% value
Deviation from hypo-thesis ⁺⁺	0.135	33	1.018	1.55	1.40
Separate regression	0.237	59			
Common regression	0.372	92			

⁺F is the variance ratio often called Fisher's 'F'.

Percentage values are taken from Fisher's table.

⁺⁺The hypothesis in tables 4.4 and 4.5 is: the same regression equation can be used for all groups of T_z -values.

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TABLE 4.4

Analysis of variance using relation (4.3)

Residual due to	Sum of squares	Degrees of free- dom.	F				
			Calcula- ted.	10% value	5% value	2.5% value	1% value
Deviation from hypo- thesis	0.160	22	1.936		1.70	1.84	
Deviation from hypo- thesis due to b_1	0.046	11	0.883	1.63	1.97		
Deviation from hypo- thesis due to b_2	0.114	11	2.747		1.97		2.41
Separate regression	0.266	71					
Common regression.	0.426	93					

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TABLE 4.5

Test of equality of b_2 assuming same b_1 for all groups.

Residual due to	Sum of squares	Degrees of freedom	F		
			Calculated	5% value	10% value
Deviation from hypo- thesis	0.114	11	2.73	1.79	1.62
Separate regression	0.312	82			
Common regression	0.426	93			

(i) there is no evidence against the hypothesis that the same regression equation $\Delta E_c = a_1 \bar{Z}/A^{1/3} + a_2 (\bar{Z}/A^{1/3})$ can be used for different T_z -groups,

(ii) for the relation $\Delta E_c = b_1 \bar{Z}/A^{1/3} + b_2$, b_1 is probably the same (to within limits of error) for all T_z -groups, whereas indication is there that b_2 perhaps somewhat varies from group to group.

Next, the quantities $\Delta E_c(\text{Expt}) - \Delta E_c(\text{Cal})$ were plotted against Z_c and N_c for fixed N_c and Z_c -values (figs. 4.2—4.4), that is against T_z . In evaluating this difference, ΔE_c as given by different groups of T_z -values, as well as for assuming them to belong to a single group (relations 4.2 and 4.3) were used; we should as such expect that the mean straight lines (in the least squares sense) through the data points in figs. (c) and (e) should lie on the T_z -axis or at least parallel to it. The straight line in each case represents the least squares fit.

The following remarks may be made from figs. 4.2—4.4.

(I) slopes of the mean straight lines drawn through the points in (a) and (b) are negative in fig. 4.2 and positive in figs. 4.3 and 4.4,

(II) slope of mean straight lines in (c) is clearly different from that in (a) and (b),

(III) slopes of the mean straight lines in (d) and (e) are not significantly different from each other.

Remarks (II) and (III) therefore confirm the conclusions drawn above, namely (ii) and (i) respectively in the proceeding paragraph.

CHAPTER - 5FINE STRUCTURE OF ANALOGUE RESONANCES5.1 Introduction

The observation of fine structure components in the analogue resonances results from the mixing of the analogue states (the $T_>$ state) with the neighbouring normal states of the compound nucleus (the $T_<$ states). The mixing between analogue states arises mainly from outside the nucleus ³⁵⁾, that is, the highly excited unbound states are considered to be situated outside the nucleus. The isospin ceases to be a good quantum number outside the nucleus and the mixing between analogue states and normal states can take place. The unmixed analogue state contains width only in the entrance channel. According to Lane ⁵⁶⁾ the mixing of the analogue state and neighbouring normal states arises from inside the nucleus which can produce resonances even when there is no width in the entrance channel for the unmixed analogue state (the $T_>$ state) provided it contains the width in the exit channel. Bloch and Schiffer ⁵⁷⁾ also pointed out that the mixing is produced by the Coulomb perturbation. This can be split up into a local and distant effect. The local effect is nothing but the mixing of analogue state $T_>$ which is considered by Robson ³⁵⁾ and Lane ⁵⁶⁾. The local effect could lead to the production of a resonance in reaction for which the unmixed analogue state $T_>$ had neither width in the entrance channel nor in the exist channel.

The number of fine structure components that one observes is a function of the level density of the compound states of the same spin and parity as the analogue state and of the spreading widths of the analogues. In practice the detection of fine structure depends upon the level density and the experimental energy resolution. For analogues of low lying states in medium weight nuclei (mass number about 40-60) the high resolution developed by Duke group^{3,13,58-61} is sufficient to resolve the fine structure components. When the variation in level density at excitation energies corresponding to the analogues of low lying states in the parent nucleus is so large that with high resolution some analogues in medium weight nuclei are observed as a single state, some analogues as a few states and some analogues with as many as fifteen or twenty fragments.

In light nuclei the levels are widely spaced and as a result the Coulomb interaction is weak. Thus the change in energy produced by Coulomb interaction is small compared to the separation energy between the analogue states and the ordinary states. But in heavier nuclei the level densities are large, the separation between the levels is small and Coulomb interaction is strong.

The ordinary normal states (T_L states) with the same spin and parity may mix with analogue T_L states. Therefore one would expect to observe an analogue state in the midst of dense ordinary

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states as sharp resonances. Due to this mixing there is an enhancement in the proton width of the compound nuclear resonance in the vicinity of the analogue states. The information one can obtain from the fine structure of analogue states is the total width and partial widths of the individual resonances comprising the analogue resonances. It was first reported by Florida State Group ⁴⁾ from ^{92}Mo (p,p) experiment and the total width Γ was found to be about three times large than proton width. This suggests that the analogue resonance was not a single level and one can interpret the analogue resonance as due to the mixing of the analogue state T_1 amongst normal T_2 states in the immediate vicinity.

The individual fine structure levels resolved in an elastic proton scattering experiment on ^{40}Ar (refs. 3,59) indicates that the fine structure components become broader as one goes through a region where the analogue state is predicted. The results of elastic scattering of protons provide an excellent test for some aspects of the existing theories of analogue states ^{35,62-64)}. A more recent version on fine structure is given by Lane ⁵⁶⁾. A characteristic feature of these fine structure states is an asymmetry of the enhancement, that is, the fine structure is expected to be strongly enhanced over a considerable energy range below the position of the analogue resonance but much less so immediately above. The asymmetry of enhancement or fluctuation is explained as a natural consequence

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of coherent interference between the two contributions to the width of each resonances, that is, the width it would have in the absence of mixing with the analogue state and the portion of the analogue state that mixes with it.

When the energy resolution is not sufficient to observe the individual fine structure components around the analogue, one usually obtains a gross structure enveloping the nearby fine resonances around the analogue, the width of which is about tens of keV. This observed width of any fine structure resonance included in gross structure does not seem to differ appreciably from those of the normal states in a distant region. The distribution of the widths about the gross structure shows an asymmetry about the analogue resonance energy and cannot be accounted for by the usual Breit-Wigner formula.

Since most analogue state experiments are not performed with high resolution, it is of considerable interest to write an expression for the averaged cross section in order to see what information can be extracted from poor resolution experiments. The expression for energy distribution of averaged cross section according to Robson³⁵⁾ can be written as

$$\sigma \propto \frac{(E_{\lambda} - E)^2}{(E_{\lambda} + \Delta - E)^2 + \Gamma^2/4}, \quad E_0 = E_{\lambda} + \Delta, \quad \dots 5.1$$

where E_0 is the resonance energy, σ is the cross section at the observed energy E , Δ is the shift in resonance energy due to

asymmetry and Γ is the total width of the resonance. The values of Δ and Γ depend on the position of the analogue and the level density of normal states in that region of excitation.

5.2 Measurements

Fine structure of analogue resonance in ^{52}Cr and ^{56}Fe from (p, γ) and (p, n) reactions in ^{51}V and ^{55}Mn respectively were studied using proton beam from 3 MeV Van de Graff accelerator at Atomic Energy Centre, Dacca. The general experimental procedure is similar to that described in chapter 2. The observation of fine structure is primarily dependent on the experimental energy resolution and level densities of the compound nucleus. Better the beam resolution the fine structure components will be more nicely resolved. The beam energy resolution depends mainly on the stability of magnet current generator, RF supply to the ion source, also on the slits, collimators and target thickness. The total observed energy spread for the present measurements was found to be about 850 eV which includes the incoherent beam spread, Doppler broadening in the target, the target thickness and the natural width of the resonance. This was achieved by adjusting the slit widths and using two collimators and thinner targets. The present experiment has a limitation in energy resolution because of the instability of magnet current generator.

The target thickness was $6-8 \mu\text{g}/\text{cm}^2$ and beam current was $1.5 - 3 \mu\text{A}$.

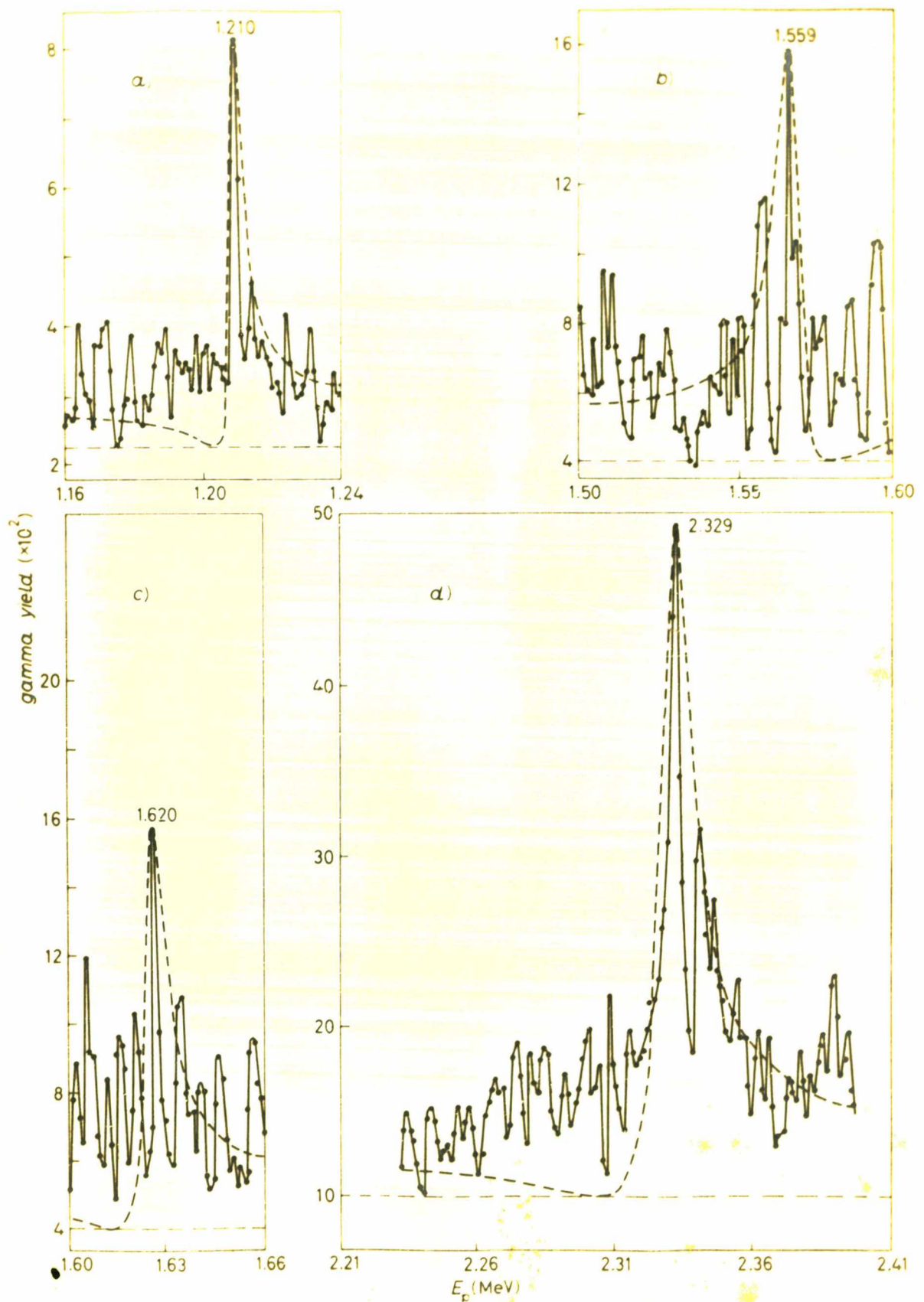


Fig.5.1 Fine structures of analogue resonances by (p, γ) reaction in ^{51}V observed at a) $E_p = 1.210$ MeV, b) $E_p = 1.559$ MeV, c) $E_p = 1.620$ MeV and d) $E_p = 2.329$ MeV.

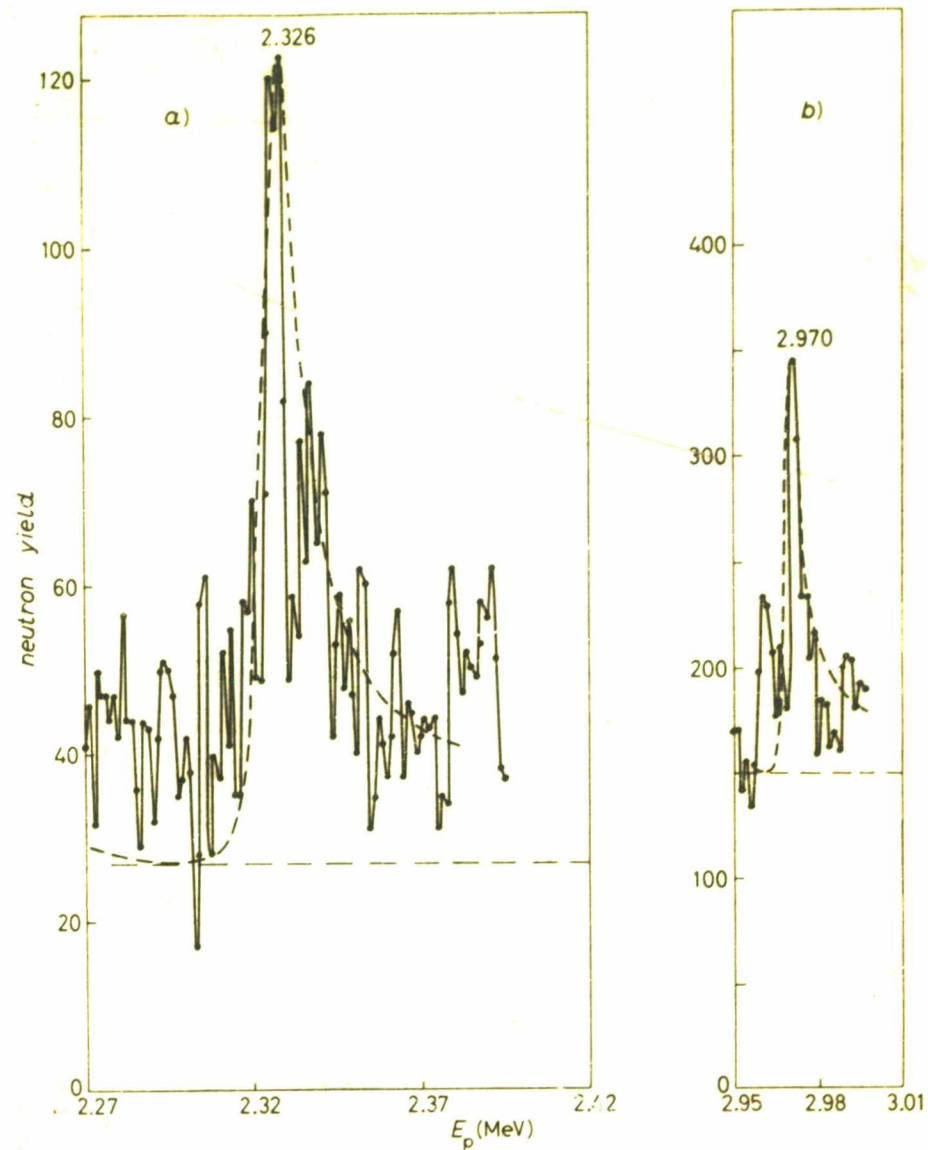


Fig.5.2 Fine structures of analogue resonances in the $^{51}\text{V}(p,n)^{51}\text{Cr}$ reaction observed at a) $E_p = 2.326$ MeV and b) $E_p = 2.970$ MeV.

5.3 Results and discussions

Some of the analogue resonances as seen from gamma and neutron yield curves (figs. 3.2, 3.3, 3.8 and 3.9) appear to have some structure. The structure of the analogue resonances at several proton energies were studied from (p, γ) and (p, n) reactions in ^{51}V and ^{55}Mn with higher resolution using thinner targets. Though the energy resolution was not sufficient to resolve the individual fine resonances, the analogue resonances showed an observable fine structure enveloping as gross structure. The gross structure showed an asymmetry about the resonance energy. A computer program was developed using equation (5.1) to analyse them. The best possible values of resonance parameters Δ and Γ were obtained in a search out procedure. The actual method employed was to compare the experimental data to a theoretical curve generated by IBM - 1620 computer. The theoretical curves were arbitrarily normalized at the peak counts using the chosen values of parameters Δ and Γ .

The (p, γ) and (p, n) reactions in ^{51}V

The structure of analogue resonances at $E_p = 1.210, 1.559, 1.620, 2.329$ and 2.970 MeV in ^{52}Cr from (p, γ) and (p, n) reactions in ^{51}V studied in this way are shown in figs. 5.1 and 5.2. The dotted lines represent the theoretical fits by Robson's formalism using parameter values summarized in table 5.1. It is seen from figs. 5.1 and 5.2 that the gross structures of the analogue

resonance at $E_p = 2.329$ MeV for both (p, γ) and (p, n) processes have the same width and asymmetry. Robson's prediction³⁵⁾, which states that if any analogue resonance is assumed to be dominated by the proton channel, the resonance shape should be the same for both (p, n) and (p, γ) reactions, holds good for the measurement.

This resonance was earlier studied by Teranishi and Furubayashi⁷⁾ from (p, γ) and (p, n) reactions. In this as well as in the present measurements the structure appears on the higher energy side of the resonance. This is contradictory with the measurement of Sekharan and Mehta⁶⁵⁾, who investigated this structure for (p, n) reaction. They considered the above mentioned structure as a separate resonance at $E_p = 2.339$ MeV analogue of a different level in ^{52}V (namely 1.578 MeV).

Thus they found the asymmetry parameter to be negative and further that the two resonances have widths 6 and 8 keV respectively ($\Gamma = 14$ keV in the present case assuming a single resonance). Another investigation is due to Egan et al.⁶⁶⁾, who completed their preliminary studies⁶⁷⁾ with (p, p) and (p, n) reactions. A strong anomaly in elastic scattering was observed and attempts were made to analyze data with a single resonance. In agreement with Sekharan and Mehta⁶⁵⁾, they concluded that the results could be explained by assuming the superposition of two resonances. Their preliminary work⁶⁷⁾, however required a positive value of Δ .

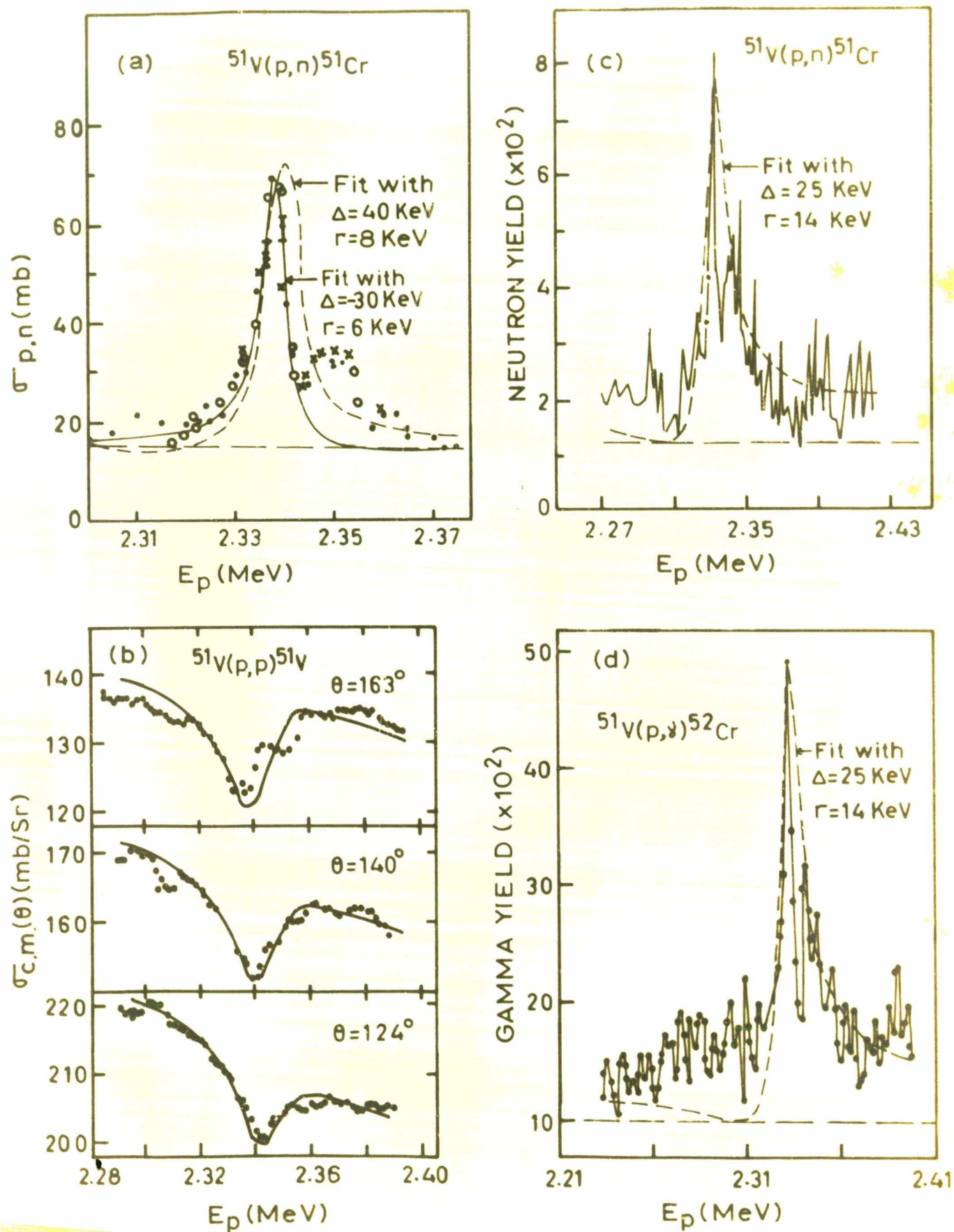


Fig.5.3 A comparison of fine structure at $E = 2.329\text{ MeV}$ observed in (a). (p,n) (ref.65); (b). (p,p) (ref.66), (c). (p,n) (ref.7) and (d). (p, γ) (present work).



Fig. 5.4 A part of decay spectra at $E_p = 2.329$ MeV and $E_p = 2.339$ MeV in $^{51}\text{V}(p, \gamma)^{52}\text{Cr}$ reaction.

The situation is, therefore, confusing; the behaviour at high energy side of the strong resonance is either a component of the structure exhibited by it (ref. 7 and present work) or is due to an altogether different analogue resonance (refs. 65,66). For comparison some of the results are reproduced in fig. 5.3.

In an attempt to solve the problem, we made measurements on (p, γ) decay at these two energies ($E_p = 2.329$ and 2.339 MeV) with the idea that two distinct resonances analogue to two different levels in ^{52}V are most unlikely to have exactly the same properties and decay modes. Proton beam was obtained from the van de graaff accelerator of the Bhabha Atomic Research Centre, Bombay and gamma rays were detected in 20 cc Ge(Li). Results are displayed in fig. 5.4 where the two measurements are plotted side by side for comparison. The two gamma spectra are identical and we, therefore, believe the structure on high energy side of the resonance ($E_p = 2.33$ MeV) belongs to the resonance itself.

It will be noticed from fig. 5.2 that minimum occurs at a higher proton energy than the resonance peak while in the remaining resonances at $E_p = 1.210, 1.620, 2.329$ and 2.970 MeV the interference minimum occurs over a considerable energy range below the position of the resonance peaks. In former case a dip is observed at higher proton energy side and in latter cases the dip is observed at lower proton energy side of the analogue resonance peaks. This reversal in asymmetry is possible at lower proton energy as is pointed out by Teranishi and Furubayashi ⁷⁾. The

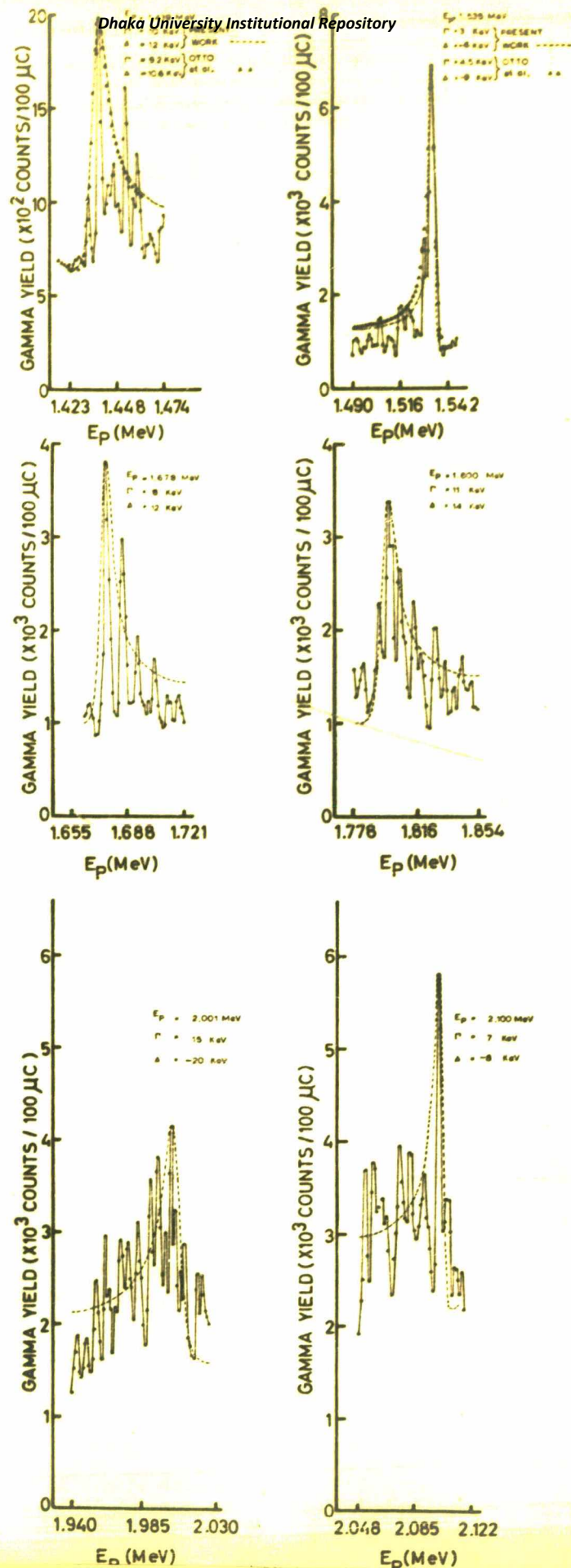


Fig.5.5 Fine structures of analogue resonances in $^{55}\text{Mn}(p,\gamma)^{56}\text{Fe}$ reaction observed at $E_p = 1.439, 1.535, 1.678, 1.800, 2.001$ and 2.100 MeV.

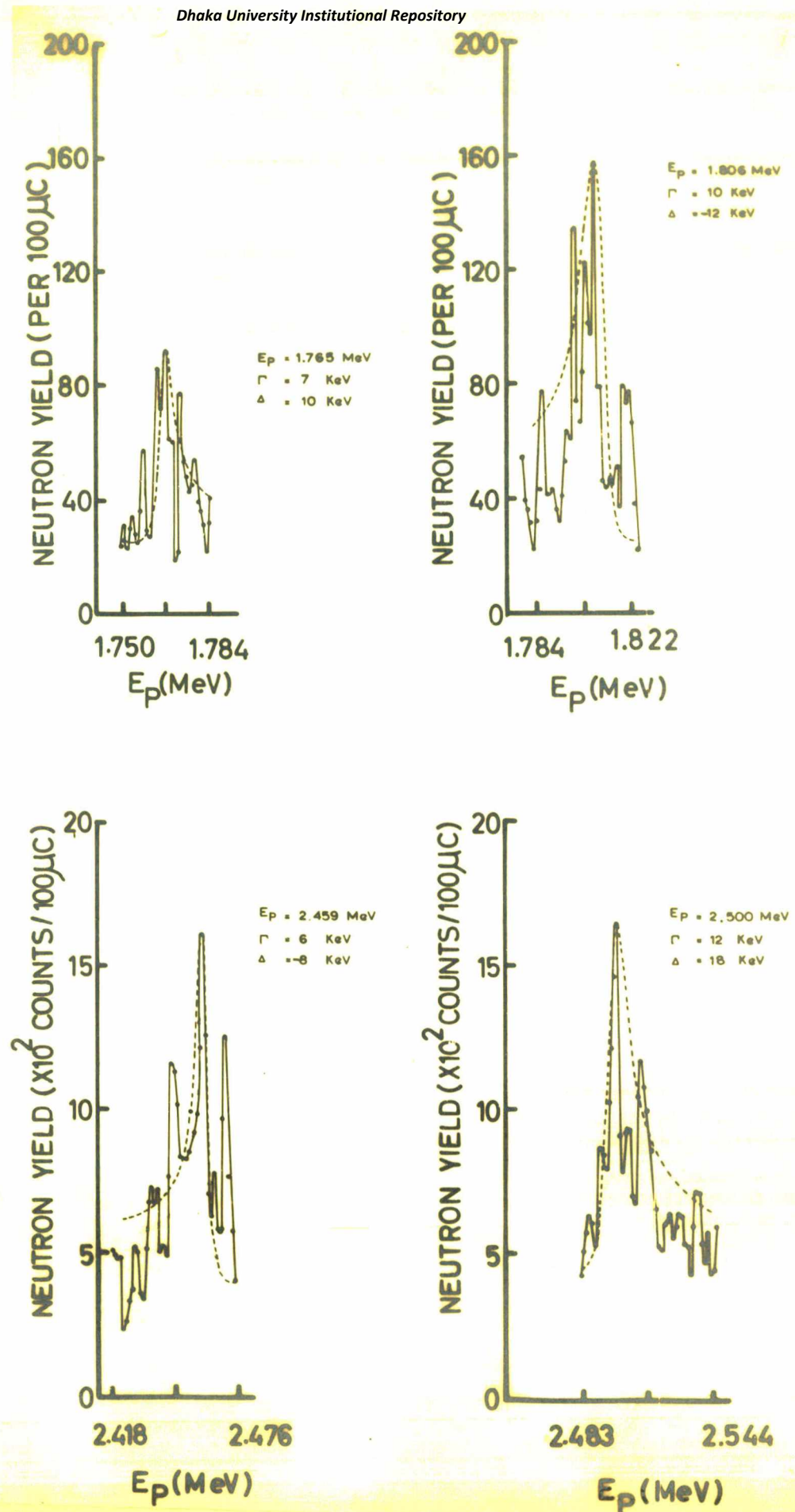


Fig.5.6 Fine structures of analogue resonances in $^{55}\text{Mn}(p,n)^{55}\text{Fe}$ reaction observed at E_p = 1.766, 1.806, 2.459 and 2.500 MeV.

asymmetry in structure of analogue resonances was also observed in several proton elastic scattering experiments following its discovery by Richard et al.⁴⁾ in ^{92}Mo (p,p) work.

The (p, γ) and (p,n) reactions in ^{55}Mn

The fine structures studied at $E_p = 1.439, 1.535, 1.675, 1.765, 1.800, 2.001, 2.459$, and 2.500 MeV from ^{55}Mn (p, γ) ^{56}Fe and ^{55}Mn (p,n) ^{55}Fe reactions are shown in figs. 5.5 and 5.6. The dotted lines represent the theoretical fits by Robson's formalism using parameter values given in table 5.2. The results of Otto et al.¹⁴⁾ are also shown in the table for comparison. It is seen from figs 5.5 and 5.6 that in case of analogue resonances at $E_p = 1.535, 1.806, 2.001, 2.100$ and 2.459 MeV the interference minimum occurs at a higher proton energy side of resonance peaks, while at $E_p = 1.439, 1.675, 1.765, 1.800$ and 2.500 MeV the interference minimum occurs at lower proton energy side of resonance peaks.

The asymmetry of the analogue resonance at $E_p = 1.800$ MeV has been found to be different in (p, γ) and (p,n) reactions as seen from fig. 5.5 and 5.6 and table 5.2. This was also reported by Otto et al.¹⁴⁾ for some analogue resonances which is very marked for $E_p = 1.441$ MeV. The structure depends on the reactions process, This behaviour is not well understood in terms of the existing theories.

TABLE 5.2

Fine Structure in ^{55}Mn (p, γ) ^{56}Fe and ^{55}Mn (p, n) ^{55}Fe reactions

E_p (MeV)			$^{55}\text{Mn}(p, \gamma) ^{56}\text{Fe}$				$^{55}\text{Mn}(p, n) ^{55}\text{Fe}$			
(p, γ)	(p, n)	(p, γ)	Γ	Δ	Γ	Δ	Γ	Δ	Γ	Δ
a)	a)	b)	a)	a)	b)	b)	a)	a)	b)	b)
1.439		1.441	10	12	9.2	10.6			2.9	-4.6
1.535		1.536	3	-6	4.5	-9			3.7	-9.4
1.678		1.678	8	12	8.5	12			7.8	17.2
	1.765						7	10		
1.800	1.806	1.799	11	14	11.3	13.9	10	-12		
2.001			15	-20						
2.100			7	-8						
	2.459						6	-8		
	2.500						12	18		

a) Present work.

b) Ref. 14).

TABLE 5.3Q-values of (p, γ) and (p,n) reactions

NUCLEI	Q(p, γ) (MeV)	Q(p, n) (MeV)
²⁷ Al	11.585	-5.5925
⁵¹ V	10.468	-1.530
⁵⁴ Fe	5.068	-9.004
⁵⁵ Mn	10.188	-1.0145

It will be noticed that fine structure enveloping as gross structure has been observed by (p,γ) and (p,n) reactions in ^{51}V and ^{55}Mn but not in the remaining cases of the present work. The possible explanation is as follows. It is to be noted that at high excitation energy, say above 10 MeV or so level density of a nucleus is very large and analogue states are practically embedded in the continuum. Mixing between analogue states and neighbouring normal states occurs and as a result fine structure components are developed. Table 5.3 gives the Q-values for (p,n) and (p,γ) reactions relevant to the present work, from which excitation energy in compound nucleus may be obtained. For reason mentioned above averaged fine structures have been observed in compound nuclei ^{52}Cr and ^{56}Fe (large Q-value for proton capture). But in ^{28}Si the level density is low (ref. 21) even though the excitation energy is high. No such structure has been observed in ^{28}Si . In ^{55}Co the level density (small Q-value for proton capture) is low at this excitation (table 5.3). The chances of occurrence of mixing between analogue state and its neighbouring normal states are less and hardly any fine structure has been observed in ^{55}Co .

CHAPTER-6

Gamma ray Angular Distribution from $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ Reaction6.1 Introduction

The properties of the levels of ^{28}Si have been studied by many authors by proton capture reactions on ^{27}Al and an up to date information up to $E_x = 13.483$ MeV resonance levels has been compiled by Endt and Van der Leun²¹⁾. This corresponds up to $E_p = 1.969$ MeV resonance energy. No information on the properties of resonating states beyond this is available. Analogue states by $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ reaction have been identified in the energy range $E_p = 0.85 - 3.00$ MeV as discussed in chapter 3.

In this chapter we discuss the properties of some analogue resonances for $E_p > 2$ MeV. In (p,p) experiment (discussed in the following chapter) several resonances were observed and above $E_p = 2$ MeV no resonance was found strong and common in both the experiments. We therefore decided to study the properties of resonant levels of isolated and sharp resonances above 2 MeV by (p, γ) reaction. This motivated us to undertake the present measurement at $E_p = 2.198, 2.482, 2.511$ and 2.735 MeV resonances to study the properties of resonating states of ^{28}Si by gamma ray angular distributions. The experimental procedure and results obtained are discussed in the following sections.

6.2 Experiment

The measurements presented in this chapter have been done by using proton beam from 5.5 MeV Van de graaff accelerator at Bhaba Atomic Research Centre, Bombay, India. The beam was collimated by using a number of tantalum collimators of various diameters inside the beam port tube. The beam energy resolution has been found to be about 1 keV. The targets were kept fixed on an adjustable frame by screwing and the frame was electrically insulated from target chamber. Moreover the chamber was insulated electrically from beam tube. The targets were cooled by water althrough the experiments. The beam currents of the order of 3-4 μ A were used. The targets were prepared by depositing natural Al (100% ^{27}Al) on tantalum backings by vacuum evaporation process. The thickness of target was about 20 $\mu\text{g}/\text{cm}^2$ and it was kept at an angle 45° to the beam direction. A 20 c.c. coaxial Ge(Li) detector (Princeton Gamma Tech) has been used for the measurements reported here. The distance between the face of the detector and the target was 2.3 cm. The energy resolution of the detector was found to be 7 keV for 1.33 MeV gamma rays of ^{60}Co source. The signals output of the detector were amplified by an Ortec pre-amplifier and a main amplifier and were then analysed by a Nuclear Data 4096 channel pulse height analyser. The gain of the main amplifier was adjusted to obtain energy dispersion (keV/Channel) so that the full scale of either 2048 or 4096 channels

in the pulse height analyser covered the maximum energy of gamma ray assuming a direct transition from compound excited state to ground state ($E_\gamma = E_x = Q(p, \gamma) + \frac{A}{A+1} E_p$ MeV). With the increase of proton energies the low energy background gamma rays increases and it becomes difficult to keep the dead time down to acceptable limits by adjusting only the beam currents. It is desirable to attenuate these low energy gamma rays by placing thin lead sheets either on the face of the detector or on outer surface of the target chamber. In this way the difficulty is removed.

The gamma rays are detected in a Ge(Li) detector by their ionizing properties, i.e. by the creation of secondary electron hole pairs. The electron hole pairs are called carriers and are collected under the influence of an electric field. These carriers result a pulse height which is proportional to the gamma ray energy absorbed. The absorption of gamma rays in the detector material takes place by any one of the following processes. Photo-electric effect, Compton scattering and pair production. At low energies the first two processes are dominant. In low energy region a monoenergetic gamma ray spectrum consists of full energy absorption peak with a continuous Compton background upto an energy $E_\gamma (1 + m_0 c^2 / 2E_\gamma)$, where E is the energy of the gamma ray and m_0 is the mass of the electron produced by Compton scattered gamma rays.

At energy of about 2.50 MeV the pair production becomes the dominant mode of interaction and it starts just at 1.022 MeV. A gamma ray having energy greater than 1.022 MeV (threshold energy) incident on a Ge(Li) detector, produces an electron-positron pair and loses all its energy by ionisation within the detector. The positron when it comes to rest, annihilates with a nearby electron emitting two oppositely directed gamma rays of 0.511 MeV each. One or both of the gamma rays may then escape from the detector without further interaction and these give rise to two peaks corresponding to $(E_\gamma - 0.511)$ and $(E_\gamma - 1.022)$ MeV respectively. The first peak is called single escape peak and the second is called the double escape peak. Therefore a spectrum of monoenergetic gamma rays consists of a full absorption peak (photo Peak/full energy peak), a Compton continuum and for energies above 1.022 MeV pair absorption peaks (single escape and double escape peaks). The relative intensity with which each of them contributes to the spectrum depends on the energy of the primary gamma ray, the detector material and the size of the detector. The energy calibration was done by taking a gamma ray spectrum of well known 0.992 MeV resonance of $^{27}\text{Al} (p, \gamma) ^{28}\text{Si}$ reaction. This is necessary to know the energies of the peaks observed in gamma ray spectra $E_p = 2.198, 2.482, 2.511$ and 2.735 MeV resonances of $^{27}\text{Al} (p, \gamma) ^{28}\text{Si}$ reaction. The energy dispersion (keV/channel) was obtained

from 0.511 MeV energy differences between appropriate pairs of full energy, single and double escape peaks associated with high energy gamma rays present in the spectrum of 0.992 MeV resonance of $^{27}\text{Al} (p, \gamma) ^{28}\text{Si}$ reaction.

6.3 Relative efficiency of Ge(Li) detector

The intensities of gamma rays can be obtained from a measured spectrum if the efficiency of the detector is known with which a particular gamma is detected by it. The efficiency is defined as the number of events counted in a peak (the full energy peak or escape peaks) in a gamma ray spectrum divided by the number of events actually produced by a reaction or by a source over the 4π .

The relative efficiency was obtained in purely experimental way based on the so-called two lines method of Van Oostrun and Meijer ⁶⁸⁾ by using 0.992 MeV resonance of $^{27}\text{Al} (p, \gamma) ^{28}\text{Si}$ reaction. This resonance produces a number of intense gamma rays ranging from 1.78 MeV to 10.76 MeV and it is formed predominantly by s-wave proton capture ($l = 0$; 99% and $l = 2$; 1%). Therefore the angular distribution of the gamma rays observed in the deexcitation of this resonance are practically isotropic ⁶⁹⁾. The intensities of the gamma rays for 0.992 MeV resonance is known ⁷⁰⁾. Intensities do not need to be equal as long as they are known as they can be accounted for. The deexcitation gamma ray spectrum and decay schemes for this resonance are shown in fig. 6.1. The relative efficiencies for full energy peaks and double escape peaks have

Fig. 6.1 The spectrum on $E_p = 0.992$ MeV resonance from $^{17}\text{Al}(p, \alpha)^{28}\text{Si}$ reaction and its decay scheme. The spectrum was taken for 5,000 C.I.C. counts.

been determined by taking known intensities of gamma rays of 0.992 MeV resonance of ^{27}Al (p, γ) ^{28}Si . This is shown in fig. 6.2. The full energy peak efficiency was obtained for gamma rays having energy less than 1.78 MeV by taking spectrum with ^{152}Eu source. The intensities of 0.779, 0.965 and 1.457 MeV are known from the works of Reidenger and Johnson ⁷¹⁾ and Mukherjee and Sen Gupta ⁷²⁾.

It is seen from fig. 6.2 that the relative efficiency of the detector for the double escape peak increases with the increase of energy. This is expected from the theoretical estimate of pair production cross section. A decrease in efficiency is also observed at about 6.00 MeV. For high energy gamma rays, electrons and positrons are produced with a high enough energy so that they can escape from the detector before losing all their energy. The other effect which reduces the efficiency is the escape of a bremsstrahlung photon accompanying the slowing down of the high energy electrons. Both effects generate a pulse of lower height and thus contribute to the background below the double escape peak.

6.4 Experimental and Analytical Procedures

Experimental

The angular distributions of gamma rays were measured at angles 0° , 30° , 55° , and 90° with a

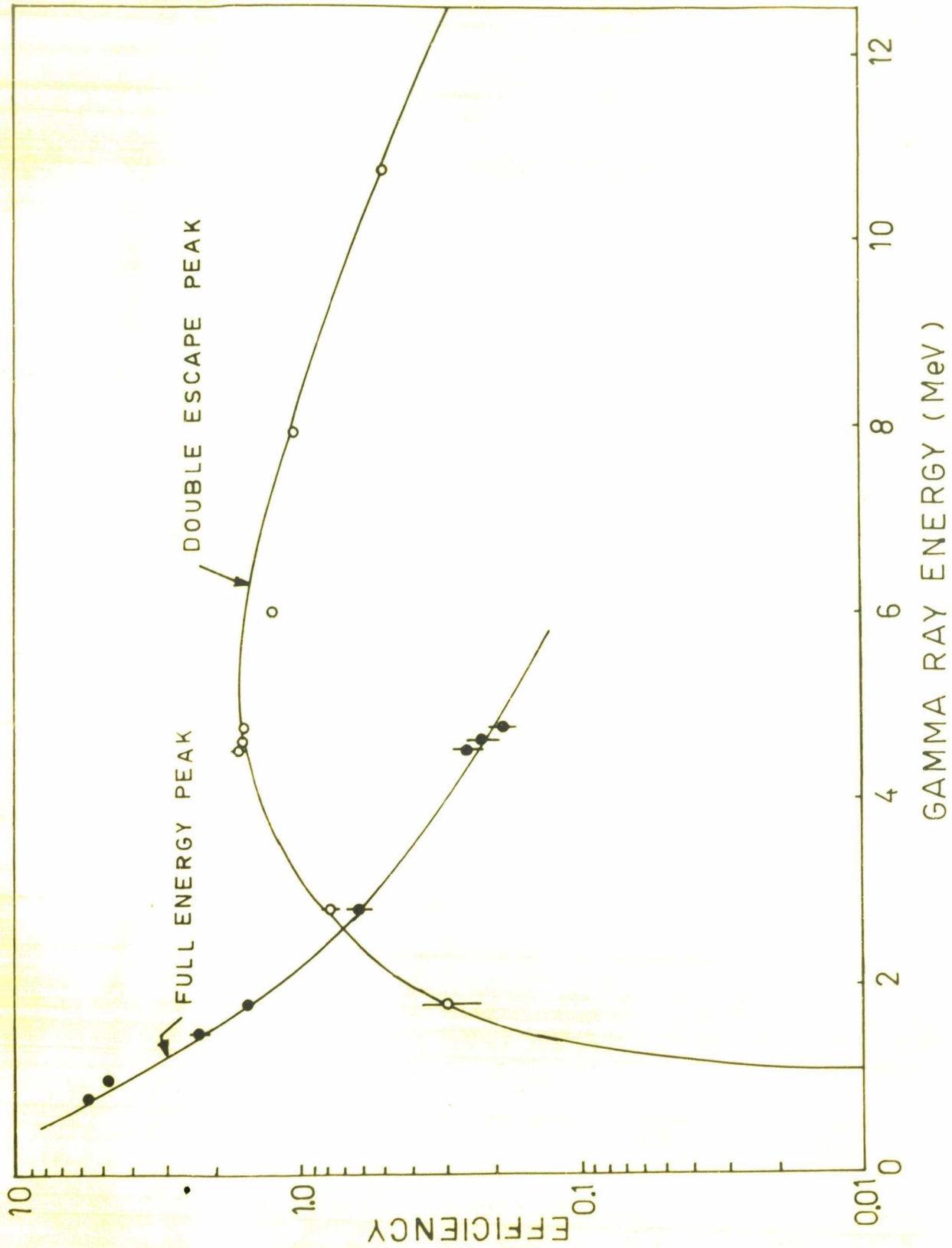


Fig.6.2 Measured photopeak and double escape efficiencies as a function of energy of gamma rays. The dots refer to photopeaks and the open circles to double escape peaks.

20 C.C. Ge(Li) detector movable between 0° and 90° to the beam direction. A 5 "x6" NaI(Tl) detector was placed at a fixed angle (90°) to the beam direction and served as a monitor for normalising counts on angular distributions so that the uncertainty in angular distributions due to any drift in beam energy was accounted for. This detector was kept at a distance of 5 cm from the target; γ -rays from radioactive sources and from the decay of the 0.992 MeV resonances in $^{27}\text{Al}(p, \gamma) ^{28}\text{Si}$ were used for the energy calibration of the 4096 channel pulse height analyser. Gamma ray angular distributions have been measured for the resonances at $E_p = 2.198, 2.482, 2.511$ and 2.735 MeV from $^{27}\text{Al}(p, \gamma) ^{28}\text{Si}$ reaction. The gamma ray spectra at $E_p = 2.198$ and 2.482 MeV for a fixed number of beam charges accumulated at 90° are displayed in figs. 6.3 and 6.4. The spectra were taken at 90° to eliminate Doppler shifts.

The output signals from the Ge(Li) detector were amplified by an Ortec pre-amplifier and a main amplifier and were then analysed by a 4096 channel pulse height analyser.

6.4b Analytical

The peak's areas were determined by adding counts in each channel under the peaks and this is described below as given by Hossain⁷³⁾. In order to determine the yield of gamma ray at a particular energy it was necessary to remove the contributions

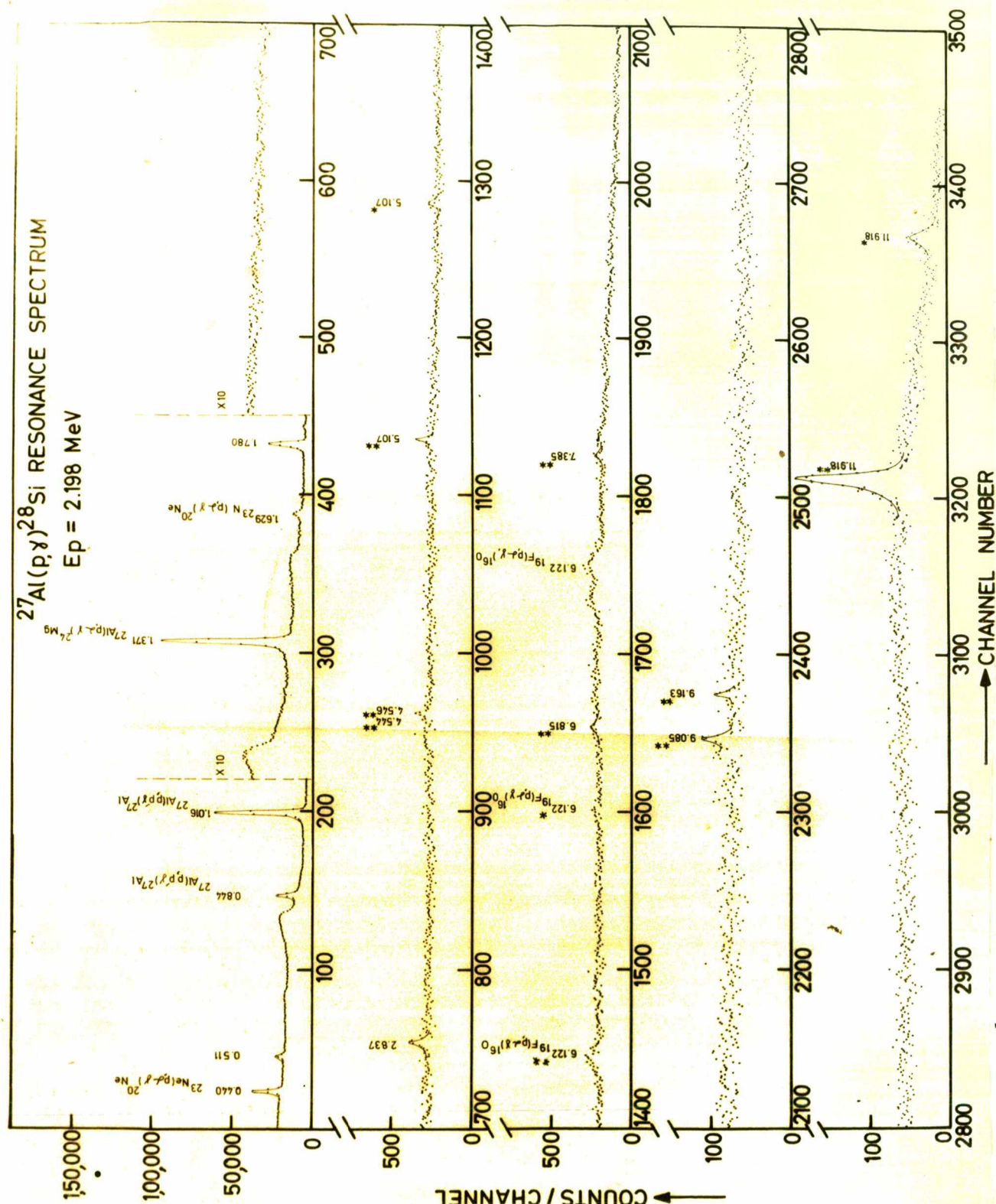


Fig.6.3 The spectrum on $E_p = 2.198 \text{ MeV}$ resonance from $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ reaction and it was taken for 8,000 C.R.C.

from the total number of counts in each pulse height analyser channel due to the background under the peak. The yield is then given by

$$Y \text{ (yield)} = T \text{ (Total counts)} - B \text{ (Background)}$$

and the error is given by

$$\Delta Y = \left[(\Delta T)^2 + (\Delta B)^2 \right]^{1/2} \quad \text{..... (6.1)}$$

when B is very small the errors in the yield are essentially the statistical errors associated with the total counts in the peak. This can be obtained by taking large background as far as possible on both sides of the peak. As for example when background varies slowly a large number of channels are added on both sides of the peak so that the statistical errors are very small. By drawing a straight line between the mean counts on both sides of the peak the background is then subtracted. The number of channels added on either side of the peak are, of course, limited by the proximity of the neighbouring peaks or Compton edges. The peak areas thus obtained were then corrected for the inequality of NaI(Tl) detector counts at 90° (which is used for the monitoring of γ rays), C.I.C. counts and anisotropy observed due to the variation of distance between the detector (Ge(Li) and the γ -rays source and or any change in position due to the placing or γ -rays source to the exact target position. Anisotropy was measured by placing ^{152}Eu source in the target position and the detector at 0° , 30° , 55° and 90° . The determination of spin of a

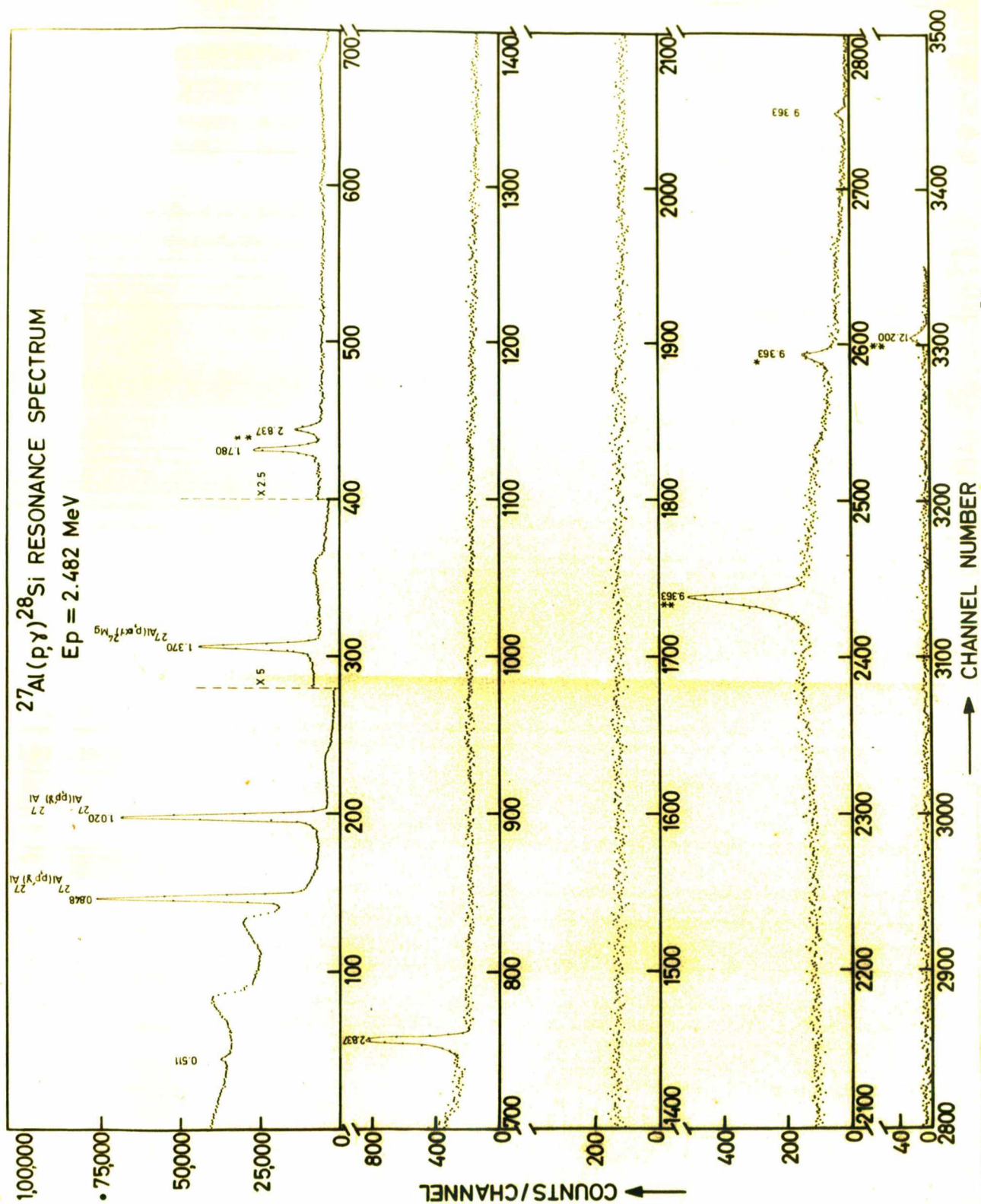


Fig.6.4. The spectrum on $E_p = 2.482 \text{ MeV}$ resonance from $^{27}\text{Al}(p,\gamma)^{28}\text{Si}$ reaction and it corresponds to 10,000 C.I.C. counts.

nuclear state has rested very largely on angular distribution measurements of a nuclear reaction. The formula for theoretical angular distribution is usually written as

$$W(\theta) = A_0 + A_2 Q_2 P_2(\cos\theta) + A_4 Q_4 P_4(\cos\theta), \quad \dots (6.2)$$

where $W(\theta)$ is the intensity of the reaction observed at the angle θ relative to the incident beam and the A_0 , A_2 and A_4 are the coefficients of the corresponding Legendre Polynomials $P_0(\cos\theta)$, $P_2(\cos\theta)$ and $P_4(\cos\theta)$. Q_2 and Q_4 are the attenuation of the gamma rays at various angles due to finite size of the detector. The values of Q_2 and Q_4 have been taken from Häusser et al. ⁷⁴⁾. The ratios $A_2/A_0 = a_2$ and $A_4/A_0 = a_4$ depend on the spins of the initial and final states of a nuclear reaction.

In order to obtain the values of the coefficients of Legendre Polynomials a computer programme has been developed. The values of A_0 , A_2 and A_4 have been obtained by least squares analyses of Legendre Polynomials fit and thereby the values of a_2 and a_4 have been obtained. They are presented in table 6.1. The gamma ray angular distributions data have been analysed by using the formula derived by Rose and Brink ⁷⁵⁾. It is written as

$$W(\theta) = \sum_{L, \pi, L', \pi'} \left[B_k(J_1) R_k(LL'J_1J_2) \delta_L^{(\pi)} \delta_{L'}^{(\pi')} Q_k P_k(\cos\theta) \right] / \sum_{L, \pi} \left| \delta_L^{(\pi)} \right|^2 \quad \dots (6.3)$$

TABLE 6.1

Summary of gamma ray angular distribution coefficients

E_p (Lab) (MeV)	Primary E_γ transition (MeV)	A_0	$a_2 = \frac{A_2}{A_0}$	$a_4 = \frac{A_4}{A_0}$
	4.544 a)			
2.198	6.815 b)	260.28 $\pm$ 13.24	0.044	0.015
	9.085 b)	210.84 $\pm$ 20.17	-0.0264	0.110
	11.918 b)	929.78 $\pm$ 27.03	-0.130	-0.078
2.482	9.363	2182.42 $\pm$ 51.53	0.351 $\pm$ 0.050	0.096 $\pm$ 0.098
	12.200	45.98 $\pm$ 7.56	0.498 $\pm$ 0.334	0.196 $\pm$ 0.652
2.511	9.390	2854.53 $\pm$ 54.04	-0.111 $\pm$ 0.041	0.046 $\pm$ 0.072
2.735	5.275	227.67 $\pm$ 29.97	-0.489 $\pm$ 0.264	0.011 $\pm$ 0.488
	7.335	122.05 $\pm$ 19.98	-0.491 $\pm$ 0.333	-0.142 $\pm$ 0.630
	9.606	422.41 $\pm$ 24.24	-0.127 $\pm$ 0.125	0.128 $\pm$ 0.238
	12.442	39.93 $\pm$ 7.12	-0.328 $\pm$ 0.308	0.082 $\pm$ 0.703

a) See table 6.2

b) Angular distribution are measured at three angles and therefore error limits in a_2 and a_4 can not be put.

Here L and L' denote the multipolarities appearing in the transition. $\langle \pi \rangle$ and $\langle \pi' \rangle$ stand for either electric or magnetic. δ_L is the mixing ratio. The formula derived by them describes the angular distribution of gamma rays emitted from an aligned nuclear level. A level which does not have all its magnetic substates equally populated but has them unequally populated with the condition that the population of the $+m$ sub-level is equal to the population of the $-m$ sub-level is called an aligned level. The angular distribution formula for de-exciting γ -rays making an angle θ with the incident beam is expressed as

$$W(\theta) = \sum_{\text{Keven}} B_k(J_1) \left[\frac{R_k(LLJ_1J_2) + 2\delta R_k(LL'J_1J_2) + \delta^2 (L'L'J_1J_2)}{1 + \delta^2} \right] \times Q_k P_k \cos\theta \quad \dots\dots\dots (6.4)$$

This expression is valid for the case when only the two lowest multipolarities L and $L' = L+1$ contribute to the gamma ray transition between the initial state of spin J_1 and the final state of spin J_2 and the polarisation of the de-exciting gamma ray is not observed. $B_k(J_1)$ is known as the population parameter. It contains information about the mode of formation of the initial state. $B_k(J_1)$ is the same for all branches originating from a

given level. $R_k \times$ power δ contains the nuclear structure information of the transition.

The mixing parameter δ is defined as

$$\delta = \frac{\langle J_1 || T_L^{<\pi>} || J_2 \rangle / (2L'+1)^{1/2}}{\langle J_1 || T_L^{<\pi>} || J_2 \rangle / (2L+1)^{1/2}} \dots (6.5)$$

where the symbol $\langle J_1 || T_L^{<\pi>} || J_2 \rangle$ stands for the reduced matrix element of the multipole interaction parameter $T_{LM}^{<\pi>}$.

The value of population parameter depends on the specific process by which the initial state $|J_1 M_1\rangle$ is formed. In the present case the alignment is achieved through the absorption of unpolarised protons in randomly oriented target nuclei. Thus the beam direction serves as the axis of quantization. In the present case the target spin is $5/2^+$ and two channel spins ($S=2,3$) contribute to the formation of the compound level. $B_k(J_1)$ is then obtained as

$$B_k(J_1) = \sum_S \left[S_k(11J_1S) A^2(1) + 2S_k(11'J_1S) A(1)A(1') \cos(\phi_l - \phi_{l'}) \right. \\ \left. + S_k(1'1'J_1S) A^2(1') \right] T(S) \dots (6.6)$$

The amplitude for the formation of the J_1 with partial waves l and l' are $A(l)$ and $A(l')$ which have the normalization

$$|A(l)|^2 + |A(l')|^2 = 1 \dots (6.7)$$

The channel spin intensity is $T(s)$ with the normalization $\sum_s T(s) = 1$. It is seen that when the state J_1 is formed by two partial waves, for each channel spin, two parameters enter in $B_k(J_1)$. The selection of l -value was made from a consideration of the $^{27}\text{Al}(d,p)$ stripping reaction populating the relevant levels in ^{28}Al when available²¹⁾. In the present case, in three out of four cases l -values were known. When two l -values (such as $l=0+2$ and $l=1+3$) contribute, the dominant l was considered. The expression for $B_k(J_1)$ then simplifies to

$$B_k(J_1) = \sum_s S_k(lJ_1s)T(s) \dots (6.8)$$

The multipolarity of the emitted gamma ray is governed by the selection rule

$$J_i + J_f \gg L \gg |J_i - J_f|,$$

The parity of a nuclear state usually can not be determined from the measurements of angular distribution because the electric and magnetic radiation of the same multipolarity L are related by the transformation $\underline{E} \rightarrow \underline{H}$, $\underline{H} \rightarrow -\underline{E}$. This transformation leaves the Poynting vector and therefore the angular distribution of the radiation unaltered. Thus the dipole produces the same angular distributions irrespective of its nature. A value of δ below unity denotes the predominance of L , where as if δ exceeds unity, there is an excess of L' . The value $\delta = 0$ characterizes pure L radiation and $\delta = \infty$ pure L' radiation.

In the analysis of results for every value of J_1 the only variable in the theoretical formula is the mixing ratio δ . A normalization constant is to be found out for a comparison of theoretical distribution with experiment. The values of coefficients Q_k , R_k and S_k are taken from ref. 74. The mixing ratio δ is then assigned a set of fixed values by putting $\phi = \arctan \delta$ and varying ϕ from -90° to $+90^\circ$ in steps 5° . For every value of ϕ the normalization constant N is then found by minimizing

$$\chi^2 = \frac{1}{n-1} \sum_{i=1}^n (Y_i - NW_i)^2 / E_i^2 \quad \dots (6.9)$$

where n is the number of data points, Y_i is the experimental yield at angle θ_i and E_i the corresponding error. W_i is the value of the theoretical distribution at angle θ_i .

The minimum condition gives

$$N = \frac{\sum \frac{Y_i W_i}{E_i^2}}{\sum \frac{W_i^2}{E_i^2}} \quad \dots (6.10)$$

A computer programme has been developed to obtain the goodness of fit χ^2 as a function of δ and angular distribution fit by using equations (6.4) and (6.8)-(6.10).

The value of χ^2 is a function of the mixing ratio δ if $J > 1/2$. Solutions with χ^2 larger than a chosen "confidence limit" are to be discarded. The confidence limit is defined as

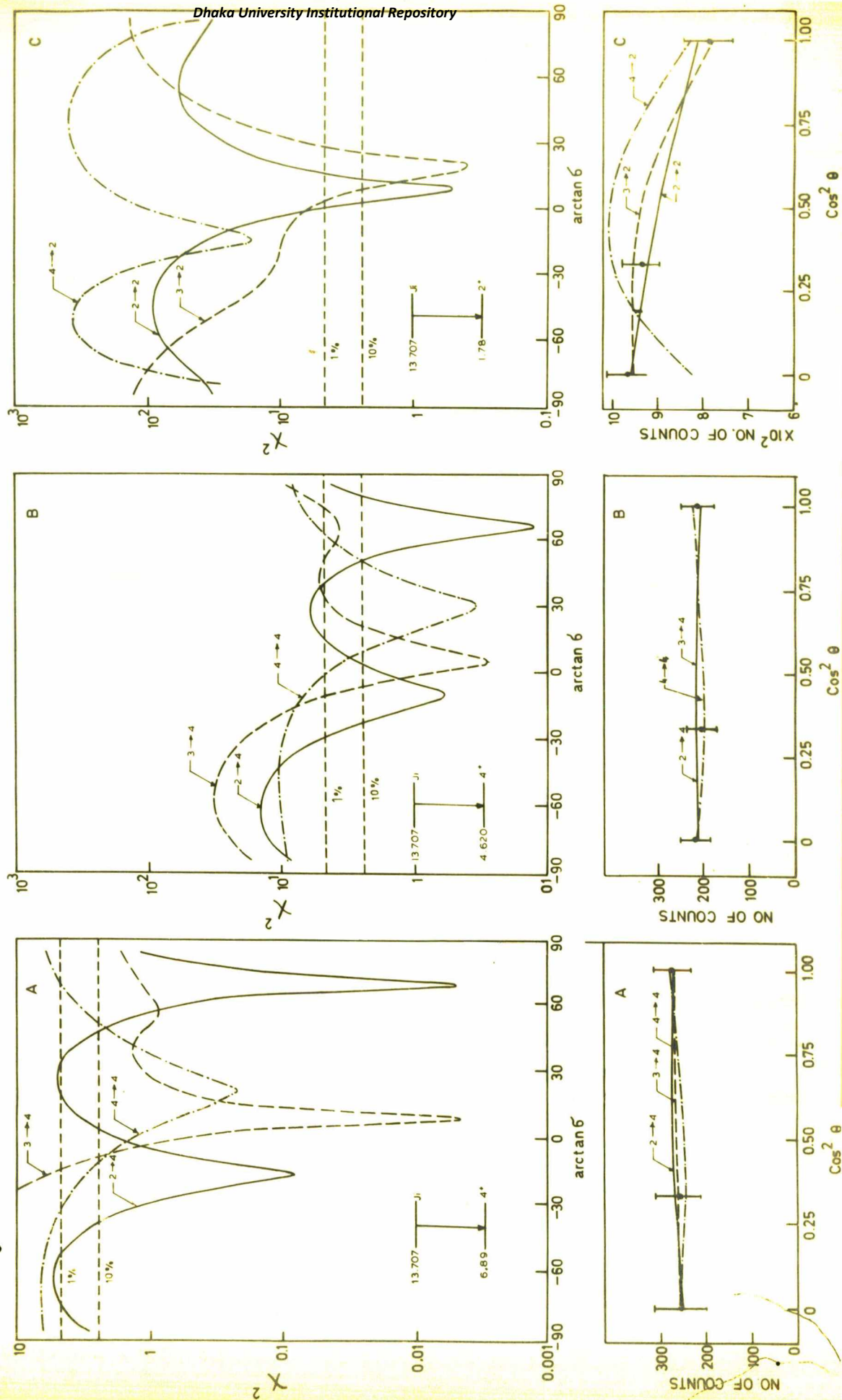


Fig.6.5 Angular distribution and χ^2 plots for (A) 6.815, (B) 9.085 and (C) 11.918 MeV gamma rays produced at $E_p = 2.198$ MeV resonance.

the probability that in an experiment under exactly the same conditions χ^2 would be smaller than a chosen χ^2_0 . This probability depends upon the number of degrees of freedom. Confidence limits for the normalized χ^2 values are taken from the graph published by Wapstra et al. ⁷⁶⁾. The general criteria adapted was that the angular distribution curve did not fit the data for values of χ^2 well outside the 1% confidence limit, while the fit was considered to be satisfactory for values of χ^2 near or inside the 10% confidence limit.

6.5 Results and Discussion

Angular distributions of gamma rays which are emitted by resonating states 13.707, 13.980, 14.007 and 14.223 MeV of ^{28}Si at $E_p = 2.198, 2.482, 2.511$ and 2.735 MeV are discussed below.

The $E_p = 2.198$ MeV resonance

The gamma rays 4.544, 6.815, 9.085 and 11.918 MeV emitted by 13.707 MeV excited state populate the levels 9.16($2^+, 3^-, 4^+$), 6.89(4^+), 4.62(4^+) and 1.78(2^+) MeV respectively of ^{28}Si . The spin of the level 9.16 MeV reached by the 4.544 MeV gamma ray is uncertain. Further more since the spin of the resonance state is assigned either 2 or 3, it was not felt worthwhile to analyse the angular distribution. The angular distributions for the last three gamma rays have been analysed. The theoretical fits to experimental angular distribution and χ^2 as a function of $\arctan \delta$ for these gamma rays are shown in fig. 6.5. The branching of each gamma ray

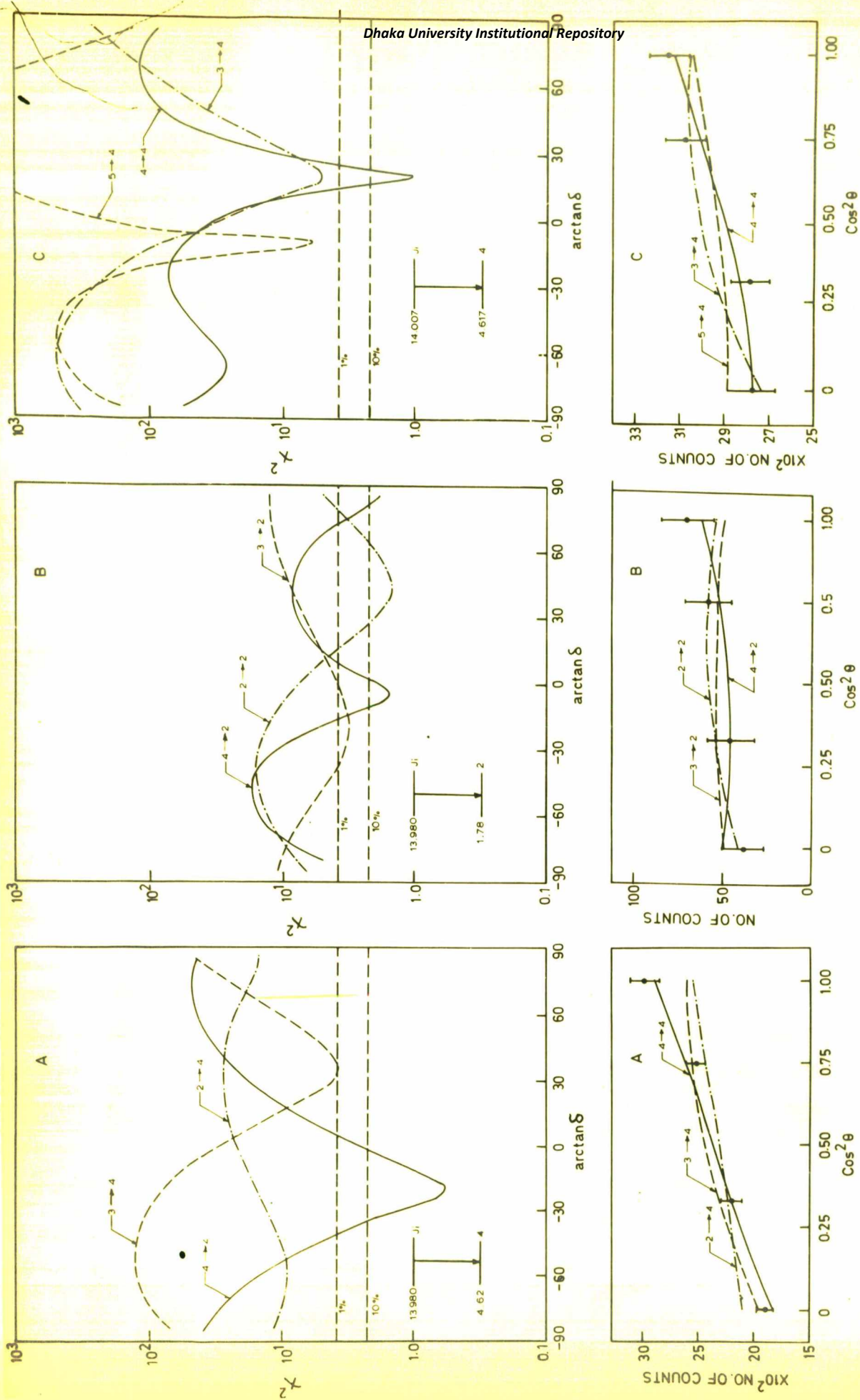


Fig.6.6 Angular distribution and χ^2 plots for (A) 9.363 and (B) 9.390 MeV gamma rays produced at $E_p=2.482$ MeV resonance and (C) 12.200 MeV gamma ray produced at $E_p=2.511$ MeV resonance.

along with δ -values at 1% and 10% confidence limits are presented in table 6.2. Spin assignment either 2 or 3 to the resonating state 13.707 MeV is favoured. Spin assignment either by 6.815 or 9.085 MeV gamma ray do not probably give true information because spin could be 2,3 or 4 (fig. 6.5A and 6.5B). But the analyses of data of 11.918 MeV gamma ray rejects the spin value 4 (fig. 6.5C). In chapter 3, this resonance was considered to be analogue of the 4.38 MeV level in ^{28}Al . The l_n -value for $^{27}\text{Al}(d,p)$ reaction leading to this level is uncertain ⁷⁷⁻⁷⁹) (table 6.3). An $l_p=3$ for the formation of this resonance was assumed in accordance with the tentative $l_n = 3$ of Endt and Van der Leun ⁷⁷).

The $E_p = 2.482$ MeV resonance

The excited state 13.980 MeV of ^{28}Si emits 9.363 and 12.200 MeV gamma rays and the 4.62(4^+) and 1.78(2^+) MeV levels of ^{28}Si are populated respectively by them. Gamma ray spectra at $E_p = 2.482$ MeV were studied by Antoufiev et al. ⁸⁰) and Hossain ⁷³) and they observed 100% branching to the 4.62 MeV level. In the present work, angular distribution of both the gamma ray were measured and analysed as shown in fig. 6.6(A and B).

The most probable spin of the resonance state is 4 ; the value 2 is rejected by fig. 6.6A and the other value 3 is barely within 1% confidence limit for both the angular distributions. In the analyses an $l_p = 3$ was considered. The spin value 4 is consistent with that of the analogue state in ^{28}Al at 4.685 ($J^\pi = (1-4)^{-1}$).

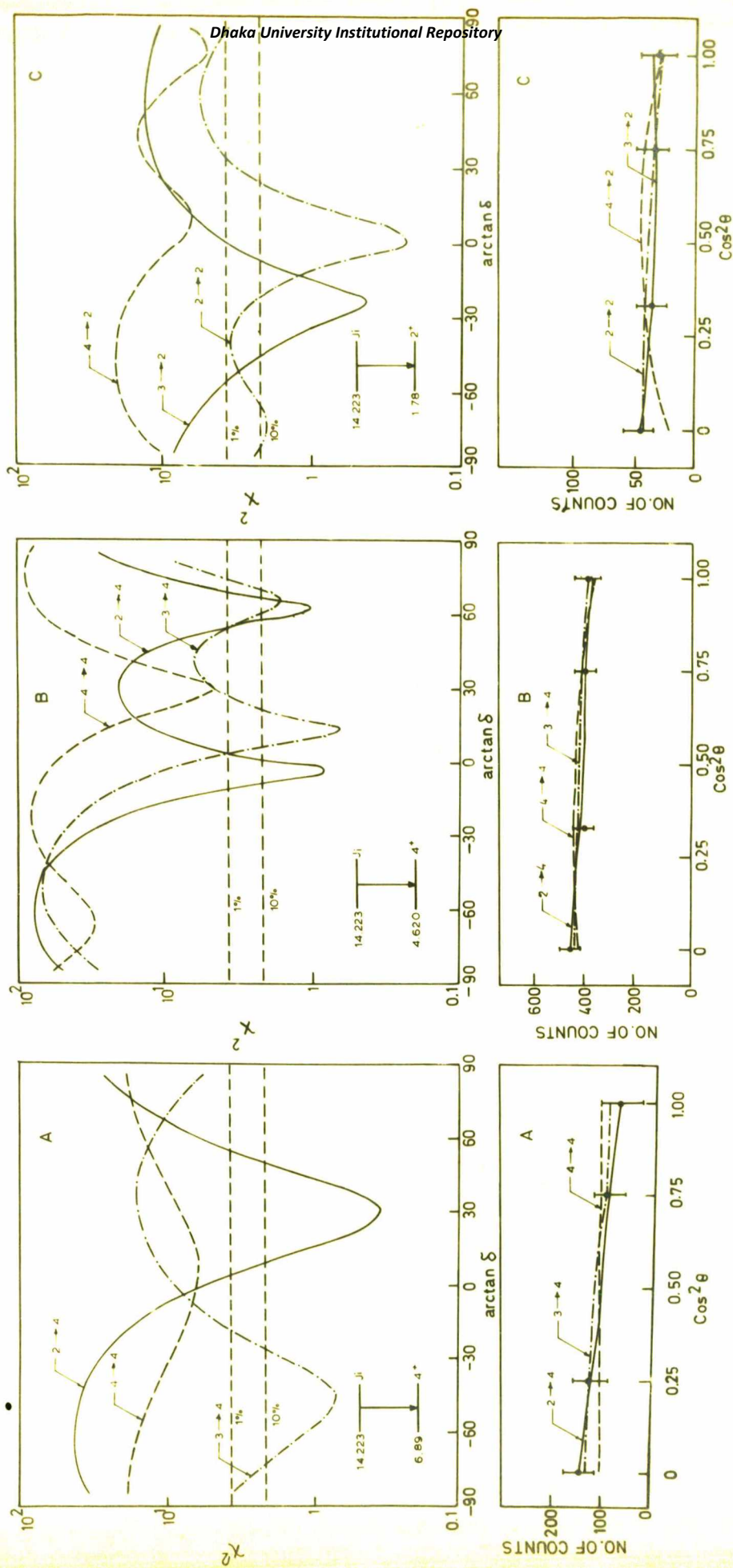


Fig. 6.7 Angular distribution and χ^2 plots for (A) 7.335, (B) 9.606 and (C) 12.442 MeV gamma rays produced at $E_p=2.735$ MeV resonance.

The values of δ at 1% and 10% confidence limits from χ^2 versus $\arctan \delta$ plot and gamma rays branching ratio are given in table 6.2

The $E_p = 2.511$ MeV resonance

The (4^+) 4.617 MeV level of ^{28}Si is populated by de-excitation of 9.390 MeV gamma ray from the resonating state 14.007 MeV. Spin to this state is 4 as can be seen from the χ^2 versus $\arctan \delta$ plot and from the angular distribution fit (fig. 6.6C). An $l_p=2$ was assumed in the analysis (table 6.3) and these values ($l_p=2$ and $J=4$) are consistent with those of the analogue state in ^{28}Al ($e_x = 4.741$ MeV). The χ^2 minimum values and δ -values at 1% and 10% confidence limits are given in table 6.2.

The $E_p=2.735$ MeV resonance

The de-excitation of the resonating state 14.223 MeV takes place through emission of 5.275, 7.335, 9.606 and 12.442 MeV gamma rays and 8.94, 6.89 (4^+), 4.62 (4^+) and 1.78 (2^+) MeV levels of ^{28}Si are populated respectively by them. The spin of the resonating 14.223 MeV state has been assigned to be 3, (2) from the χ^2 versus $\arctan \delta$ fit and theoretical fits to experimental angular distributions data of 7.335, 9.606 and 12.442 MeV gamma rays (fig. 6.7A-C). Spin 4 to the excited state 14.223 MeV is rejected by the angular distribution, spin 2 is not favoured since 66% branching of 9.606 MeV gamma ray takes place by decaying to

TABLE 6.2
Summary of gamma ray angular distributions, multipole mixing ratios and assigned spins for the resonances studied.

E_p (MeV)	Primary transition E_γ (MeV)	Branching ratio (%)	Spin sequence $J_i \rightarrow J_f$	χ^2 (Min)	Mixing ratio δ at confidence limits			Probable Spin J_i
					1%	10%	Minimum	
2.198	6.815	12	2 4	0.08	-1.15	-0.73	-0.27 M2/E1	+0.36
			3 4	0.0045	-0.23	-0.11	+0.18 M2/E1	∞
	9.085	11	2 4	0.58	-0.55	-0.40	-0.18 M2/E1	+0.26
			3 4	0.28	-0.19	-0.11	+0.087 M2/E1	0.65
2.482	11.918	70	2 2	0.50	0.00	+0.056	+0.14 M2/E1	+0.28
			3 2	0.39	+0.052	+0.14	+0.34 M2/E1	+0.53
	4.544 a)	7						
	9.363	95	4 4	0.56	-0.88	-0.71	-0.36 M2/E1	+0.073
2.511	12.200	5	4 2	1.52	-0.28	-0.19	-0.087 M2/E1	+0.18
	9.390	~ 100	4 4	1.04	+0.24	+0.29	+0.36 E2/M1	+0.45
2.735	7.335	7	2 4	0.36	+0.070	+0.16	+0.58 E2/M1	+1.43
			3 4	0.71	-14.3	-3.27	-1.04 E2/M1	-0.33
	9.606	66	2 4	0.82	-0.19	-0.14	-0.061 E2/M1	+0.059
			3 4	0.64	+0.070	+0.11	+0.23 E2/M1	+0.51
2.735	12.442	14	2 2	0.23	-0.84	-0.40	0 E2/M1	+0.65
			3 2	0.43	-1.48	-1.02	-0.44 E2/M1	-0.009
	5.275	13	3 4	1.4	+0.45		+0.73	+1.23
								$J_f = 4$

a) Spin of the final state (Exc = 9.16 MeV) reached by this gamma de-excitation is uncertain (2^+ , 3^- , 4^+) ; angular distribution was not, therefore, analyzed.

the 4.620 MeV state (4^+). An $l_p=2$ was taken in the analysis again from a consideration of $^{27}\text{Al} (d,p) ^{28}\text{Al}$ work as well as the spin of the final state. The J^π of the assumed analogue state (4.928 MeV in ^{28}Al) is not known, the present value $J = 3$ is consistent within the expected range of spin (0-6). It is worthwhile to repeat $^{27}\text{Al} (d,p)$ measurement at higher deuteron energy. The values of δ obtained at χ^2 minimum at 1% and 10% confidence limits are given in table 6.2.

With the present spin assignment of the resonance state ($J=3$), the angular distribution of 5.275 MeV gamma populating the 8.94 MeV level of ^{28}Si was analysed. This leads to $J=4$ for the latter level. This level decays to 4^+ level ($E_x = 4.62$ MeV) with about 100% branching which is consistent with the above spin assignment.

We now make some general remarks regarding all the resonances mentioned above.

The spin values of resonating states 13.707, 13.980, 14.007 and 14.223 MeV corresponding to 2.198, 2.482, 2.511 and 2.735 MeV proton resonances as assigned in this experiment are shown in fig. 6.8 and given in table 6.3. They were identified as analogue resonances from a consideration of intensity and excitation as discussed in chapter 3. The spin values are consistent with the range of spin values of ~~parent~~ ^{parent} states. From the l_p values required in the present analyses for the formation of the resonance states, the parities are also tentatively shown in table 6.3. They are consistent

TABLE 6.3
Properties of analogue resonances

E_p (Lab) (MeV)	^{28}Si		^{28}Al			J^π		
	E_x (MeV)	Probable J^π	E_x (MeV)	l_n from $^{27}\text{Al}(d,p)$			a)	b)
				a)	b)	c)		
2.198	13.707	$2^-, 3^-$	4.383	(3)			$(\leq 6)^-$	$(0-5)^+$
2.482	13.980	4^-	4.685	1	$1+3$	$1+3$	$(\leq 4)^-$	$(1-4)^-$
2.511	14.007	4^+	4.741	2	$(0)+2$	2	$(\leq 5)^+$	$(0-5)^+$
2.735	14.223	$3^+, (2)^+$	4.928		$(0+2)$			$(0-5)^+$

a) Ref. 77
b) Ref. 78
c) Ref. 79

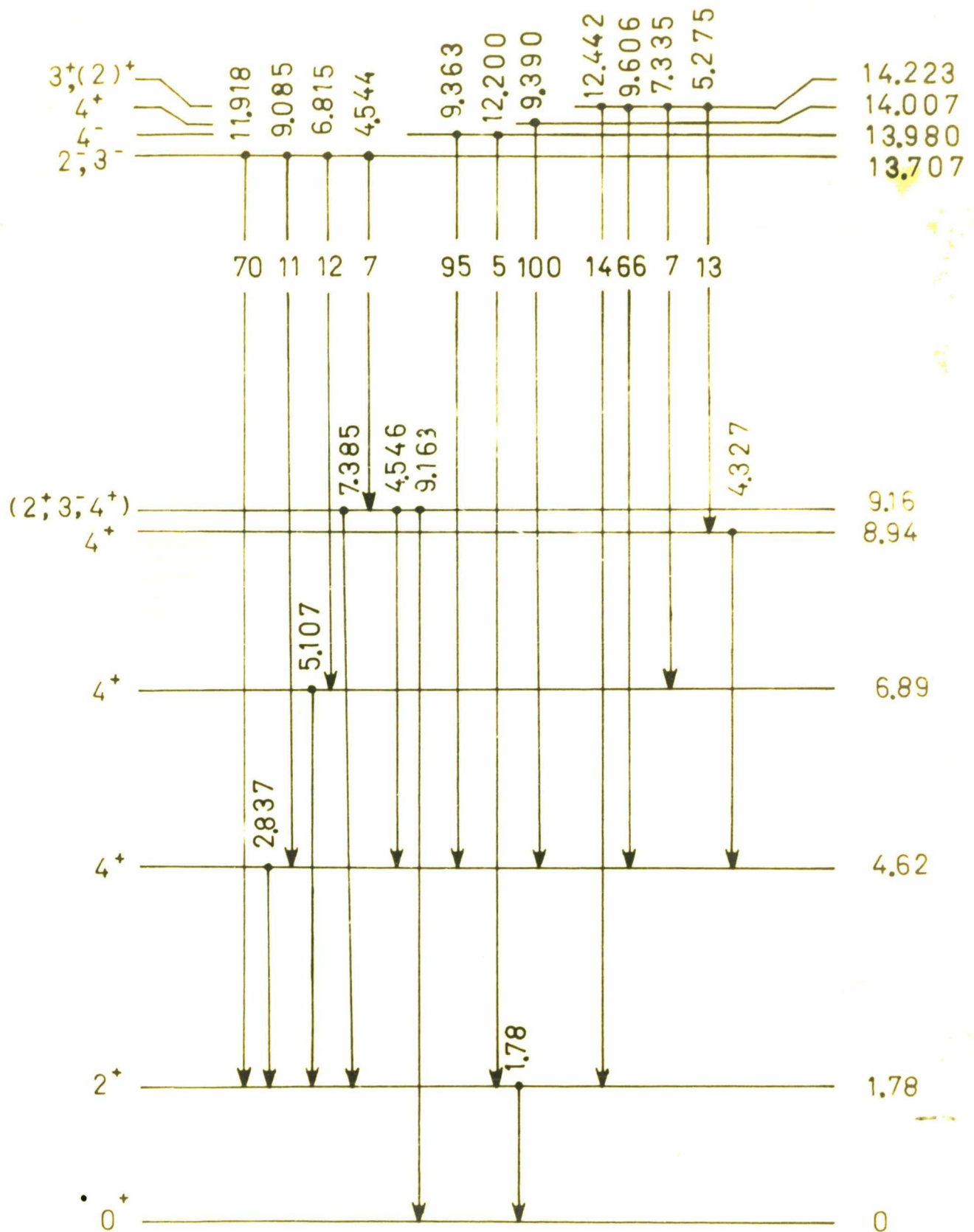


Fig.6.8 Probable spin-parity values to resonating states..

in all cases with those of ~~parent~~ states in ^{28}Al except for the resonance $E_p = 2.198$ MeV, where parity assignment of the parent state is not quite certain (table 6.3). As has been said before the l_p -values of 3, 3, 2 and 2 respectively for $E_p = 2.198$, 2.482, 2.511 and 2.735 MeV consistent with the acceptable spin of the resonant levels and also with the corresponding l_n values in ^{27}Al (d,p) ^{28}Al measurement (table 6.3) were considered in the analyses. A possible $l_p = 1$ mixture with $l_p = 3$ resonance was neglected from a consideration of the weak excitation of the $E_p = 2.198$ MeV and 2.482 MeV resonances reported in the following chapter. Further, since the ground state spin of ^{27}Al is $5/2^+$, the possible channel spins are 2 and 3. Both these components with varying proportion were tried in the present analysis. An equal mixture of the two was usually considered; other proportion did not change the $\arctan \delta$ by more than 10° .

The small values of mixing ratio δ from table 6.3 (with a possible exception for the gamma transition $14.223 \text{ MeV} \rightarrow 6.89 \text{ MeV}$ at $E_p = 2.735 \text{ MeV}$) suggests small multipolarity mixing of the emitted gamma rays.

For $E_p = 2.511 \text{ MeV}$ resonance it is seen from fig. 6.8 that the strong transition ($\sim 100\%$ branching) is between 14.007 MeV and 4.620 MeV levels each with $J^\pi = 4^+$. This probably is a case of analogue to antianalogue M1 transition which is found to be quite dominant in the s-d shell⁸¹⁾. It may be mentioned here that the properties of $1f_{7/2}$ nuclei including analogue resonances has recently been reviewed by Ricci⁸²⁾. Contrary to the s-d shell, no such strong analogue to antianalogue transition is usually observed.

CHAPTER - 7

THE ^{27}Al (p,p) MEASUREMENT7.1 Introduction

Information on the properties of nuclear states such as the orbital angular momentum, total and partial widths and spin-parity of resonant states can be obtained from the study of elastic resonance scattering of protons on a target nucleus. The partial width obtained from this measurement provides a valuable cross check on the information obtained by independent measurements such as (d,p) and (t,d) neutron stripping reactions in the same target nucleus.

In nuclei in the $1f_{7/2}$ shell region Duke group has studied the elastic proton scattering with high resolution. In light nuclei (s-d) shell region) levels are widely spaced at lower excitation energy and resonating states can be observed experimentally with relatively poor resolution (~ 1 keV). With these knowledge and our present limitations (poor machine resolution and limited computer facilities) we intended to study the elastic scattering of protons on ^{27}Al .

The ^{27}Al (p,p) resonance reaction was investigated by Awaya ¹⁹⁾ at $E_p = 0.936, 0.991, 1.117, 1.182, 1.198, 1.362, 1.380$ and 1.387 MeV at centre of mass angle 140.46° and at $E_p = 1.117, 1.182$ and 1.198 MeV resonances at $\theta_{\text{C.M.}} = 90^\circ$. Tentative spin-parity assignments of some of the resonances were also made. The experiments by Shoemaker et al. ⁸³⁾ in the energy range $E_p = 1.40 - 4.10$ MeV were concerned with the location of resonance energies and do not give information on the properties

of resonance states. The properties of nuclear states by (p, γ) and (p, p) reactions on ^{27}Al upto $E_p = 1.968$ MeV are available as compiled by Endt and Van der Leun²¹⁾.

The present measurement was, therefore, undertaken to study the excitation of functions in the energy range $E_p = 0.85 - 3.00$ MeV in order to derive information on properties of resonances.

7.2 Experimental arrangement

The experiment has been performed with proton beam from the 3 MeV Van de Graaff accelerator at Atomic Energy Centre, Dacca. The spread in beam was about 850 eV as stated earlier. During the measurements ^{27}Al targets $5-20 \mu\text{g}/\text{cm}^2$ thick were used. These targets were prepared in A.E.C. laboratory by Vacuum evaporation technique on carbon backing of $5-20 \mu\text{g}/\text{cm}^2$ thick. A high vacuum carbon arc evaporation method was used to put the carbon backing onto a 1"x3" glass microscope slide which was coated with a very thin film of detergent (soap solution) to facilitate separation of carbon from the glass. The ^{27}Al was evaporated onto the carbon backed glass slides in high vacuum. The target foil was then removed from the glass slide by floating in water. The target foils were lifted off the water using square aluminium or brass target frames having circular opening 10 mm in diameter which were so designed as to fit into a target holder in the scattering chamber.

Elastically scattered protons were detected by two ORTEC surface barrier detectors of 100 mm^2 sensitive area and

depletion depths of 500μ and 1000μ respectively. The energy resolutions of the detectors for $5.477\text{ MeV } \alpha$ -particles from ^{241}Am source has been found to be 60 keV and 67 keV respectively. The target was kept at an angle of 45° with respect to the proton beam and the detectors were placed at distances of 10 cm inside a $18''$ scattering chamber. The target holder can contain three targets at a time, the target position with respect to the beam axis can be changed from outside without breaking the vacuum. Both the target angle and the detector angle can be similarly adjusted from outside. The proton beam enters the scattering chamber through a tantalum collimator 2 mm in diameter. The elastically scattered protons fall on the sensitive area of the detector through a button magnet and two tantalum collimators of $2\text{ \& } 3\text{ mm}$ in diameter placed just in front of the detector. The magnet was used as a suppressor of electrons. The protons after passing through the target are collected in a Faraday cup which is insulated from the chamber. Each point on the measurements corresponds to $100\mu\text{c}$ of charge collected by the Faraday cup. This yields about 3% counting statistics in the off resonance scattering cross-section. Excitation functions were measured in energy steps of no more than 1 keV .

The detector pulses were fed to a set of scalers via a charge sensitive preamplifier, a linear amplifier and a single channel analyser. The experimental set up is shown in Fig. 7.1

The desired peak area of elastically scattered proton from the

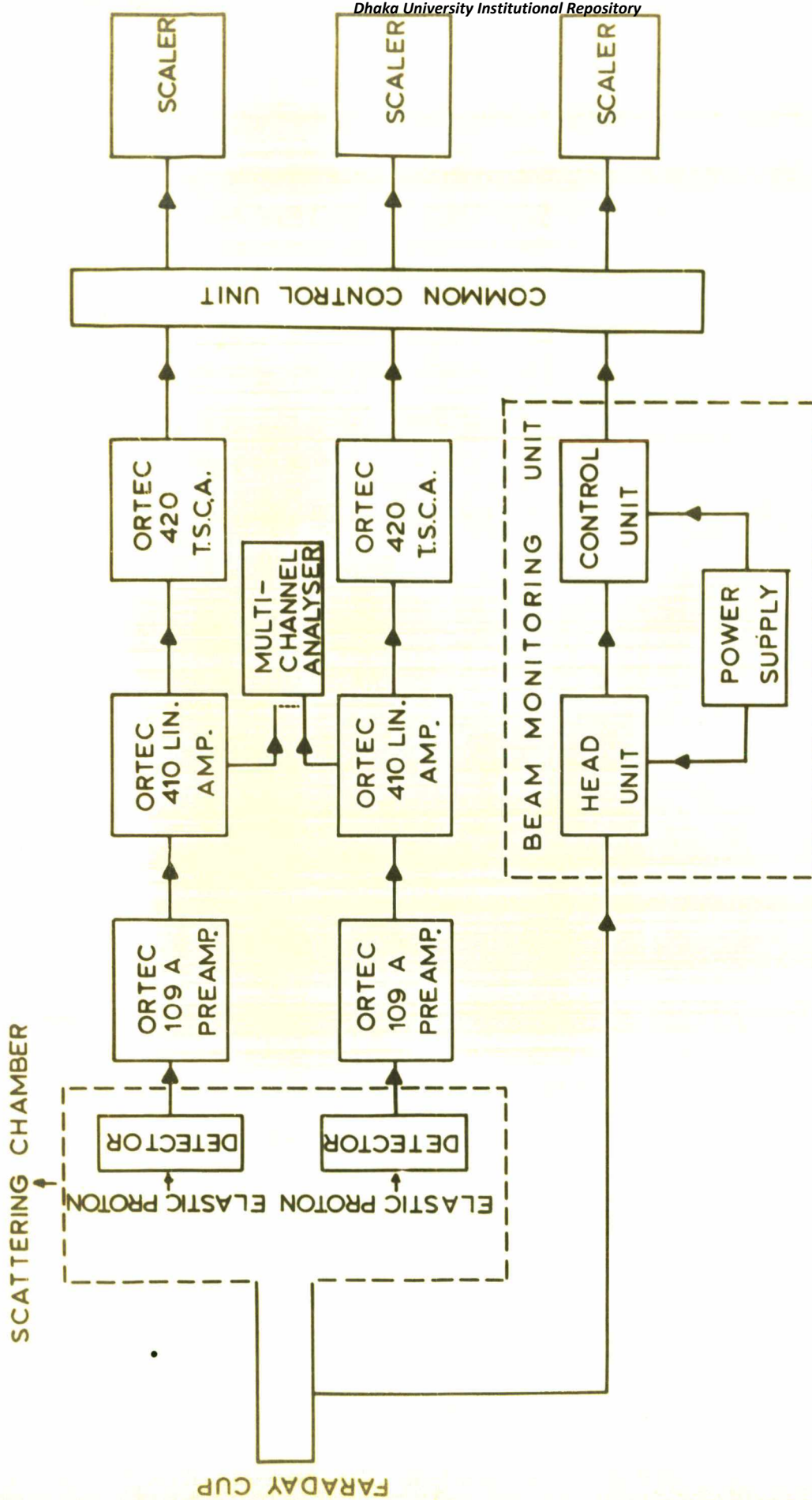


Fig.7.1 Block diagram of the experimental set up for (p,p) measurement.

target is gated by the discriminator levels of the single channel analyser ORTEC 420 which was previously calibrated. The discriminator levels are adjusted accordingly for each increase in the proton beam energy say every 5-10 keV increase in proton energy so that only the counts in the desired peak area (elastically scattered protons from ^{27}Al) are registered in the scalers. A typical spectrum from proton elastic scattering on ^{27}Al at $E_p = 1.50$ MeV at an angle $\theta_{\text{Lab}} = 88^\circ$ is shown in fig. 7.2. This spectrum shows proton groups from elastic scattering on carbon, Oxygen and from the nucleus being studied. The method of target preparation and floating made it quite likely that a detectable amount of oxygen molecules might be present in the target. Spectra at higher beam energies and at larger angles had better resolution than that of 90° , i.e., the ^{12}C , ^{16}O and ^{27}Al peaks were separated even more distinctly.

When a charged particle passes through a semiconductor detector it creates free electron hole pairs by the loss of energy at a rate of 3.6 eV per electron hole pair for silicon and 2.9 eV per electron hole pair for Germanium. The rate of formation of charge carrier is independent of energy and type of particle. Free charge carriers created in sensitive region along the path of ionizing particle are separated under the influence of electric field and the resulting net current represents the basic source of information about the number of charge carriers created by the incident radiation.

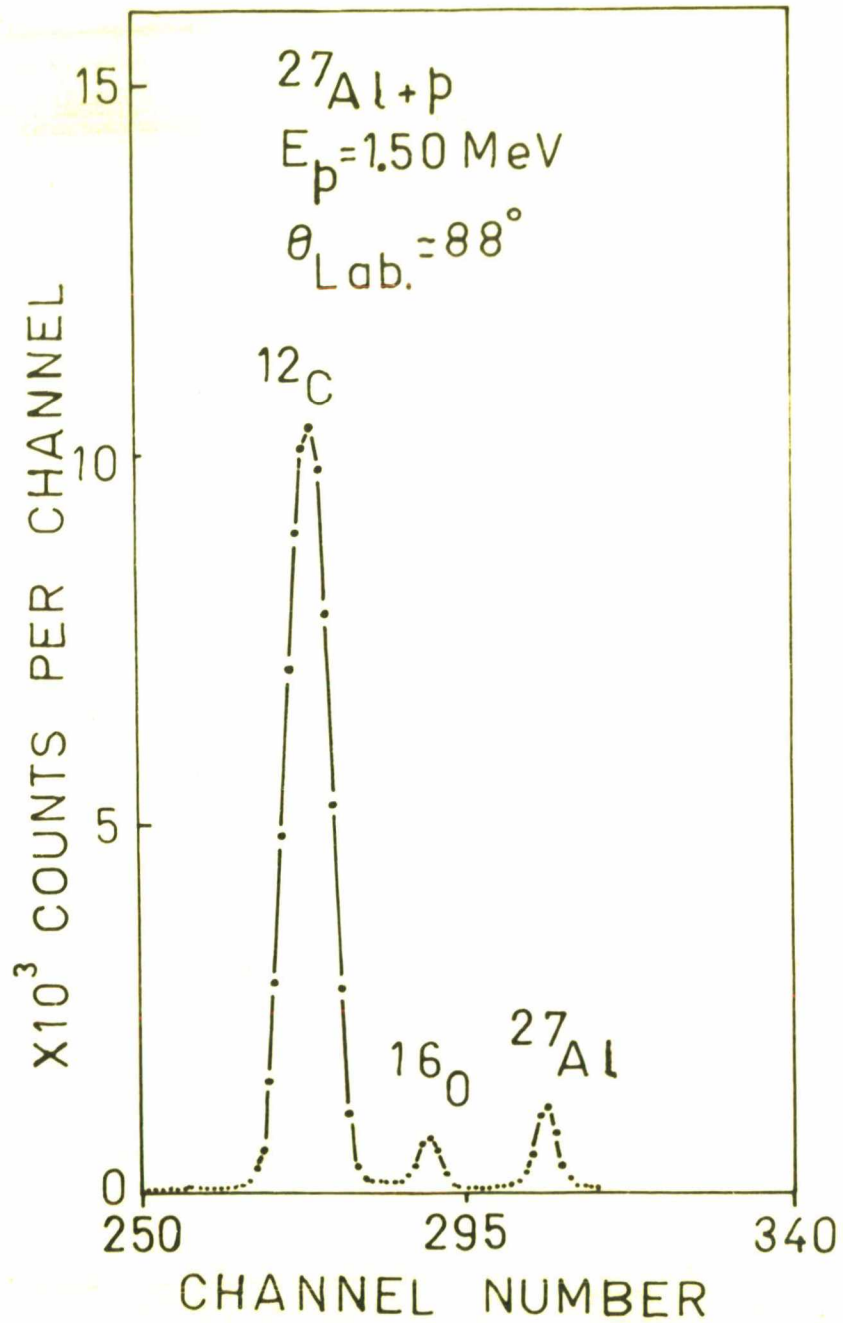


Fig.7.1 .A sample spectrum for $^{27}\text{Al}(p,p)$ resonance reaction at $E=1.50\text{ MeV}$ at $\theta_{\text{Lab.}}=88^\circ$.

7.3 Analysis of data

Excitation functions are usually measured at several angles in the study of resonances from proton elastic scattering. The l -value of a resonances can easily be determined from the variation of resonance shape with angle. The variation in shape of resonances occurs due to interference between Rutherford scattering and resonance scattering. For even-even initial nuclei the interference term in the expression of cross section is proportional to the Legendre polynomial $P_l(\cos\theta)$. In other words one is required to determine the angle/angles at which the interference is minimum and then these angles corresponds to zeros of the Legendre polynomials which occur as a factor in the interference term in the expression for the differential scattering cross-section. The zeros of the first four Legendre polynomials for scattering angles in the centre of mass system are shown below:

$P_0(\cos\theta)$	None
$P_1(\cos\theta)$	90°
$P_2(\cos\theta)$	$54.73^\circ, 125.26^\circ$
$P_3(\cos\theta)$	$39.23^\circ, 90^\circ, 140.76^\circ$

The absence of resonances at 90° shows that no resonances with even values of l are present. The Rutherford scattering is very much larger than the resonance scattering at forward angles while at backward angles the contribution due to Rutherford scattering is very much less. For this reason sharpest resonances are observed in the backward angles.

In ideal case the measurements are done at several angles say, 90° , 125° , 140° , and 160° simultaneously with several detectors having same resolution, size and sensitive depth. Resonance parameters such as proton width and partial width can be extracted from one excitation function particularly at a far-back angle. The analysis of (p,p) resonances data yields information similar to that from the (d,p) stripping reaction. The l-values of proton resonances are in general assigned from the vanishing of the resonances at particular angles just as the l-value of the captured neutron in a stripping reaction can be obtained from the angular distribution. In the present case the channel spin is 2 or 3. Therefore for different l-values obtained from $^{27}\text{Al}(p,p)$ analyses, the J^π limits of the resonance levels in ^{28}Si are as follows

$$l = 0 : \quad J^\pi = 2^+, 3^+$$

$$l = 1 : \quad J^\pi = 1^-, 4^-$$

$$l = 2 : \quad J^\pi = 0^+, 5^+$$

The measurements in the present experiment were carried out at centre of mass angles 90° , 125° and 141° . The absolute cross-section was obtained from the proton counts by normalizing the off-resonance yield at $E_p \leq 1$ MeV with the Rutherford scattering

formula given below.

$$\sigma_R = 1.296 \left(\frac{Z_1 Z_2}{E} \right)^2 \left[\text{Cosec}^4(\psi/2) - 2(M_1/M_2)^2 + \dots \right]$$

where Z_1 = Charge of the incident particle,

Z_2 = number of protons in target nucleus,

M_1 = mass of scattering particle,

M_2 = mass of target nucleus,

E = energy and ψ = scattering angle. The differential elastic scattering cross section for proton from a target nucleus near an isolated resonance relative to the non-resonant potential scattering cross-section is expressed by the relation ⁸⁴⁾ as

$$\frac{\sigma}{\sigma_R}(\theta, E) = 1 + \frac{(E-E_0) A(\theta)}{(E-E_0)^2 + (\Gamma/2)^2} + \frac{B(\theta)}{(E-E_0)^2 + (\Gamma/2)^2} \dots (7.1)$$

Where E is the energy of incident projectile, E_0 is the resonance energy and $A(\theta)$ and $B(\theta)$ are angle factors which depend upon l , J , total resonance width Γ and ratio between proton width and total resonance width Γ_p/Γ . The right hand side of the above equation consists of Coulomb plus interference term due to the coherent parts of the Coulomb and resonance scattered waves and resonance term due to the formation of

resonant compound nuclear state. The angle factors are given as

$$A(\theta) = u \Gamma \cos \beta \quad \dots (7.2)$$

$$B(\theta) = \Gamma^2/4 (u^2 + 2u \sin \beta + v^2) \quad \dots (7.3)$$

$$\text{Where } u = \frac{2J+1}{\eta} \frac{\Gamma_p}{\Gamma} (\sin \theta/2)^2 P_\ell(\cos \theta) \quad \dots (7.4)$$

$$v = \frac{2}{\eta} \Gamma_p/\Gamma (\sin \theta/2)^2 P_\ell^1(\cos \theta) \quad \dots (7.5)$$

$$\beta = 2 \left[\eta \ln(\sin \theta/2) + \sum_{\ell'=0}^{\ell} \arctan \eta/\ell' - \pi/2 \right] \quad \dots (7.6)$$

$$\eta = 0.1575 Z_1 Z_2 \left[\frac{A_1 A_2}{(A_1 + A_2) E} \right]^{1/2} \quad \dots (7.7)$$

Here Z_1 is the incident projectile charge number, Z_2 is the target charge number, A_1 is the mass of the incident projectile and A_2 is the mass of the target nucleus. $P_1(\cos \theta)$ is the Legendre polynomial and $P_1^1(\cos \theta)$ is the associated Legendre polynomial of first order. A computer program has been developed using these relations for the analysis of data. The above formulae are strictly valid for elastic scattering from spin -0 target nuclei. For target nuclei with non-zero spin, there will be an additional term arising from spin-spin interaction. There is no clear knowledge about this interaction and as such most optical model analyses are carried out neglecting target spin (ref. 85). It has further been suggested⁸⁵⁾ that unless there is positive evidence in favour of its existence, it is not worthwhile to incorporate such a complex spin-spin interaction. Awaya¹⁹⁾ in his analysis of $^{27}\text{Al}(p,p)$ resonance scattering found the effect of channel spin to be unimportant.

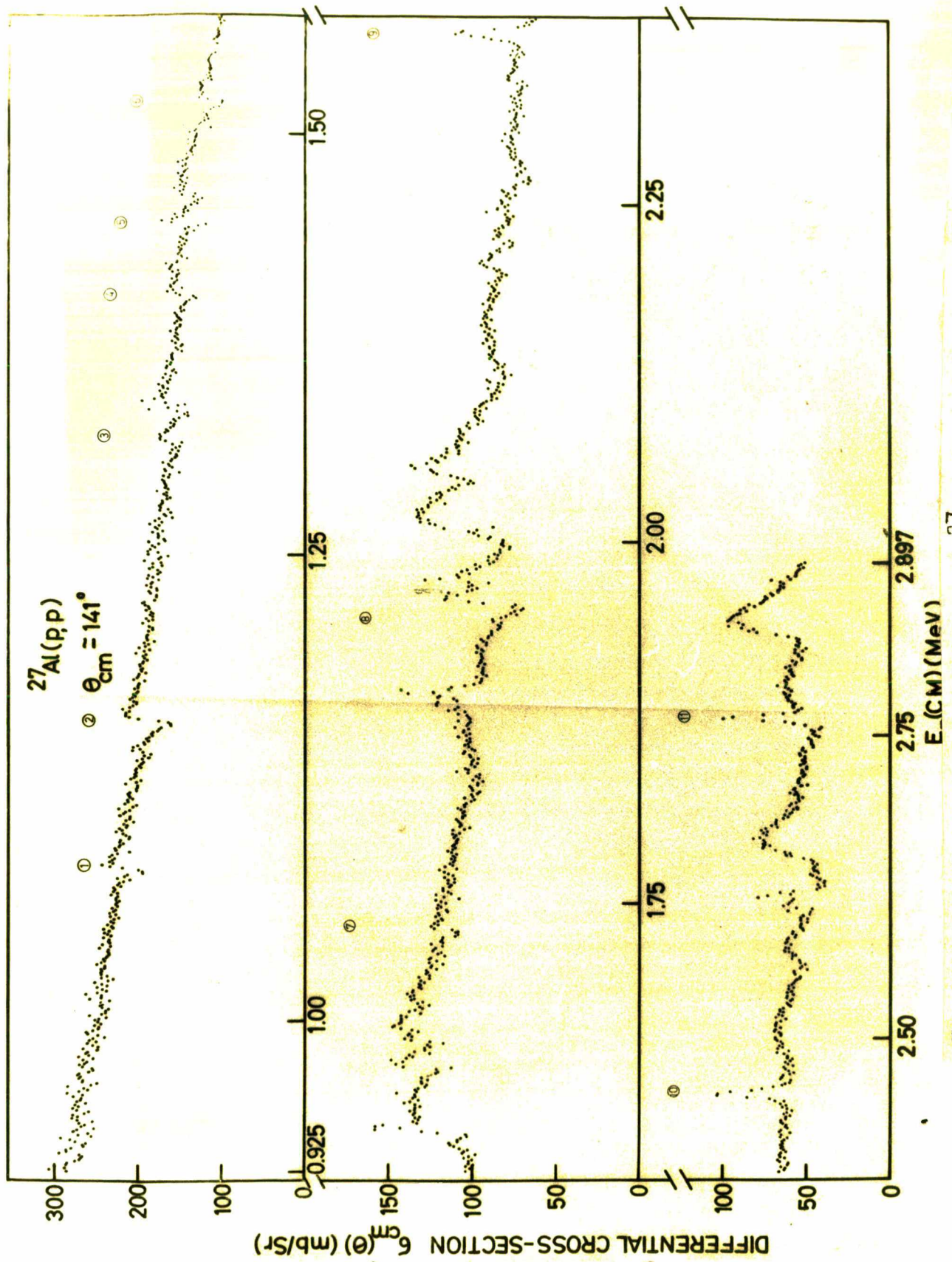


Fig. 7.3 Differential cross-section for $^{27}\text{Al}(p,p)$ resonance reaction at the centre of mass angle 141° in the energy range $E_{\text{cm}} = 0.85 - 3.0$ MeV.

In view of this and also for limited computer facilities at our disposal, we neglected the target spin. The different resonance parameters extracted from the present analyses are, therefore, subject to an uncertainty, which we believe to be small.

The above formulae (7.1-7.7) are further applicable to a case where the beam resolution is negligible compared to the natural width of the resonances. But in most experiments it is not so and therefore correction for this is taken into account. In analysing our data this part was taken into consideration.

7.4 Results and discussions

The differential cross-section of elastically scattered protons at the centre of mass angles at 90° , 125° and 141° were measured as a function of incident proton energy in the range $E_p = 0.85-3.00$ MeV as mentioned earlier. Error in absolute cross-section is not more than 10%. The measured differential cross-section at $\theta_{cm} = 141^\circ$ is shown in fig. 7.3. Isolated resonances observed have been serially numbered at all three CM angles but due to sudden breakdown of machine the measurement at $\theta_{cm} = 125^\circ$ could not be performed above 2.00 MeV. The analyses started with the determination of l-values. In order to determine l-values the shape of the resonances for fixed values of E_0 , Γ , Γ_p/Γ and J but for different values of l at those three centre of mass angles

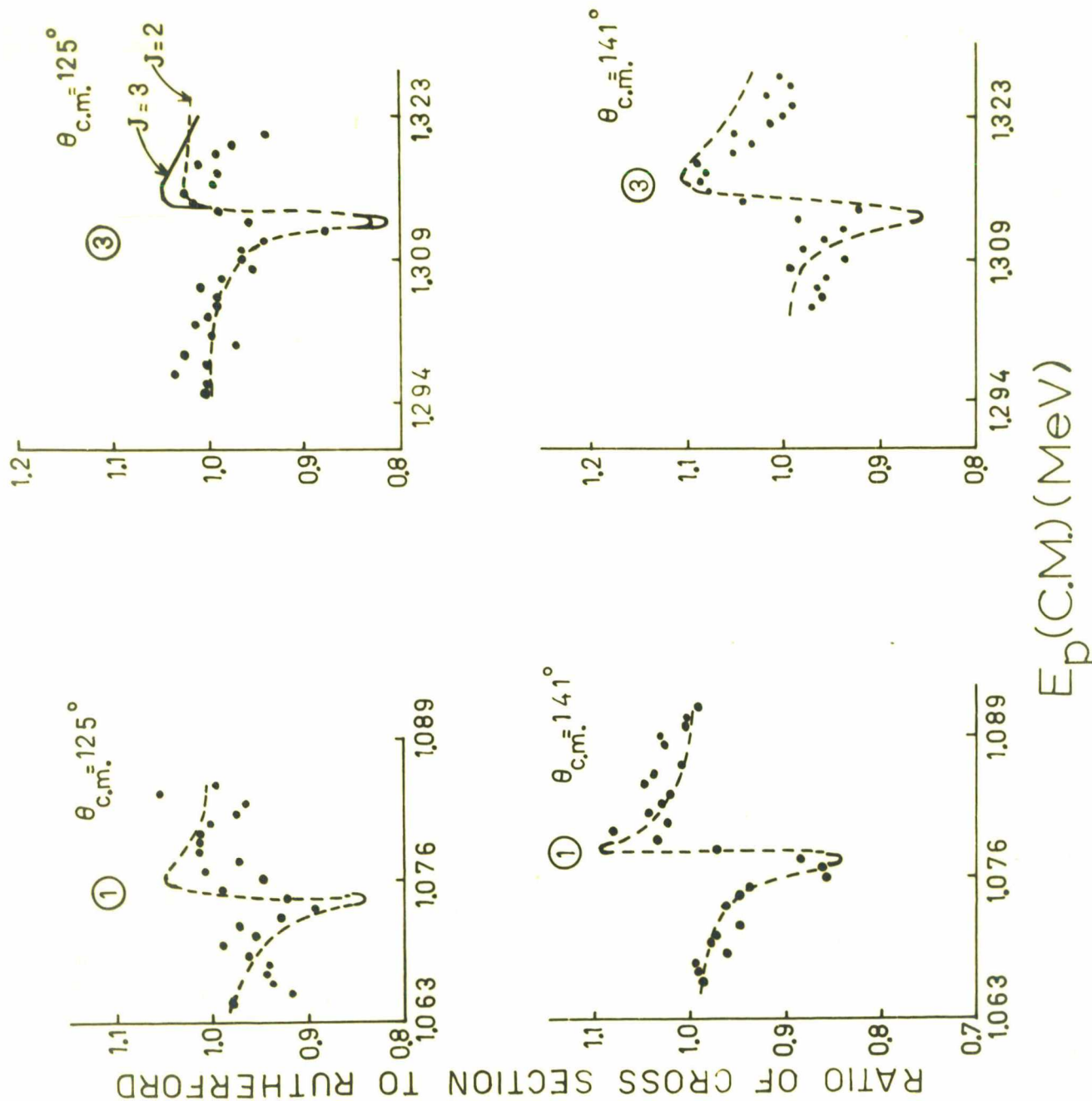


Fig.7.4 The dots and the broken lines show the experimental points and the theoretical fit respectively for 1.117 MeV resonance ($J^\pi = 3^-, 4^-$, $\Gamma = 0.80$ keV and $\Gamma_p = 0.64$ keV) and 1.363 MeV resonance ($J^\pi = 2^-, 3^-$, $\Gamma = 1.0$ keV and $\Gamma_p = 0.65$ or 0.60 keV).

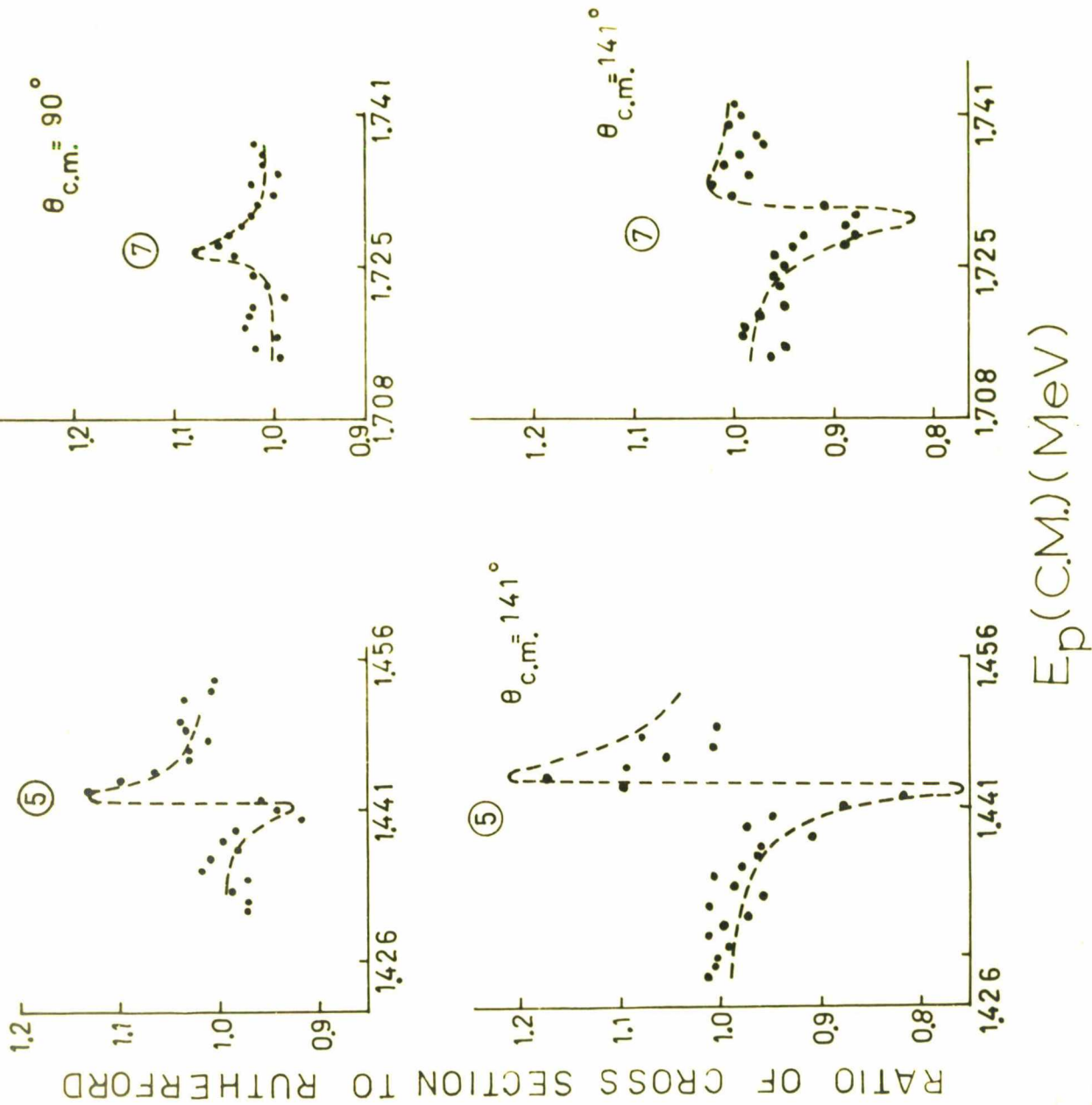


Fig.7.5 The dots and the broken lines show the experimental points and the theoretical fit respectively for 1.496 MeV resonance ($J^\pi = 2^+$, $\Gamma = 0.60$ keV and $\Gamma_p = 0.54$ keV) and 1.793 MeV resonance ($J^\pi = 3^-$, $\Gamma = 1.2$ keV and $\Gamma_p = 0.80$ keV).

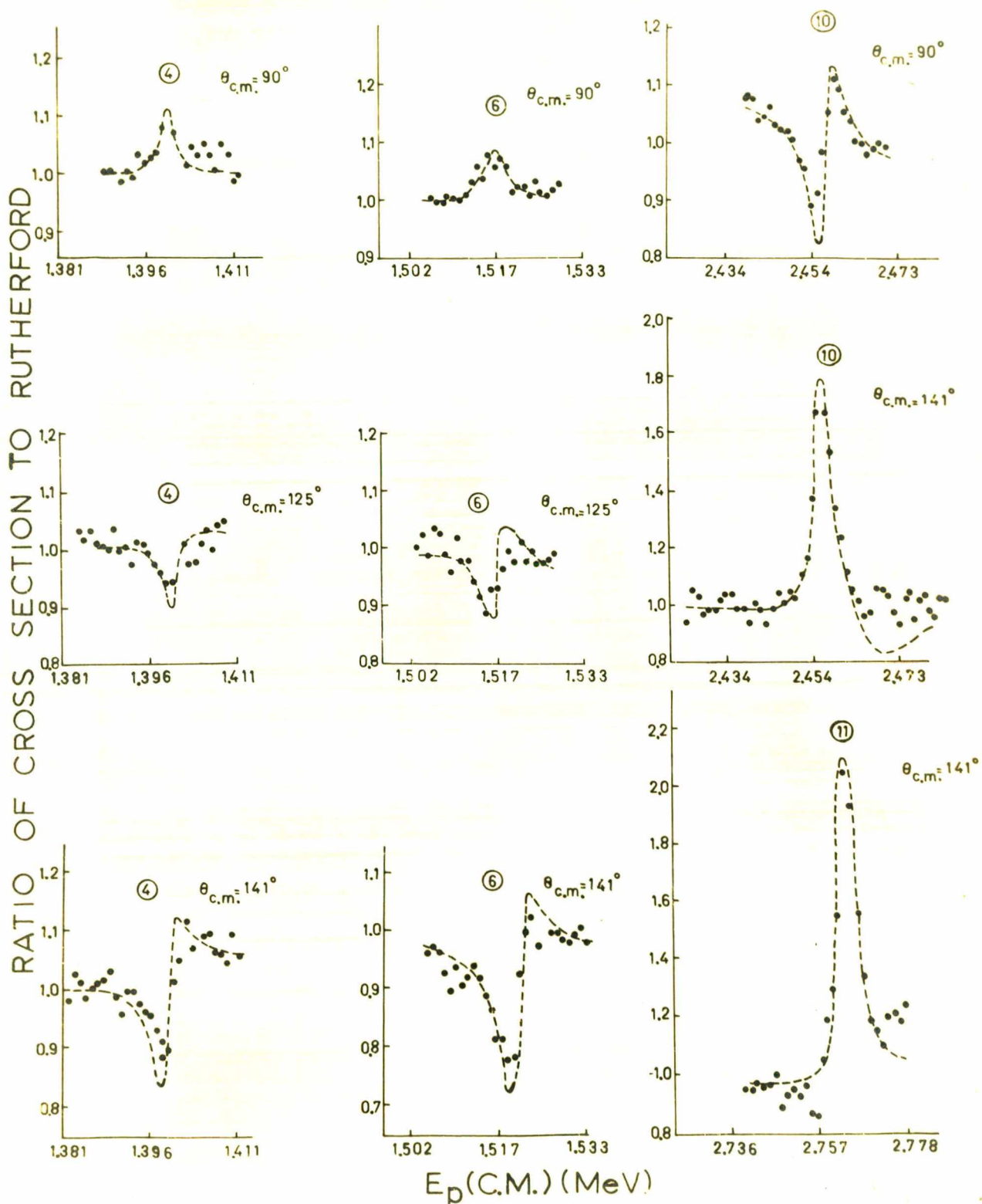


Fig. 7.6 The dots and the broken lines shows the experimental points and the theoretical fit respectively for 1.452, 1.574, 2.548 and 2.866 MeV resonances. The values of parameters are given in table 7.1.

were generated by computer with the use of expressions (7.1)-(7.7). With the l -values accurately known, the parity of the resonance can be ascertained positively. Once the l -values are known a search out procedure is repeated for all observed isolated resonances at each angle to find out suitable parameter values of Γ , Γ_p/Γ and J . Results of the present analyses are summarized in table 7.1. Resonance energies are correct to within 3 keV and errors in Γ and Γ_p are estimated to be 20% and 30% respectively; also included are those given by refs.^{16,21}). Figs. 7.4-7.6 illustrate fits to experimental data for resonances 1, 3, 4, 5, 6, 7, 10 and 11. Discussions on the results are as follows. The resonance No. 10 at $E_p = 2.548$ MeV was fitted with $l=2$. The shape of the resonance at 90° is different from all other resonances at this angle. All other resonances needed $l=1$. The resonances at 90° for many cases (Nos. 1, 3, 5, 8, 9 and 11) are either very weak or altogether absent.

The first three resonances (Nos. 1-3) were studied by Awaya¹⁹⁾ and the properties for resonance Nos. 1 and 2 are given. Properties for resonance levels Nos. 1-7 are compiled by Endt and Van der Leun²¹⁾. There is in general a good agreement between the present and previous measurements. A notable exception is resonance No. 6, where Γ value in the present work is very small compared to that quoted in ref.²¹⁾. There are also discrepancies in parity assignment in some cases, namely for resonances $E_p = 1.363$ and 1.496 MeV.

TABLE 7.1
Summary of $^{27}\text{Al}(\text{p},\text{p})$ resonances

Resonance No.	Resonance energy E_p (Lab) (MeV)			^{28}Si Excitation (MeV)	1 from $^{27}\text{Al}(\text{p},\text{p})$			Γ (keV)			Γ_p (keV)			J^π			S_p
	a)	b)	c)	a)	a)	b)	c)	a)	b)	c)	a)	b)	c)	a)	b)	c)	
1	1.117	1.117	1.118	12.662	1	1	0.80	0.80	0.80	0.62	0.64	~0.80	~0.80	3 ⁻ , 4 ⁻	3 ⁻ , 4 ⁻	4 ⁻	0.035
2	1.199	1.198	1.199	12.742	1	1	4.73	6.3	5.5	5.5	4.73	~6.3	~6.3	3 ⁻	3 ⁻	3 ⁻	0.17
3	1.363	1.362	1.363, 1.364, 1.368	12.899	1		1.0		0.07, 1.4	0.07, 1.4	0.65 ^{d)} , 0.60 ^{e)}			2 ⁻ , 3 ⁻	2 ⁻ , 3 ⁻	(4 ⁺) 2 ⁺	0.01 ^{d)} , 0.01 ^{e)}
4	1.452		1.457	12.985	1		1.2		2.0	2.0	0.60			3 ⁻	3 ⁻	3 ⁻	0.01
5	1.496		1.502	13.027	1		0.60		0.51	0.51	0.54			3 ⁻	3 ⁻	2 ⁺	0.008
6	1.574		1.578	13.103	1		1.2		2.75	2.75	0.70			3 ⁻	3 ⁻	3 ⁻	0.009
7	1.793		1.800	13.314	1		1.2		<2.0	<2.0	0.80			3 ⁻	3 ⁻	(1-3)	0.007
8	2.028			13.540	1		1.1				0.90			3 ⁻	3 ⁻		0.005
9	2.472			13.969	1		2.5				2.0			3 ⁻	3 ⁻		0.006
10	2.548			14.042	2		2.2				1.1			3 ⁺	3 ⁺		0.03
11	2.866			14.349	1		3.0				2.7			2 ⁻	2 ⁻		0.006

a) Present work

b) Ref. 19

c) Ref. 21

d) For $J^\pi = 2^-$ e) For $J^\pi = 3^-$

The resonance at $E_p = 1.117$ Mev was fitted equally well with $J=3$ and 4 in agreement with Awaya¹⁹⁾, whereas in (p, γ) work Meyer et al.⁸⁶⁾ assigned $J=4$ only.

The resonance No.3 is similarly fitted with two J -values (table 7.1). This resonance is an unresolved doublet both with positive parity (ref.21). We did not find any observable anomaly at 90° as stated earlier, and could not fit the data at 125° and 141° with any even l -value; data were reproduced by $l_p=1$ only. Whether this discrepancy between the present measurement and that of Meyer et al.⁸⁶⁾ (quoted in ref. 21) is due to an interference between the two resonances, unresolved in the present work, is difficult to ascertain; a resonance due to two overlapping levels giving $l=1$ shape simultaneously at all three angles is not very likely.

For resonance No.5 there is no anomaly in the excitation function at 90° and analyses at other angles suggest $l=1$, $J^\pi=3^-$ in contradiction to $J^\pi=2^+$ of ref. 21.

The resonance No.4 at 90° could be fitted with two J -values (namely $J=3$ and 4), whereas data at other angles needed $J=3$ only. The latter value was, therefore, accepted.

From the proton width Γ_p and the proton penetration factor P_n^+ the spectroscopic factor S_p was calculated using the relation

$$S_p = (2T+1) \Gamma_p P_n.$$

+The values of penetration factor P_n were kindly sent by Professor W.J. Thomson⁸⁷⁾.

TABLE 7.2

Properties of analogue resonances

Level properties of ^{28}Al from $^{27}\text{Al}(d,p)$ reaction				Level properties of ^{28}Si from $^{27}\text{Al}(p,p)$ resonance reaction			
Excita- tion(MeV)	l_n -value	J^π	$(2J+1)S_n$	E_p (MeV)	Excita- tion (MeV)	l_p -values	J^π
a)	b) c)	a)	b) c)	d) e)	d)	d) e)	d) e) a) d)
3.461	1+3	(1-4) ⁻	1,0,5.6 ^{a)} 0.78 ^{f)} 3.2 ^{g)}	1.117 1.119 1.118	12.662	1 1 3 ⁻ 4 ⁻ 3 ⁻ 4 ⁻	4 ⁻ 4 ⁻ 0.25 ^{h)} 0.32 ⁱ⁾
4.030	3	(1-4) ⁻	9.3 0.12 ^{f)} 4.7 ^{g)}	1.793 1.800	13.314	1 3 ⁻	(1-3) 0.05

a) Ref. 21
b) Ref. 78
c) Ref. 79
d) Present work
e) Ref. 19

f) For $l_n=1$
g) For $l_n=3$
h) For $J^\pi=3^-$
i) For $J^\pi=4^-$

The results obtained are shown in table 7.1. No previous values of S_p are available for comparison.

Two of the resonances, at $E_p = 1.117$ and 1.793 MeV, were identified as analogues. Their properties are summarized in table 7.2. The J^π values are consistent with those of the parent states namely 3.461 and 4.030 MeV of ^{28}Al respectively. The former resonance was also identified by Awaya¹⁹⁾ as analogue. The two parent levels in ^{28}Al were observed by Carola and Van der Baan⁷⁸⁾ and Chen et al.⁷⁹⁾ from ^{27}Al (d,p) stripping reactions. The spectroscopic transition strengths given by them are presented in table 7.2. The (p,p) transition strengths obtained from the present work are much smaller than the above (d,p) values. It may be noted that there is usually an uncertainty of about 30% in (d,p) spectroscopic factors arising from DWBA calculations. As stated earlier the Γ_p values are correct to within 30%. Even on consideration of these, values of neutron and proton spectroscopic factors do not overlap. Similarly the $(2J+1) S_p$ values for two analogue resonances studied by Awaya¹⁹⁾ from ^{27}Al (p,p) reaction at $E_p = 1.117$ and 1.198 MeV are 0.31 , 0.39 (for $J^\pi = 3^-$ and 4^- respectively) and 1.60 respectively, again much too small compared to the corresponding ^{27}Al (d,p) strengths of 0.78 (ref. 78), 1.0 (ref. 79) and 4.2 (ref. 78), 4.1 (ref. 79) respectively.

CHAPTER - 8

CONCLUSIONS

Isobaric analogue states in ^{52}Cr from (p, γ) and (p, n) reactions in ^{51}V corresponding to the ground and low lying excited states in ^{52}V in the proton energy range upto about 3.12 MeV have been observed. Sixteen analogue states have been identified. It is seen that strong resonances appear at about the same proton energy in both (p, γ) and (p, n) spectra agreeing within a few keV. The results listed in table 3.1 are in excellent agreement with those of others^{7,10)}. The ambiguities in the results^{7,8,10)} such as analogues corresponding to possible 0.768 MeV and 1.490 MeV states in ^{52}V marked as 'X' and 'Y' at the correct proton energies $E_p = 1.553$ and 2.28 MeV respectively in fig. 3.2 have been resolved.

By (p, γ) reaction in ^{54}Fe in the proton energy range $E_p = 0.854$ -2.980 MeV eleven analogue resonances have been observed as against previous three or four. Of this, six analogue states are identified to be new. The present results are in good agreement with others¹¹⁻¹³⁾. The 2.773 MeV analogue resonance observed by Ahlgren et al.¹²⁾ is weakly excited in the present measurement and is marked 'X' in fig. 3.7 at the correct proton energy $E_p = 2.779$ MeV. There is as yet no positive evidence for the existence of a state in ^{55}Fe to which this may be a possible analogue.

By (p, γ) and (p, n) reactions in ^{55}Mn in the energy range $E_p = 1.28$ -3.05 MeV and 1.50-3.05 MeV respectively twenty four analogue states have been observed as against seven analogue states of

Otto et al.¹⁴⁾ in the energy range $E_p = 1.30-1.85$ MeV. The results are in excellent agreement with those of Otto et al.¹⁴⁾

By (p, γ) reaction in ^{27}Al in the energy range $E_p = 0.85-3.00$ MeV, a large number of resonances have been tentatively identified as analogue as against previous two or three^{18,19)}.

The Coulomb displacement energy ΔE_c were obtained from the position of isobaric analogue states. The observed values of ΔE_c from the present work on four isobaric pairs of nuclei e.g. $^{52}\text{V}-^{52}\text{Cr}$, $^{55}\text{Fe}-^{55}\text{Co}$, $^{56}\text{Mn}-^{56}\text{Fe}$ and $^{28}\text{Al}-^{28}\text{Si}$ are in excellent agreement with available measurements. A semi-empirical relation similar to that of Anderson et al.²⁰⁾ has been obtained using a large amount of data on Coulomb displacement energy with better accuracy available in the mass region $A=27$ to 238 since the above work. An attempt has also been made to study any possible T_z -dependence of ΔE_c . As theoretical models overestimate the T_z -dependence⁵⁵⁾, we started with experimental data. The ΔE_c values were carefully selected for several sets of isobaric pairs of nuclei, arranged according to T_z . The least squares analyses by assuming them to belong to different groups or to single group give almost indistinguishable fit. It is, therefore, concluded that a T_z -dependence is very small and more refined sets of experimental Coulomb displacement energies are necessary to observe T_z -dependence.

Some of the analogue resonances in compound nuclei ^{52}Cr and ^{56}Fe exhibit fine structures enveloping gross structures. These

are accounted for by Robson's theory. The values of parameters, namely, Δ and Γ were obtained for analogue resonances displaying gross structures. Of particular interest is the analogue resonance at $E_p = 2.329$ MeV observed in (p, γ) and (p, n) reactions in ^{51}V . The gross structure exhibited in both these reactions could be fitted with same values of Δ and Γ in agreement with Teranishi and Furubayashi⁷⁾. The structure at slightly higher energy ($E_p = 2.34$ MeV) is, however, considered to be a separate resonance analogue of the 1.578 MeV level in ^{52}V by Sekharan and Mehta⁶⁵⁾ and Egan et al.⁶⁶⁾, which in the present work and in ref. 7 is treated as a component of the resonance at $E_p = 2.329$ MeV. The gamma decay was therefore studied at these two proton energies and the spectra were found to be identical. It is, therefore, concluded that they belong to the same resonance.

An attempt has been made to study the properties of resonance states including analogues through (p, γ) and (p, p) reactions in ^{27}Al . In chapter 6 the properties of 13.707, 13.980, 14.007 and 14.223 MeV resonating states in ^{28}Si have been studied by angular distribution of gamma rays. The spin-parity of these states are assigned as 13.707— 2^- , 3^- , 13.980— 4^- , 14.007— 4^+ and 14.223— 3^+ , $(2)^+$. These are excited states due to 2.198, 2.482, 2.511 and 2.735 MeV proton resonances and are analogues of the parent states in ^{28}Al at 4.383, 4.685, 4.741 and 4.928 MeV. The small values of mixing ratio (table 6.2) suggests a small multipolarity mixing^{of} emitted gamma rays. It is also noted,

that there occurs a strong transition between 14.007 and 4.620 MeV levels of ^{28}Si each with $J^\pi = 4^+$. This is probably a case of analogue to antianalogue M1 transition, usually found in s-d shell⁸¹⁾, whereas in the $1f_{7/2}$ shell region there is a strong hindrance of analogue to antianalogue transition⁸²⁾.

The properties of resonances by (p,p) reaction on ^{27}Al including proton spectroscopic factors have been obtained. In general there is a good agreement between the present measurement and those of previous works except the Γ of resonance at $E_p = 1.574$ MeV and J^π of resonance at $E_p = 1.363$ MeV and $E_p = 1.496$ MeV. In the present measurement properties of eleven isolated resonances have been obtained. Two of the resonances namely $E_p = 1.117$ and 1.793 MeV are found to be analogues, the former being in agreement with Awaya¹⁹⁾. The proton spectroscopic factors obtained in this measurement are in poor agreement with the neutron spectroscopic factor obtained from $^{27}\text{Al}(d,p)$ reaction by Carola and Van der Baan⁷⁸⁾ and Chen et al.⁷⁹⁾ populating the parent states.

No resonance above 2 MeV has previously been studied. In the present measurement resonances at $E_p = 2.028, 2.472, 2.548$ and 2.866 MeV have been observed and their properties are obtained.

REFERENCES

1. J.D. Anderson and C. Wong, Phys. Rev. Letts. 7 (1961) 250
2. J.D. Fox, C.F. Moore and D. Robson, Phys. Rev. Letts. 12 (1964) 693
3. G.A. Keyworth, G.C. Kyker Jr., E.G. Bilpuch and H.W. Newson, Nucl. Phys. 89 (1966) 590
4. P. Richard, C.F. Moore and D. Robson, Phys. Rev. Letts. 13 (1964) 343
5. L.R.B. Elton, Phys. Rev. 158 (1967) 970
6. J.A. Nolen, J.P. Schiffer, N. Williams and D. Von Ehrenstein, Phys. Rev. Letts. 18 (1967) 1140
7. E. Teranishi and F. Furubayashi, Phys. Letts. 20 (1966) 511
E. Teranishi and F. Furubayashi: Isobaric Spin in Nuclear Physics, ed. by J.D. Fox and D. Robson (Academic Press, New York, 1966) P.640
8. E. Arai and H. Miessner, Kernforschungszentrum, Karlsruhe Report, KFK 704 (1967)
9. H. Coleman, M. Divadeenam, H. McEver, J.M. Joyce, E.J. Ludwig and S.M. Shafroth, Nuclear Isospin ed. by J.D. Anderson, S.D. Bloom, J. Cerny and W.W. True (Academic Press, N.Y. and London, 1969) P.103
10. Nuclear Data Sheets, B3, Nos. 5,6, April, 1970 (Academic Press N.Y. and London)
11. S. Maripuu, Ark. f. Fys. 32 (1968) 77
12. H. Ahlgren, S. Idetjärn, H. Linusson, S. Maripuu and J. Ryfors, Ark. f. Fys. 39 (1969) 345
13. D.P. Lindstrom, H.W. Newson, E.G. Bilpuch and G.E. Mitchell, Nucl. Phys. A168 (1971) 37
14. G. Otto, R. Mehnert and Tomaselli, Nucl. Phys. A109 (1968) 118
15. G. Otto, R. Mehnert and G. Tomaselli, Phys. Letts. B25 (1967) 412
16. Von R. Friedrich, M. Kiessling and G. Otto, Annalen der Physik, 3 (1969) 168
17. M. Sakai, R. Berti and C. Gehringer, Nucl. Phys. A157 (1970) 113

18. A.A. Jaffe and M. Harchol, Isobaric Spin in Nuclear Physics, ed. by J.D. Fox and D. Robson, New York, Academic Press, 1966, P.835.
19. T. Awaya, J. Phys. Soc. Jap 20 (1965) 669
20. J.D. Anderson, C. Wong, J.W. McClure, Phys. Rev. 138 (1965)B615
21. P.M. Endt and C. Van der Leun, Nucl. Phys. A214 (1973) 1
22. P.J.M. Smulders and P.B. Smith, Nucl. Instr. and Methods 8 (1960)40
23. T.W. Bonner, Phys. Rev. 94 (1954) 807
24. Hornyak, Rev. Sci. Instr. 23 (1952)264
25. T.K. Alexander and F.S. Goulding, Nucl. Instr. and Meth. 13 (1961)241;
M.L. Roush, M.A. Wilson and W.F. Hornyak, Nucl. Instr. and Meth. 31 (1964) 112;
T.G. Miller, Nucl. Instr. and Meth. 63(1968) 121;
Y. Wakuta, H. Tawara, M. Hyakutake and M. Sonoda, Nucl.Instr. and Meth. 71 (1969) 133;
26. E.L. Chupp, J.W.M. Dumond, F.J. Gordon, R.C. Jobson and Hans Mark, Phys. Rev. 112 (1958) 518
27. P.H. Stelson and F.K. McGowen, Phys.Rev.99 (1955) 112
28. D.D. Armstrong and A.G. Blair, Phys. Rev. 140 (1965)B1226
29. B. Rosner and C.H. Holbrow, Phys. Rev. 154 (1967) 1080
30. G. Vourvapoulos, J.D. Fox and B. Rosner, Phys.Rev. 177(1969) 1789
31. G. Bruge, J.C. Faivre, H.Farragi, A. Bussiere and P.Roussel, Journ. de Phys. 29, Suppl. No.1. Colloq. C1-109(1968)
32. H. Ohmura, M.Sekiguchi, J.Phys. Soc. Japan,21 (1966) 1844
33. C. Maples, G.W. Goth and J. Cerny, Nuclear Reaction Q-values (UCRL-16964) July (1966)
34. Nuclear Data Sheets, B3, Nos. 3,4 Jan. 1970

35. D. Robson, Phys. Rev. 137 (1965) B535
36. J.C. Hardy, H. Brunnader, J.Cerny and J.Jänecke, Univ. of California Lawrence Radiation Lab. report, UCRL-18566(1969)
37. W.A. Fowler, L.A. Delsasso and C.C. Lauritsen, Phys. Rev. 49 (1936) 561
38. J. Jänecke, Z. Phys. 160 (1960) 171
39. O. Kofoed-Hansen, Rev. Mod. Phys. 30 (1958) 449
40. S. Sengupta, Nucl. Phys. 21 (1960) 542
41. J.D. Anderson, C.Wong and J.W. McClure, Phys.Rev. 126 (1962) 2170
42. J.D. Anderson, C.Wong and J.W. McClure, Phys.Rev. 129 (1963) 2718
43. C.J. Batty, R.S.Gilmore and G.H.Stafford, Nucl.Phys. 75 (1966) 599
44. C.D.Goodman, J.D. Anderson and C.Wong, Phys.Rev. 156 (1967) 1249
45. M.W. Green, Phys. Letts. B24 (1967) 273.
46. R. Sherr, A.G. Blair and D.D. Armstrong Phys.Letts. 20 (1966) 392, 511
47. J.A. Cookson and D. Dandy, Nucl. Phys. A97 (1967) 232
48. J.M. Freeman, J.H. Montague, G.Murray, R.E.White and W.E. Burcham, Nucl. Phys. 65 (1965) 113.
49. A.G. Blair and D.D. Armstrong, Phys.Letts. 16 (1965) 57
50. J.Jänecke, Isopin in Nuclear Physics, ed. by D.H.Wilkinson (North Holland Publishing Company, Amsterdam, 1969) P.379, 824, 279
51. J.Jänecke, Z. Phys. 196 (1966) 477
J. Jänecke, Phys. Rev. 147 (1966) 735
J. Jänecke Nucl. Phys. A128 (1969) 632
52. D.D. Long, P.Richards, C.F.Moore and J.D. Fox, Phys.Rev. 149 (1966) 906

384993



53. M. Harchol, A.A. Jaffe, J.Miron, I.Unna and J. Nioni,
Nucl. Phys. A90 (1967) 459
54. P.A. Seeger, Proc. Third Int. Conf. on Atomic Masses,
Winnipeg, Manitoba, ed. R.C. Barber, (University of
Manitoba Press, 1967) 85
55. A. Lindner, Z. Phys. 211 (1968) 195
56. A.M. Lane, Isospin in Nuclear Physics, ed. by D.H. Wilkinson
(North Holland, Amsterdam, 1969) P.509
57. C. Block and J.P. Schiffer, Phys. Letts. 12 (1964) 22
58. E.G. Bilpuch, Isobaric Spin in Nuclear Physics, ed. by
J.D. Fox and D. Robson (Academic Press N.Y. 1966) 235
59. J.C. Browne, H.W. Newson, E.G. Bilpuch and G.E. Mitchell,
Nucl. Phys. A153 (1970) 481
60. E.G. Bilpuch, Statistical Properties of Nuclei ed. by
J.B. Grag, (Plenum Publishing Corporation, N.Y. 1971) P.99
61. J.D. Moses, J.C. Browne, H.W. Newson, E.G. Bilpuch and
G.E. Mitchell, Nucl. Phys. A168 (1971) 406
62. D. Robson, J.D. Fox, P. Richard and C.F. Moore, Phys.
Letts. 11 (1964) 329
63. W. MacDonald and A. Mekjian, Phys. Rev. 160 (1967) 730
64. H.A. Weidenmuller and C. Mahaux, Nucl. Phys. 89 (1966) 33
65. K.K. Sekharan and M.K. Mehta, Phys. Rev. C6 (1972) 2304
66. J.J. Egan, K.K. Sekharan, G.C. Dutt, J.E. Wiest and F. Gabbard,
Phys. Rev. C5 (1972) 1562
67. J.J. Egan, Bull. Am. Phys. Soc. 14 (1969) 1216
68. K.J. Van Oostrun and A.C. Meijer, Nucl. Intr. and Methods
10 (1961) 31
69. L. Simons, K.E. Nysten, M. Kokeling, O. Siltmen, E. Spring
and G. Wendt, Phys. Letts. 3 (1963) 306
70. R.E. Azuma, L.E. Carlson, A.M. Charlesworth, K.P. Jackson,
N. Anyas-Weiss and B. Lalovic, Can. J. Phys. 44 (1966) 3075.
71. L.L. Riedinger and N.R. Johnson, Phys. Rev. C2 (1970) 2362
72. P. Mukherjee and A.K. Sen Gupta, Nucl. Intr. and Methods
68 (1969) 165

73. D. Hossain, D. Phil. Thesis, Oxford Univ., 1972
74. O. Häusser, J.S. Lopes, H.J. Rose and R.D. Gill, Nuclear Physics Lab. Report (Oxford, 1966)
75. H.J. Rose and D.M. Brink, Rev. Mod. Phys. 39(1967)306.
76. A.H. Wapstra, G.J. Nijgh and R. Van Lieshout, Nuclear Spectroscopy tables (North-Holland Publishing Company Amsterdam, 1959).
77. P.M. Endt and C. Van der Leun, Nucl. Phys. 34 (1962) 111
78. T.P.G. Carola and J.G. Van der Baan, Nucl. Phys. A173(1971)414
79. S. Chen, J. Rapaport, H. Enge and W.W. Buechner, Nucl. Phys. A197 (1972) 97
80. Y.P. Antoufiev, D.A. Darwish, C.E. Badawy, L.M. El-Nadi and P.V. Sorokin, Nucl. Phys. 56 (1964) 401
81. P.M. Endt: in Nuclear Structure, edited by A. Hossain et al. (Amsterdam 1967) P. 58
82. R.A. Ricci: in Nuclear Structure and Nuclear Reactions, edited by M. Jean and R.A. Ricci (Academic Press 1969) P.80
83. F.C. Shoemaker, J.E. Faulkner, G.M. Bouricins, S.G. Kaufman and F.P. Mooring, Phys. Rev. 83 (1951) 1011
84. R. Block, R.E. Pixlay and H. Winkler, Helvetica Physica Acta, 40 (1967) 832
85. P.E. Hodgson: in The Optical Model of Elastic Scattering (The Clarendon Press, Oxford, 1963) P.57
86. M.A. Meyer, N.S. Wolmarans and D. Reitmann, Nucl. Phys. A144 (1970)261
87. W.J. Thomson, Private Communication, 1973
88. R. Sherr, Phys. Letts. 24B(1967) 321
89. R. Sherr, B.F. Bayman, E. Rost, M.E. Rickey and C.G. Hoot, Phys. Rev. 139 (1965) B1272
90. A.J. Armini, J.W. Sunier and J.R. Richardson, Phys. Rev. 165 (1968) 1194

91. W.C. Anderson, L.T. Dillman and J.J. Kraushaar, Nucl. Phys. 77 (1966) 401
92. T.A. Belote, F.T. Dao, W.E. Dorenbusch, T. Kuperns, J. Rapaport and S.M. Smith, Nucl. Phys. A102(1967) 462
93. A.A. Jaffe, 1967, in: Proc. Third Int. Conf. on Atomic Masses, Winnipeg, Manitoba, ed. by R.C. Barber (University of Manitoba Press, 1967) P.609
94. W.E. Dorenbusch, F.T. Dao, J. Rapaport and T.A. Belote, Phys. Letts. B26(1968a) 148
95. R.E. Berg, J.L. Shelgrove and E. Kashy, Phys. Rev. 153 (1967) 1165
96. R.G. Miller and R.W. Kavanagh, Nucl. Phys. A94(1967) 261
97. A.M. Aldridge, H.S. Plendl and J.P. Aldridge, Nucl. Phys. A98 (1967) 323
98. L. Broman, D.J. Pullen and B. Rosner, Bull. Am. Phys. Soc. 12 (1967) 682
- 98^b. T.G. Dzubay, Bull. Am. Phys. Soc. 12 (1967) 1194
99. J.M. Freeman, J.G. Jenkin and G. Murray, Phys. Letts. 22 (1966a) 177
100. G.A. Barthalomew, E.D. Darle and M.R. Gunye, C.J. Phys. 44 (1966) 211
101. A. Langsford, P.H. Bowen, G.C. Cox and M.J.M. Saltmarsh, Nucl. Phys. A113 (1968) 433
102. J.M. Freeman, J.G. Jenkin, G. Murray and W.E. Burckson, Phys. Rev. Letts. 16 (1966b) 959
103. C.J. Batty, E. Friedman, P.C. Rowe and J.B. Hunt, Phys. Letts. 19 (1965) 33
104. N. Williams, J.A. Nolen, J.P. Schiffer and G.C. Morrison, Bull. Am. Phys. Soc. 13 (1968) 105
105. L.L. Lee and J.P. Schiffer, Phys. Letts. 8 (1964) 352
106. G.P. Couchell, D.P. Balamuth, R.N. Horosko and G.E. Mitchell, Phys. Rev. 161 (1967) 1147.
107. D. P. Balamuth, G.P. Couchell and G.E. Mitchell, Phys. Rev. 170 (1968) 995

108. D.D. Long, P. Richards, C.F. Moore and J.D. Fox, Phys. Rev. 149 (1966) 906
109. E.W. Hamburger, J. Kremenek, B.L. Cohen, J.B. Moorhead and C. Shin, Phys. Rev. 162 (1967) 1115
110. J. Solf, A. Heusler and J.P. Wurm, 1967; in : Max-Planck Institut, Heidelberg, Jahresbericht, P.59
111. R.K. Jolly and C.F. Moore, Phys. Rev. 155 (1967) 1377
112. D.L. Allen, H.C. Britt and F.A. Rickey Jr., Phys. Letts. B27 (1968) 11
113. G.H. Lenz and G.M. Timmer, Nucl. Phys. A112(1968) 625
114. C.D. Kavaloski, J.S. Lilly, P. Richard and N. Stein, Phys. Rev. Letts. 16 (1966) 807
115. S. A. A. Zaidi, J.L. Parish, J.G. Kulleck, C.F. Moore and P. Von Brentano, Phys. Rev. 165 (1968) 1312
116. P. Von Brentano, W.K. Dawson, C.F. Moore, P. Richard, W. Wharton and H. Wieman, Phys. Letts. B26 (1968) 666

TABLE A-1
Coulomb displacement energy

Isobaric pair	Z ₁	Z ₂	A	Z/A ^{1/3}	ΔE _c (Obs) (MeV)	ΔE _c (Cal) (MeV) from relation (3.6)	ΔE _c (Cal) (MeV) from relation (3.7)	References
Al-Si	13	14	27	4.500	5.57±0.050	5.368±0.062	5.385±0.033	44
	13	14	28	4.446	5.467±0.007	5.290±0.062	5.308±0.033	36
	13	14	28	4.446	5.439±0.051	5.290±0.062	5.308±0.033	P.W.
S-cl	16	17	33	5.144	6.250±0.050	6.298±0.065	6.311±0.035	89
			37	4.951	6.250±0.070	6.020±0.064	6.034±0.034	88
Cl-Ar	17	18	35	5.350	6.660±0.050	6.595±0.066	6.606±0.036	89
			39	5.160	6.435±0.030	6.321±0.065	6.334±0.035	88
Ar-K	18	19	37	5.551	6.88±0.070	6.886±0.067	6.897±0.036	89
			40	5.409	6.658±0.070	6.681±0.067	6.692±0.036	50
K-Ca	19	20	39	5.750	7.190±0.070	7.173±0.068	7.182±0.037	89
			40	5.701	7.138±0.006	7.103±0.068	7.112±0.037	90
			40	5.701	7.130±0.005	7.103±0.068	7.112±0.037	91
			40	5.701	7.069±0.100	7.103±0.068	7.112±0.037	50
			41	5.655	7.040±0.015	7.036±0.068	7.045±0.036	92
			42	5.609	7.000±0.030	6.970±0.068	6.980±0.036	93
			43	5.566	6.973±0.020	6.907±0.067	6.917±0.036	94
Ca-Sc	20	21	40	5.994	7.445±0.008	7.525±0.069	7.532±0.037	95
			41	5.945	7.220±0.020	7.454±0.069	7.462±0.037	89
			42	5.897	7.214±0.013	7.386±0.069	7.393±0.037	88
			43	5.851	7.246±0.013	7.319±0.069	7.327±0.037	88
			44	5.806	7.228±0.013	7.255±0.069	7.263±0.037	88
Ga-Ge	20	21	45	5.763	7.236±0.013	7.192±0.068	7.201±0.037	88
			46	5.721	7.209±0.013	7.131±0.068	7.140±0.037	88

Isobaric pair	Z_1	Z_2	A	$Z/A^{1/3}$	ΔE_c (Obs) (MeV)	ΔE_c (Cal) from rela- tion. (3.6)	ΔE_c (Cal) (MeV) from rela- tion. (3.7)	Refer- ences
Ca-Sc	20	21	47	5.680	7.194 ± 0.013	7.072 ± 0.068	7.082 ± 0.037	6
			48	5.640	7.175 ± 0.013	7.015 ± 0.068	7.024 ± 0.036	6
			49	5.602	7.089 ± 0.013	6.959 ± 0.068	6.969 ± 0.036	6
			50	5.564	7.010 ± 0.013	6.905 ± 0.067	6.915 ± 0.036	6
Sc-Ti	21	22	42	6.185	7.766 ± 0.009	7.801 ± 0.067	7.807 ± 0.038	96
			43	6.136	7.635 ± 0.020	7.731 ± 0.070	7.737 ± 0.038	97
			44	6.090	7.489 ± 0.125	7.664 ± 0.070	7.670 ± 0.038	88
			45	6.044	7.640 ± 0.030	7.598 ± 0.070	7.605 ± 0.038	89
			45	6.044	7.580 ± 0.040	7.598 ± 0.070	7.605 ± 0.038	44
			46	6.000	7.620 ± 0.030	7.534 ± 0.070	7.541 ± 0.038	98
			47	5.957	7.680 ± 0.050	7.472 ± 0.069	7.480 ± 0.037	89
			49	5.875	7.720 ± 0.050	7.734 ± 0.069	7.362 ± 0.037	89
Ti-V	22	23	46	6.279	7.847 ± 0.012	7.937 ± 0.071	7.942 ± 0.038	89
			46	6.279	7.835 ± 0.005	7.937 ± 0.071	7.942 ± 0.038	88
			46	6.279	7.800 ± 0.040	7.937 ± 0.071	7.942 ± 0.038	44
			46	6.279	7.837 ± 0.003	7.937 ± 0.071	7.942 ± 0.038	99
			47	6.234	7.87 ± 0.04	7.873 ± 0.071	7.878 ± 0.038	89
			47	6.238	7.846 ± 0.018	7.873 ± 0.071	7.878 ± 0.038	88
			47	6.234	7.810 ± 0.04	7.873 ± 0.071	7.878 ± 0.038	44
			47	6.234	7.860 ± 0.030	7.873 ± 0.071	7.878 ± 0.038	88
			48	6.191	7.789 ± 0.018	7.810 ± 0.070	7.815 ± 0.038	88
			48	6.191	7.740 ± 0.03	7.810 ± 0.070	7.815 ± 0.038	44
			48	6.191	7.828 ± 0.012	7.810 ± 0.070	7.815 ± 0.038	88

Table A1 (Contd.)

Isobaric pair	Z ₁	Z ₂	A	Z ⁻ /A ^{1/3}	ΔE_c (Obs) (MeV)	ΔE (Cal) from rela- tion. (3.6)	ΔE_c (Cal) (MeV) from rela- tion. 3.7)	Refer- ences
Ti-V	22	23	49	6.148	7.807±0.018	7.748±0.070	7.754±0.038	88
			49	6.148	7.730±0.030	7.748±0.070	6.754±0.038	44
			49	6.148	7.796±0.030	7.748±0.070	7.754±0.038	88
			50	6.107	7.805±0.009	7.689±0.070	7.695±0.038	88
			50	6.107	7.960±0.030	7.689±0.070	7.695±0.038	89
			50	6.107	7.778±0.020	7.689±0.070	7.695±0.038	88
			50	6.107	7.805±0.030	7.689±0.070	7.695±0.038	44
			51	6.067	7.754±0.030	7.631±0.070	7.637±0.038	88
V-Cr	23	24	49	6.422	8.135±0.030	8.143±0.072	8.148±0.039	88
			51	6.336	8.050±0.100	8.020±0.071	8.025±0.039	41
			51	6.336	8.100±0.105	8.020±0.071	8.025±0.039	42
			51	6.336	8.100±0.200	8.020±0.071	8.025±0.039	100
			51	6.336	7.950±0.130	8.020±0.071	8.025±0.039	101
			51	6.336	8.184±0.040	8.020±0.071	8.025±0.039	47
			51	6.336	8.29±0.050	8.020±0.071	8.025±0.039	89
			51	6.336	8.139±0.020	8.020±0.071	8.025±0.039	88
			52	6.296	8.075±0.043	7.961±0.071	7.966±0.038	P.W.
			52	6.296	8.060±0.030	7.961±0.071	7.966±0.038	47
			52	6.296	8.075±0.020	7.961±0.071	7.966±0.038	7
			52	6.296	8.406±0.020	7.961±0.071	7.966±0.038	47
			52	6.296	8.290±0.030	7.961±0.071	7.966±0.038	44
			52	6.296	8.050±0.020	7.961±0.071	7.966±0.038	88
			53	6.256	8.010±0.050	7.904±0.071	7.909±0.038	93

Table A1 (Contd.)

Isobaric pair	Z_1	Z_2	A	$\bar{Z}/A^{1/3}$	ΔE_c (Obs) (MeV)	ΔE_c (Cal) (MeV) from relation (3.6)	ΔE_c (Cal) (MeV) from relation (3.7)	References
Cr-Mn	24	25	50	6.650	8.379 ± 0.027	8.873 ± 0.073	7.475 ± 0.039	89
			50	6.650	8.412 ± 0.005	8.473 ± 0.073	8.475 ± 0.039	89
			50	6.650	8.414 ± 0.003	8.473 ± 0.073	8.475 ± 0.039	102
			51	6.606	8.423 ± 0.022	8.410 ± 0.073	8.412 ± 0.039	14
			52	6.564	8.290 ± 0.039	8.348 ± 0.072	8.351 ± 0.039	44
			52	6.564	8.415 ± 0.020	8.348 ± 0.072	8.351 ± 0.039	88
			53	6.522	8.375 ± 0.050	8.288 ± 0.072	8.291 ± 0.039	88
			54	6.481	8.306 ± 0.040	8.229 ± 0.072	8.233 ± 0.039	88
Mn-Fe	25	26	52	6.831	8.773 ± 0.105	8.735 ± 0.074	8.736 ± 0.040	88
			53	6.788	8.850 ± 0.070	8.672 ± 0.073	8.674 ± 0.040	89
			53	6.788	8.775 ± 0.020	8.672 ± 0.073	8.674 ± 0.040	88
			55	6.705	8.530 ± 0.100	8.552 ± 0.073	8.554 ± 0.040	44
			55	6.705	8.390 ± 0.100	8.552 ± 0.073	8.554 ± 0.040	101
			55	6.705	8.644 ± 0.019	8.552 ± 0.073	8.554 ± 0.040	89
			55	6.705	8.641 ± 0.200	8.552 ± 0.073	8.554 ± 0.040	47
			55	6.705	8.644 ± 0.020	8.552 ± 0.073	8.554 ± 0.040	88
			56	6.665	8.641 ± 0.047	8.494 ± 0.073	8.497 ± 0.039	P.W.
			56	6.665	8.593 ± 0.015	8.494 ± 0.073	8.496 ± 0.039	14
			56	6.665	8.590 ± 0.010	8.494 ± 0.073	8.496 ± 0.039	15
			57	6.626	8.790 ± 0.200	8.438 ± 0.073	8.440 ± 0.037	89

P.W. Present work.

Table A1 (Contd.)

Isobaric pair	Z ₁	Z ₂	A	Z/A ^{1/3}	ΔE _c (Obs) (MeV)	ΔE _c (Cal) (MeV) from rela- tion (3.6)	ΔE _c (Cal) (MeV) from rela- tion (3.7)	Refer- ences
Fe-Co	26	27	54	7.011	9.137±0.041	8.994±0.075	8.993±0.041	89
			54	7.011	9.030±0.200	8.994±0.075	8.993±0.041	50
			54	7.011	9.033±0.005	8.994±0.075	8.993±0.041	48
			54	7.011	9.033±0.005	8.994±0.075	8.993±0.041	88
			55	6.968	9.079±0.54	8.932±0.074	8.932±0.040	P.W.
			55	6.968	8.950±0.070	8.932±0.074	8.932±0.040	49
			55	6.968	8.993±0.028	8.932±0.074	8.932±0.040	49
			56	6.926	8.790±0.050	8.872±0.074	8.872±0.040	44
			56	6.926	8.900±0.050	8.872±0.074	8.872±0.040	89
			56	6.926	8.933±0.017	8.872±0.074	8.872±0.040	47
			56	6.926	8.939±0.015	8.872±0.074	8.872±0.040	88
			57	6.885	8.890±0.030	8.813±0.074	8.814±0.040	88
			58	6.846	8.770±0.050	8.755±0.074	8.756±0.040	44
			58	6.846	8.818±0.021	8.755±0.074	8.756±0.040	46
			59	6.807	9.1±0.136	8.699±0.074	8.700±0.040	101
Co-Ni	27	28	56	7.188	9.214±0.105	9.249±0.075	9.248±0.041	50
			57	7.145	9.300±0.050	9.188±0.075	9.187±0.041	89
			57	7.145	9.240±0.050	9.188±0.075	9.187±0.041	88
			59	7.064	9.300±0.050	9.070±0.075	9.070±0.041	89
			59	7.064	8.910±0.140	9.070±0.075	9.070±0.041	101

P.W. Present work.

Table A1 (Contd.)

Isobaric pair	Z_1	Z_2	A	$\bar{Z}/A^{1/3}$	ΔE_c (Obs) (MeV)	ΔE_c (Cal) (MeV) from relation (3.6)	ΔE_c (Cal) (MeV) from relation (3.7)	References.
Co-Ni	27	28	59	7.064	9.149 ± 0.019	9.070 ± 0.075	9.070 ± 0.041	89
			59	7.064	9.260 ± 0.150	9.070 ± 0.075	9.070 ± 0.041	89
			60	7.244	9.050 ± 0.043	9.013 ± 0.075	9.013 ± 0.041	103.
			60	7.244	9.100 ± 0.150	9.013 ± 0.075	9.013 ± 0.041	103
			61	6.986	9.950 ± 0.070	8.957 ± 0.074	8.957 ± 0.040	88
Ni-Cu	28	29	58	7.362	9.557 ± 0.006	9.501 ± 0.076	9.499 ± 0.042	88
			59	7.320	9.480 ± 0.015	9.441 ± 0.076	9.439 ± 0.041	88
			60	7.280	9.463 ± 0.010	9.382 ± 0.076	9.350 ± 0.041	88
			61	7.240	9.421 ± 0.015	9.324 ± 0.076	9.322 ± 0.041	104
			62	7.200	9.372 ± 0.010	9.268 ± 0.076	9.266 ± 0.041	88
			63	7.162	9.300 ± 0.010	9.212 ± 0.075	9.211 ± 0.041	88
			64	7.125	9.290 ± 0.012	9.158 ± 0.075	9.157 ± 0.041	88
			65	7.088	9.246 ± 0.055	9.105 ± 0.075	9.104 ± 0.041	89
			65	7.088	9.607 ± 0.035	9.105 ± 0.075	9.104 ± 0.041	89
			65	7.088	9.216 ± 0.035	9.105 ± 0.075	9.104 ± 0.041	105
			66	7.052	9.212 ± 0.015	9.053 ± 0.075	9.053 ± 0.041	104
Cu-Zn	29	30	63	7.413	9.700 ± 0.120	9.575 ± 0.077	9.572 ± 0.042	89
			63	7.413	9.550 ± 0.100	9.575 ± 0.077	9.572 ± 0.042	42
			63	7.413	9.612 ± 0.032	9.575 ± 0.077	9.572 ± 0.042	47.
			65	7.337	9.420 ± 0.100	9.464 ± 0.076	9.462 ± 0.042	42
			65	7.337	9.570 ± 0.040	9.464 ± 0.076	9.462 ± 0.042	50

Table A1 (Cond)

Isobaric pair	Z_1	Z_2	A	$\bar{A}/A^{1/3}$	ΔE_c (Obs) (MeV)	ΔE_c (Cal) (MeV) from relation (3.6)	ΔE_c (Cal) (MeV) from relation (3.7)	References
Co-Zn	29	30	66	7.299	9.508 ± 0.015	9.410 ± 0.076	9.408 ± 0.041	53
			67	7.263	9.490 ± 0.040	9.358 ± 0.076	9.356 ± 0.041	50
Zn-Ga	30	31	64	7.250	9.890 ± 0.040	9.880 ± 0.078	9.876 ± 0.042	98 ^b
			66	7.547	9.800 ± 0.040	9.768 ± 0.077	9.764 ± 0.042	98 ^b
			67	7.509	9.790 ± 0.040	9.713 ± 0.077	9.710 ± 0.042	98 ^b
			68	7.472	9.760 ± 0.040	9.660 ± 0.077	9.657 ± 0.042	98 ^b
			69	7.436	9.680 ± 0.020	9.608 ± 0.077	9.604 ± 0.042	53
			70	7.400	9.620 ± 0.040	9.556 ± 0.077	9.553 ± 0.042	98 ^b
Ga-Ge	31	32	71	7.365	9.577 ± 0.020	9.506 ± 0.076	9.503 ± 0.042	106
			69	7.680	10.000 ± 0.050	9.960 ± 0.078	9.955 ± 0.043	47
			71	7.607	9.800 ± 0.030	9.854 ± 0.078	9.850 ± 0.042	50
Ge-As	32	33	75	7.706	10.016 ± 0.020	9.998 ± 0.078	9.993 ± 0.043	53
			77	7.639	9.950 ± 0.040	9.901 ± 0.078	9.896 ± 0.042	53
As-Se	33	34	76	7.908	10.339 ± 0.015	10.290 ± 0.079	10.284 ± 0.043	53
Se-Br	34	35	77	8.109	10.480 ± 0.020	10.580 ± 0.080	10.572 ± 0.044	107
			79	8.040	10.457 ± 0.020	10.480 ± 0.080	10.473 ± 0.044	107
			81	7.973	10.488 ± 0.012	10.384 ± 0.079	10.377 ± 0.043	106
			83	7.909	10.468 ± 0.020	10.290 ± 0.079	10.284 ± 0.043	106

Table A1 (Contd.)

Isobaric pair	Z_1	Z_2	A	$Z/A^{1/3}$	ΔE_c (Obs) (MeV)	ΔE_c (Cal) (MeV) from relation (3.6)	ΔE_c (Cal) (MeV) from relation (3.7)	References.
Rb-Sr	37	38	88	8.430	11.160 ± 0.090	11.044 ± 0.082	11.043 ± 0.045	14
Sr-Y	38	39	88	8.655	11.450 ± 0.020	11.368 ± 0.083	11.357 ± 0.045	53
			89	8.623	11.395 ± 0.010	11.321 ± 0.083	11.310 ± 0.045	53
Y-Zn	39	40	89	8.847	11.650 ± 0.025	11.645 ± 0.084	11.632 ± 0.046	53
			90	8.814	11.635 ± 0.015	11.597 ± 0.084	11.585 ± 0.046	53
Zn-Nb	40	41	90	9.037	11.854 ± 0.300	11.920 ± 0.085	11.905 ± 0.047	103
			91	9.004	11.899 ± 0.025	11.872 ± 0.085	11.855 ± 0.047	108
			92	8.971	11.810 ± 0.025	11.824 ± 0.084	11.811 ± 0.04	108
			93	8.939	11.735 ± 0.025	11.778 ± 0.084	11.764 ± 0.046	108
			95	8.876	11.650 ± 0.025	11.687 ± 0.084	11.673 ± 0.046	108
			97	8.814	11.570 ± 0.025	11.598 ± 0.084	11.585 ± 0.046	108
Nb-Mo	41	42	93	9.159	11.900 ± 0.0150	12.096 ± 0.085	12.081 ± 0.047	42
			93	9.159	12.090 ± 0.120	12.096 ± 0.085	12.081 ± 0.047	101
			94	9.127	12.000 ± 0.025	12.049 ± 0.085	12.035 ± 0.047	53
Mo-Tc	42	43	93	9.380	12.380 ± 0.030	12.415 ± 0.086	12.399 ± 0.048	108
			95	9.314	12.277 ± 0.021	12.319 ± 0.086	12.303 ± 0.047	108
			96	9.281	12.170 ± 0.030	12.273 ± 0.086	12.257 ± 0.047	108
			97	9.241	12.150 ± 0.025	12.226 ± 0.086	12.211 ± 0.047	108
			98	9.218	12.120 ± 0.030	12.181 ± 0.086	12.165 ± 0.047	108
			99	9.187	11.990 ± 0.025	12.136 ± 0.085	12.121 ± 0.047	108
			101	9.126	11.935 ± 0.025	12.048 ± 0.085	12.033 ± 0.047	108

Table A1 (Contd.)

Isobaric pair	Z_1	Z_2	A	$Z/A^{1/3}$	ΔE_c (Obs) (MeV)	ΔE_c (Cal) (MeV) from relation (3.6)	ΔE_c (Cal) (MeV) from relation (3.7)	References.
Pd-Ag	46	47	103	9.920	13.140 $\pm$ 0.040	13.194 $\pm$ 0.089	13.174 $\pm$ 0.049	108
			105	9.856	13.050 $\pm$ 0.025	13.103 $\pm$ 0.089	13.083 $\pm$ 0.049	108
			107	9.794	13.000 $\pm$ 0.030	13.013 $\pm$ 0.088	12.994 $\pm$ 0.049	108
			109	9.734	12.915 $\pm$ 0.030	12.926 $\pm$ 0.088	12.907 $\pm$ 0.049	108
Ag-Cd	47	48	108	9.974	13.300 $\pm$ 0.040	13.273 $\pm$ 0.089	13.252 $\pm$ 0.049	53
			108	9.974	13.340 $\pm$ 0.160	13.273 $\pm$ 0.089	13.252 $\pm$ 0.049	101
			108	9.974	13.250 $\pm$ 0.150	13.273 $\pm$ 0.089	13.252 $\pm$ 0.049	89
			108	9.974	13.070 $\pm$ 0.150	13.273 $\pm$ 0.089	13.252 $\pm$ 0.049	43
			110	9.913	13.190 $\pm$ 0.020	13.185 $\pm$ 0.089	13.165 $\pm$ 0.049	53
Cd-In	48	49	112	10.061	13.368 $\pm$ 0.020	13.399 $\pm$ 0.090	13.377 $\pm$ 0.050	53
			113	10.032	13.350 $\pm$ 0.035	13.356 $\pm$ 0.090	13.335 $\pm$ 0.050	50
			114	10.002	13.310 $\pm$ 0.015	13.313 $\pm$ 0.090	13.292 $\pm$ 0.050	50
			115	9.973	13.280 $\pm$ 0.030	13.271 $\pm$ 0.089	13.250 $\pm$ 0.049	109
In-Sn	49	50	115	10.179	13.500 $\pm$ 0.200	13.568 $\pm$ 0.090	13.546 $\pm$ 0.050	42
			115	10.179	13.210 $\pm$ 0.150	13.568 $\pm$ 0.090	13.546 $\pm$ 0.050	43
Sn-Sb	50	51	113	10.445	13.930 $\pm$ 0.030	13.953 $\pm$ 0.092	13.929 $\pm$ 0.051	108
			115	10.384	13.890 $\pm$ 0.025	13.865 $\pm$ 0.091	13.841 $\pm$ 0.051	108
			117	10.325	13.803 $\pm$ 0.015	13.779 $\pm$ 0.091	13.756 $\pm$ 0.050	108
			118	10.296	13.760 $\pm$ 0.020	13.737 $\pm$ 0.091	13.714 $\pm$ 0.050	108
			119	10.267	13.737 $\pm$ 0.015	13.695 $\pm$ 0.091	13.672 $\pm$ 0.050	108
			120	10.238	13.692 $\pm$ 0.012	13.654 $\pm$ 0.091	13.631 $\pm$ 0.050	108
			123	10.154	13.609 $\pm$ 0.012	13.533 $\pm$ 0.090	13.511 $\pm$ 0.050	108
			125	10.100	13.550 $\pm$ 0.015	13.454 $\pm$ 0.090	13.432 $\pm$ 0.050	108

Table A1 (Contd.)

Isobaric pair	Z_1	Z_2	A	$Z/A^{1/3}$	ΔE_c (Obs) (MeV)	ΔE_c (Cal) (MeV) from relation (3.6)	ΔE_c (Cal) (MeV) from relation (3.7)	References
Sb-Te	51	52	124	10.327	13.850 ± 0.030	13.783 ± 0.061	13.760 ± 0.050	53
Te-I	52	53	126	10.472	14.030 ± 0.040	13.992 ± 0.092	13.967 ± 0.051	53
			127	10.444	14.030 ± 0.020	13.952 ± 0.092	13.928 ± 0.051	53
			129	10.390	13.935 ± 0.040	13.873 ± 0.091	13.850 ± 0.051	53
			131	10.337	13.845 ± 0.030	13.797 ± 0.091	13.773 ± 0.051	53
Ba-La	56	57	131	11.124	14.898 ± 0.020	14.934 ± 0.095	14.905 ± 0.053	50
			133	11.068	14.879 ± 0.020	14.853 ± 0.095	14.825 ± 0.053	50
			135	11.013	14.797 ± 0.020	14.774 ± 0.095	14.746 ± 0.053	50
			137	10.960	14.752 ± 0.020	14.696 ± 0.094	14.668 ± 0.052	50
			139	10.907	14.651 ± 0.015	14.620 ± 0.094	14.592 ± 0.052	53
La-Ce	57	58	139	11.100	14.800 ± 0.120	14.898 ± 0.095	14.870 ± 0.053	101
			140	11.073	14.800 ± 0.120	14.860 ± 0.095	14.832 ± 0.053	101
Ce-Pr	58	59	141	11.239	15.108 ± 0.015	15.100 ± 0.096	15.070 ± 0.053	53
Pr-Nd	59	60	142	11.404	15.342 ± 0.015	15.338 ± 0.097	15.370 ± 0.054	53
Nd-Pm	60	61	143	11.569	15.540 ± 0.015	15.576 ± 0.097	15.544 ± 0.054	53
			145	11.576	15.427 ± 0.015	15.499 ± 0.097	15.467 ± 0.054	110
			147	11.463	15.333 ± 0.015	15.423 ± 0.097	15.392 ± 0.054	110
			149	11.412	15.259 ± 0.015	15.349 ± 0.097	15.318 ± 0.054	110
			151	11.361	15.180 ± 0.015	15.276 ± 0.096	15.245 ± 0.054	110
Sm-Eu	62	63	145	11.896	15.992 ± 0.015	16.049 ± 0.099	16.014 ± 0.055	110
			149	11.789	15.760 ± 0.030	15.893 ± 0.098	15.860 ± 0.055	111
			151	11.737	15.700 ± 0.030	15.818 ± 0.098	15.785 ± 0.055	111

Isobaric pair	Z ₁	Z ₂	A	Z/A ^{1/3}	ΔE_c (Obs) (MeV)	ΔE_c (Cal) (MeV) from relation (3.6)	ΔE_c (Cal) (MeV) from relation (3.7)	References.
Er-Tm	68	69	171	12.341	16.687 $\pm$ 0.051	16.691 $\pm$ 0.101	16.653 $\pm$ 0.057	50
Hf-Ta	72	73	181	12.816	17.240 $\pm$ 0.050	17.377 $\pm$ 0.104	17.337 $\pm$ 0.058	112
Ta-W	73	74	181	12.993	17.220 $\pm$ 0.190	17.633 $\pm$ 0.104	17.591 $\pm$ 0.058	101
			181	12.993	17.840 $\pm$ 0.200	17.633 $\pm$ 0.104	17.591 $\pm$ 0.058	43
Os-Ir	76	77	189	13.330	18.032 $\pm$ 0.032	18.119 $\pm$ 0.106	18.075 $\pm$ 0.059	50
			191	13.283	18.000 $\pm$ 0.102	18.051 $\pm$ 0.106	18.007 $\pm$ 0.009	50
			193	13.237	17.940 $\pm$ 0.104	17.985 $\pm$ 0.106	17.941 $\pm$ 0.059	50
Pt-Au	78	79	195	13.537	18.363 $\pm$ 0.028	18.417 $\pm$ 0.107	18.372 $\pm$ 0.060	50
			197	13.491	18.320 $\pm$ 0.029	18.351 $\pm$ 0.107	18.306 $\pm$ 0.060	50
			199	13.445	18.250 $\pm$ 0.102	18.286 $\pm$ 0.107	18.240 $\pm$ 0.060	*
Au-Hg	79	80	197	13.663	18.500 $\pm$ 0.200	18.599 $\pm$ 0.108	18.553 $\pm$ 0.060	43
			197	13.663	18.770 $\pm$ 0.230	18.599 $\pm$ 0.108	18.553 $\pm$ 0.060	101
Pb-Bi	82	83	205	13.991	19.024 $\pm$ 0.015	19.074 $\pm$ 0.109	19.025 $\pm$ 0.061	113
			205	13.991	18.972 $\pm$ 0.011	19.074 $\pm$ 0.109	19.025 $\pm$ 0.061	113
			207	13.946	18.955 $\pm$ 0.036	19.009 $\pm$ 0.109	18.960 $\pm$ 0.061	114
			207	13.946	18.899 $\pm$ 0.011	19.009 $\pm$ 0.109	18.960 $\pm$ 0.061	113
			208	13.924	19.140 $\pm$ 0.100	18.976 $\pm$ 0.109	18.928 $\pm$ 0.061	101
			208	13.924	18.868 $\pm$ 0.013	18.976 $\pm$ 0.109	18.928 $\pm$ 0.061	113
			208	13.924	18.855 $\pm$ 0.022	18.976 $\pm$ 0.109	18.928 $\pm$ 0.061	113
			208	13.924	18.877 $\pm$ 0.022	18.976 $\pm$ 0.109	18.928 $\pm$ 0.061	113
			209	13.902	18.841 $\pm$ 0.010	18.944 $\pm$ 0.109	18.896 $\pm$ 0.061	113
			209	13.902	18.841 $\pm$ 0.030	18.944 $\pm$ 0.109	18.896 $\pm$ 0.061	114
			209	13.902	18.813 $\pm$ 0.025	18.944 $\pm$ 0.109	18.896 $\pm$ 0.061	115
U-Np	92	93	238	14.926	19.770 $\pm$ 0.150	20.423 $\pm$ 0.114	20.368 $\pm$ 0.064	101
			138	14.926	19.860 $\pm$ 0.200	20.423 $\pm$ 0.114	20.368 $\pm$ 0.064	43