

NUCLEAR RESONANCE FLUORESCENCE IN Si^{28}

by

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TABLE OF CONTENTS

	Page
I. Introduction	4
II. Governing equations	7
III. Experimental apparatus	10
A. Accelerator	10
B. Detectors	17
C. Target	17
D. Gamma ray selector	17
IV. Procedure	22
V. Analysis	28
VI. Results	30
VII. Acknowledgments	36
VIII. Literature cited	37
IX. Vita	39

TABLE OF FIGURES

Figure		Page
1.	Van de Graaff support columns	12
2.	Terminal end of Van de Graaf	13
3.	Partially assembled Van de Graaff	14
4.	Gamma ray spectrum of Co ⁶⁰	18
5.	Target chamber	19
6.	Gamma ray selector	21
7.	Typical background run	23
8.	Typical spectrum for one hour run	24
9.	Gamma ray spectrum of B ¹¹ (P,)C ¹²	25
10.	Resonant absorption I	31
11.	Resonant absorption II	32
12.	Energy levels	34

I. INTRODUCTION

Momentum considerations dictate that the energy of a gamma ray emitted to the ground state be less than the excitation energy of the corresponding nuclear energy level. Similarly the energy of a gamma ray absorbed in a nucleus must be greater than the associated excitation energy. This deficiency can be made up by motion of the emitting nucleus¹. In the case of this experiment such motion is provided by the recoil of a target nucleus after absorption of an energetic proton.

It will be seen in the following analysis that the energy of a gamma ray emitted from a recoiling nucleus varies with the angle between the direction of the gamma ray and the direction of recoil. By accepting gamma rays in a single but variable direction one is provided with a variable and very nearly monoenergetic source of gamma rays. The transmission through an absorption should then exhibit the effects known as nuclear resonant fluorescence. This technique can be used to investigate any energy level which lies in the range over which the variation takes place.

The energy variation does indeed take place over a relatively small range and it is this fact which most severely limits this method. In this experiment the energy variation amounts to approximately 200 ev per degree. This method is generally referred to as "Doppler shift by previous absorption."

Smith and Endt² used this method to investigate the energy level excited in the reaction $\text{Al}^{27}(p,\gamma)\text{Si}^{28}$ at $E_p = 771$ kev. In a preliminary report³ Smith had indicated a lack of results for the energy level excited in the same reaction at $E_p = 504$ kev. This report indicated that the ground state radiation had not been adequately resolved from the more intense radiation to the first excited state. Furthermore this level has been found to be a doublet⁴ with a 2 kev separation. The present work is an investigation of the assumed doublet level at $E_p = 504$ kev excited in the $\text{Al}^{27}(p,\gamma)\text{Si}^{28}$ reaction.

Both levels have been reported to give rise to ground state radiation.⁵ No lower energy levels are known giving rise to ground state radiation.⁶ This permitted the use of a thick target and eased the requirements on proton beam energy stability and purity. The required target and absorber were easily

obtainable and highly suitable for this sort of experiment. The principal drawback to the experiment is the relatively low cross section for the reaction. Since only a small fraction of the gammas produced in the reaction can be used and absorption by Compton effect and pair production eliminates many of those which do have the correct energy, the counting rate was very low.

On the basis of a doublet level the transmission versus angle curve should exhibit three dips. One would correspond to emission from the 504 keV level and absorption by the 506 keV level. One would correspond to emission from the 506 keV level and absorption by the 504 keV level. The third would be a combination of emission then absorption by the 504 keV level and emission then absorption by the 506 keV level. Such a clear cut result was not seen.

II. GOVERNING EQUATIONS

Suppose a nucleus of mass M recoiling from a proton reaction with momentum \underline{P} emits a gamma in a direction having an angle α to \underline{P} and is absorbed in an identical nucleus at rest. The energy and momentum relations are:

$$E_0 + E_r = E_{r_1} + E_{r_2} + E_0' \quad (1)$$

and

$$\underline{P} = \underline{P}_1 + \underline{P}_2 \quad (2)$$

where E_0 is the excitation energy of the emitting nucleus, E_r is the kinetic energy of recoil possessed by the emitting nucleus, E_{r_1} is the kinetic energy of the emitting nucleus after emission, E_{r_2} is the kinetic energy of the absorbing nucleus after absorption. E_0' is the excitation energy of the absorbing nucleus, \underline{P} is the momentum before the event, \underline{P}_1 and \underline{P}_2 are the momenta of the nuclei after the event. Resolving the momenta parallel and perpendicular to the direction of emission we get:

$$P \cos \alpha = P_1 \cos \beta + P_2 \quad (3)$$

$$P \sin \alpha = P_1 \sin \beta \quad (4)$$

where β is the angle between \underline{P}_1 and the direction of the gamma ray. Since the recoil velocities are non relativistic the energy equation can be rewritten:

$$E_0 + \frac{P^2}{2M} = \frac{P_1^2}{2M} + \frac{P_2^2}{2M} + E_0' \quad (5)$$

Eliminating β and P_1 from (4), (5) and (6) we get:

$$E_0 - E_0' = \frac{P^2}{M} - \frac{PP_2}{M} \cos \alpha \quad (6)$$

P is actually the momentum of the bombarding proton i.e.

$$P = (2M_p E_p)^{1/2} \quad \text{and} \quad P_2 = \frac{h\nu}{c}$$

thus:

$$E_0 - E_0' = \frac{1}{Mc^2} [(h\nu)^2 - h\nu(2E_p M_p c^2)^{1/2} \cos \alpha] \quad (7)$$

h can be found as $h = Mc^2 \left[1 - \left(1 - \frac{2E_0'}{Mc^2} \right)^{1/2} \right]$ which

is very nearly E_0' itself.

If $E_0 = E_0'$ and assuming $h\nu = E_0$ then

$$\cos \alpha = E_0 / (2E_p M_p c^2)^{1/2} \quad (8)$$

For an E_0 of 12.067 Mev and $E_p = 504$ kev the value of α is 66.54° .

III. EXPERIMENTAL APPARATUS

A. Accelerator

The principal tool of this investigation was the V.P.I. Van de Graaff accelerator. This machine has been extensively described in previous papers, 7,8,9,10,11,12 but a large number of modifications have been made. These will be described briefly.

The most significant change was the replacement of the main structural members supporting the high voltage terminal. These had originally consisted of three tubes of textolite fastened to the base plate and furnishing cantilever support to the terminal. The textolite would not support the voltage gradients required. The replacements consisted of columns glued up from alternating discs of glass and metal. One attempt involved discs sawed from one inch thick pyrex plate, aluminum discs one eighth inch thick, and Eastman 910 cement. The differential expansion of the aluminum and the pyrex broke these columns.

The columns finally used were made from pyrex discs polished on the cylindrical surfaces and ground on the flat surfaces, feritic stainless steel discs, and Armstrong A 9, an epoxy cement. These columns

proved highly satisfactory both structurally and electrically.

The hardware supporting the gradient bars and corona rings was modified to accept the new columns. This permitted the covering of the relatively sharp edges presented by the stainless steel discs. Two of these columns with associated hardware are shown in figure 1.

Both the generator pulley plate and the ground support plate were made more rigid. A triangular brace seen in figure 2 accomplishes this for the generator pulley plate. The ground support plate was attached at the major points of stress directly to the end plate of the tank. This was thought to be necessary because these plates were originally designed for textolite. The glass columns could not be expected to tolerate certain bending moments which would be unimportant to the textolite.

The generator pulley support plate was also modified by cutting it into two parts, one a central disc, the other a piece approximately the size and shape of a corona ring. This can be seen reassembled in figure 3. Two purposes were served by this modification. The corona rings could then be welded

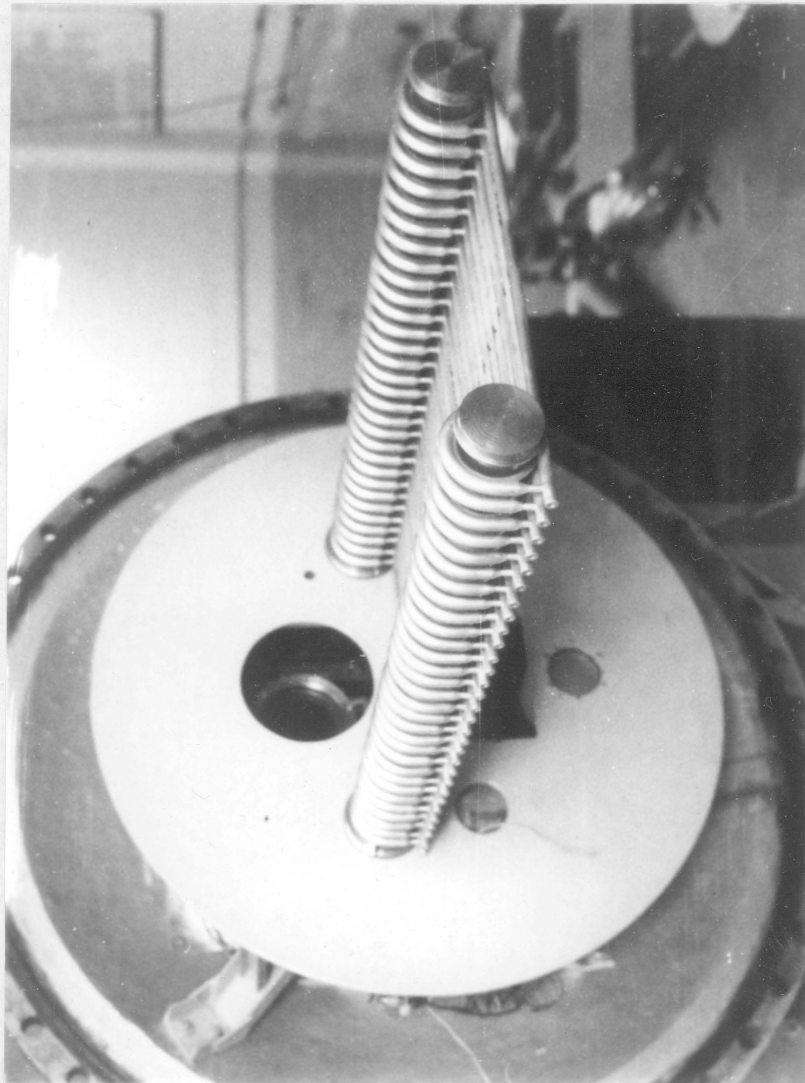


Figure 1. Van de Graaff support columns

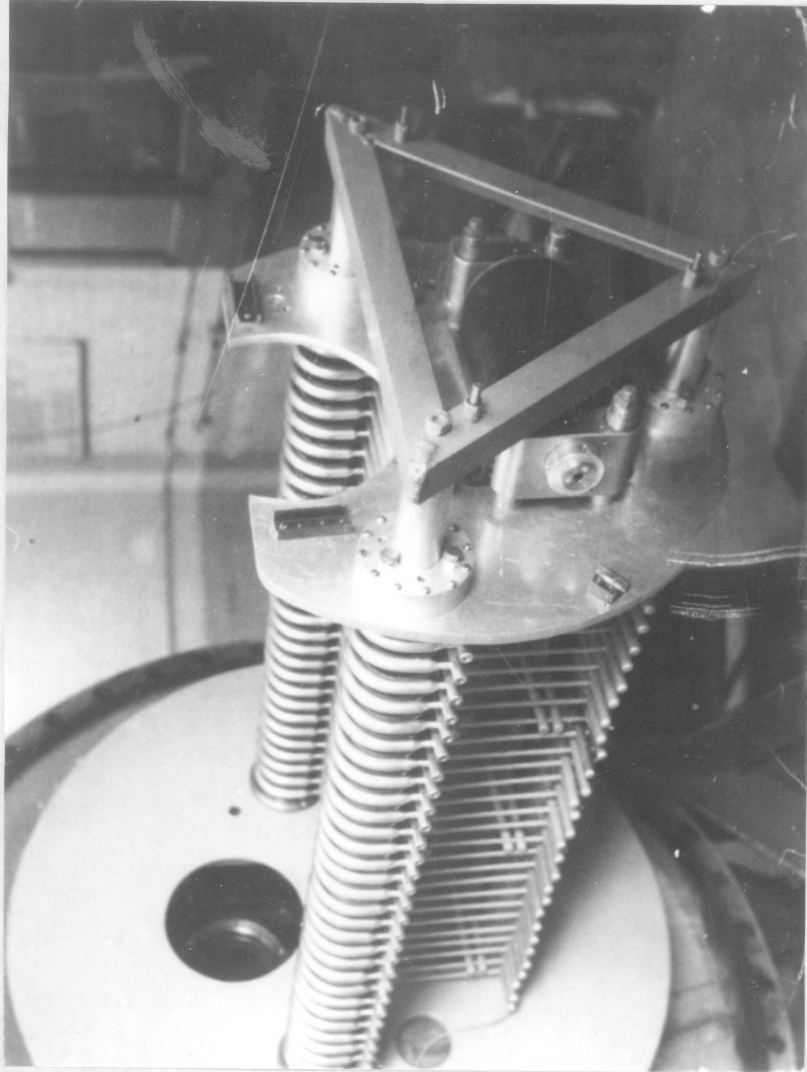


Figure 2. Terminal end of Van de Graaff

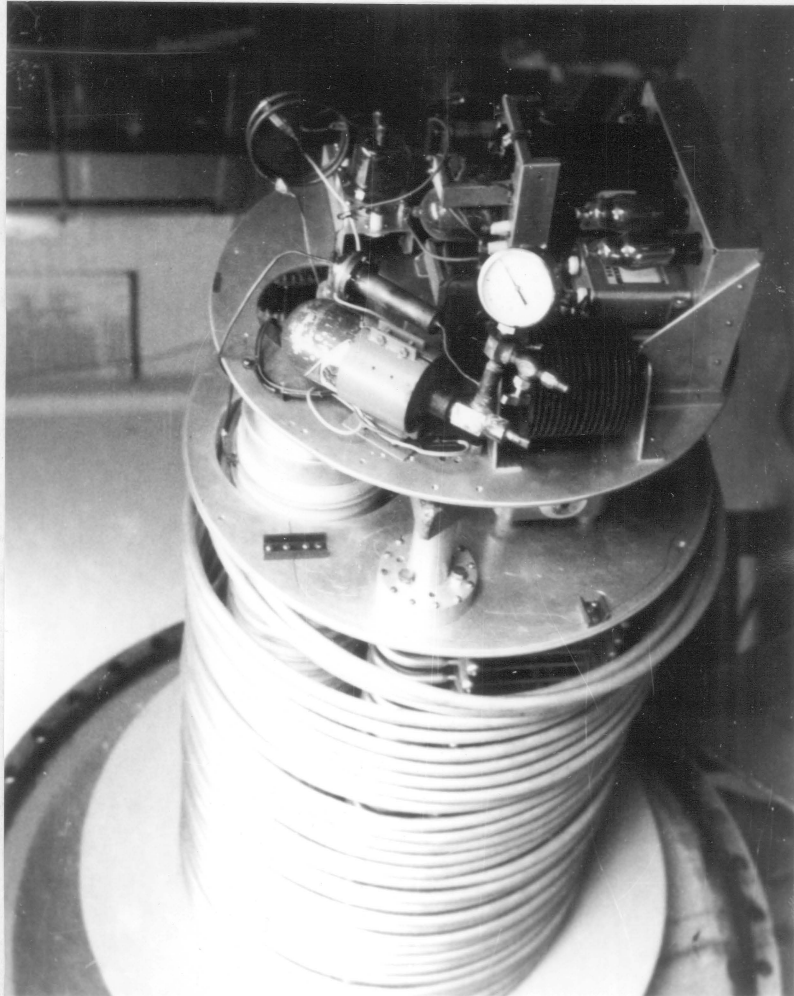


Figure 3. Partially assembled Van de Graaff

into continuous hoops and still be conveniently removed and the removal of the accelerating tube was made considerably easier.

The control rod linkages were made more dependable by constructing gear boxes for the variac drives and by introducing flexible shafts at both the high voltage and ground ends of the rods.

Additional gradient bars were fabricated of aluminum and installed. These bars were adjustable and furnished with pyrex inserts to prevent the belt from rubbing the metal. They were mounted on vertical rods which also provided positive contact between the different parts of the hardware making up each equipotential plane.

New spring loaded clips were fashioned to connect the lens elements of the tube to the equipotential planes.

The entire wiring inside the pressure tank was redone. This included ion source electronics and selsyn connections. The feed through insulators in the tank end plate were rebuilt.

The mechanism for adjusting the position of the needles in the corona feedback system was modified and rebuilt for smoother operation and electrical integrity.

New commercial vacuum gate valves now replace the old modified water valves. A high capacity fore pump was installed and use of the booster pump was discontinued. Contamination of the octoil in the main pump by butyl thalate from the booster was thereby eliminated.

A manual control for recycling the magnet was installed.

The copper gasket sealing the tank to its end plate was replaced by a linear O-ring stock gasket.

The jaws of the stabilizing slit were replaced and a second defining slit was installed near the target chamber.

After the foregoing modifications were accomplished the upper limit of the machine as measured with generating voltmeter and with no beam was found to be approximately 1.4 MV. With usable beam on target the upper limit was found to be approximately 1.0 MV. New gas plumbing permitting higher pressures should extend these limits. Analyzed beams of protons on target of $20\mu\text{a}$ could be obtained routinely in the energy range used in this experiment.

B. Detectors

The principal detector used in this experiment was a 3 x 3 Na I crystal mounted on a Dumont 6363 photomultiplier tube. This combination had excellent resolution as may be seen in figure 4. For a gamma ray energy of 1.28 Mev the resolution is measured to be 6.2%.

The output of the detector consisting of a 1 1/2 x 1 1/2 Na I crystal and Dumont 6292 photomultiplier tube was also employed as a rough check during runs. This was supplemented by a conventional current integrator.

C. Target

The target consisted of a 1/32 inch sheet of aluminum mounted in a lucite target chamber (figure 5).

D. Gamma ray selector

The main detector was placed in a vertical position and surrounded by a lead shield approximately two inches thick in most directions and six inches thick toward the target. The shield eliminated much of the machine background and reduced the dead time for the multichannel analyzer. A window or slit one eighth inch wide was provided between the target and the crystal. Thus the entire spectrum of gamma rays

Co⁶⁰ SPECTRUM

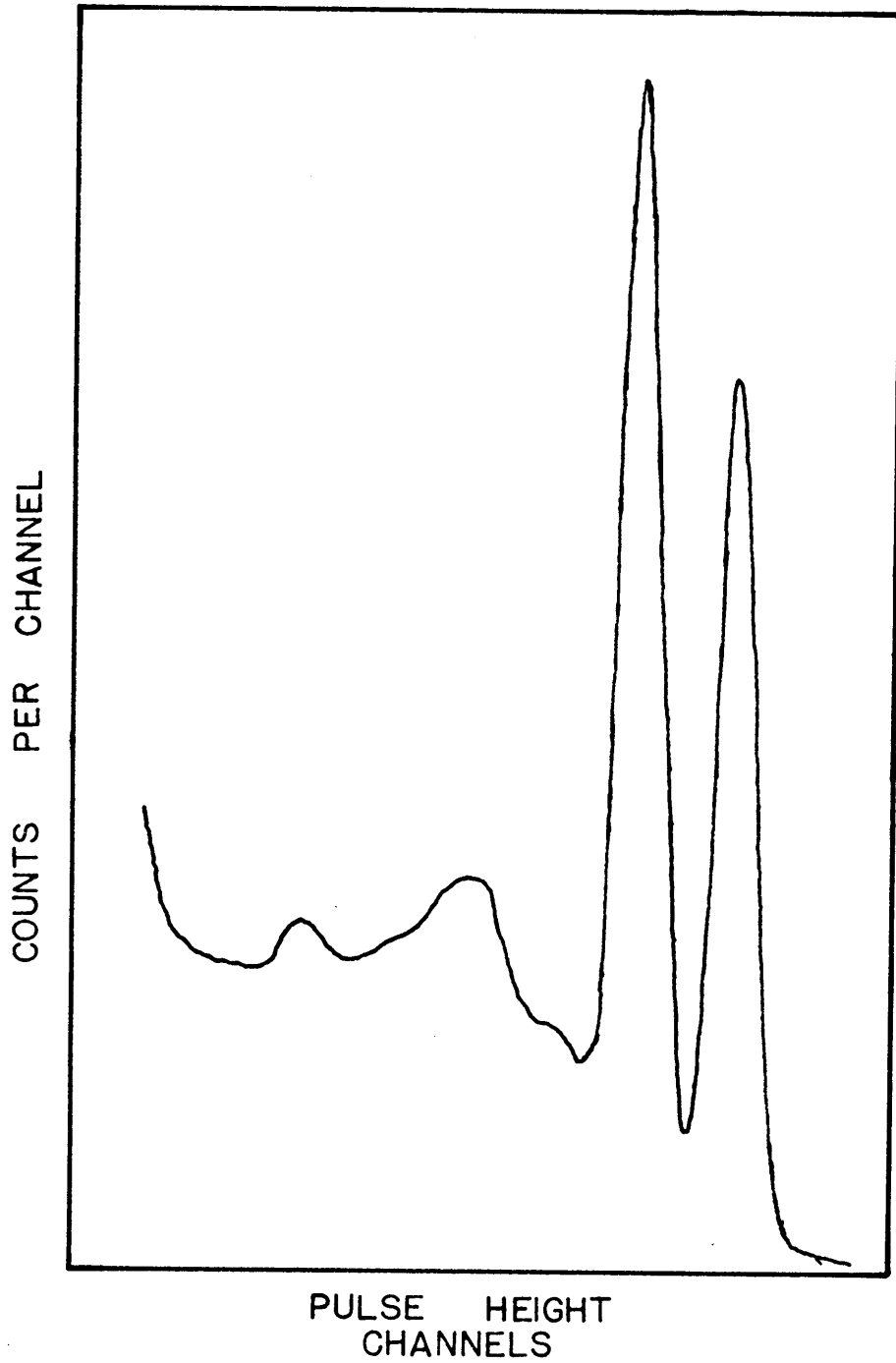


Figure 4. Gamma ray spectrum of Co⁶⁰

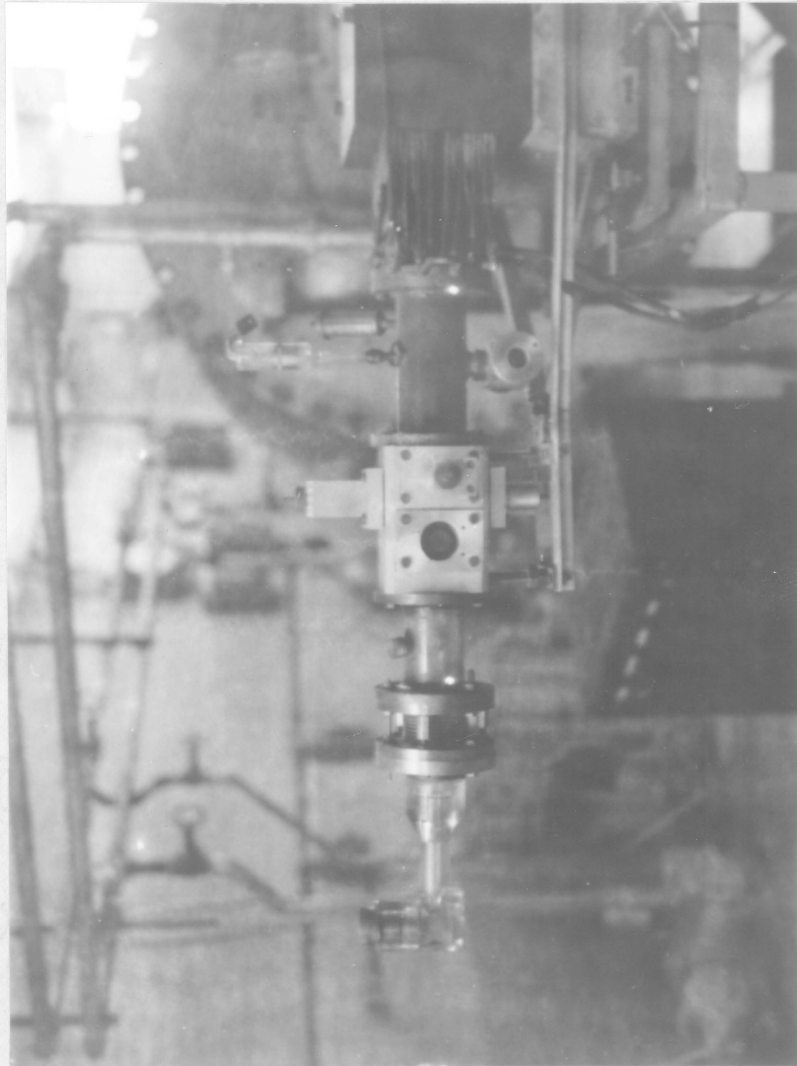


Figure 5. Target chamber

from the reaction could be observed through the slit but only those gammas making a particular angle to the beam were detected.

The slit was completely filled with silicon in the form of a sheet. The entire arrangement, detector, shield and silicon absorber, was mounted on a bar pivoted immediately below the target (figure 6). The position of this bar could be changed conveniently in one third degree increments. The range of motion was approximately 20° . No attempt was made to measure the exact angle between the slit and the beam direction but the center of the range was set to approximately 67° .

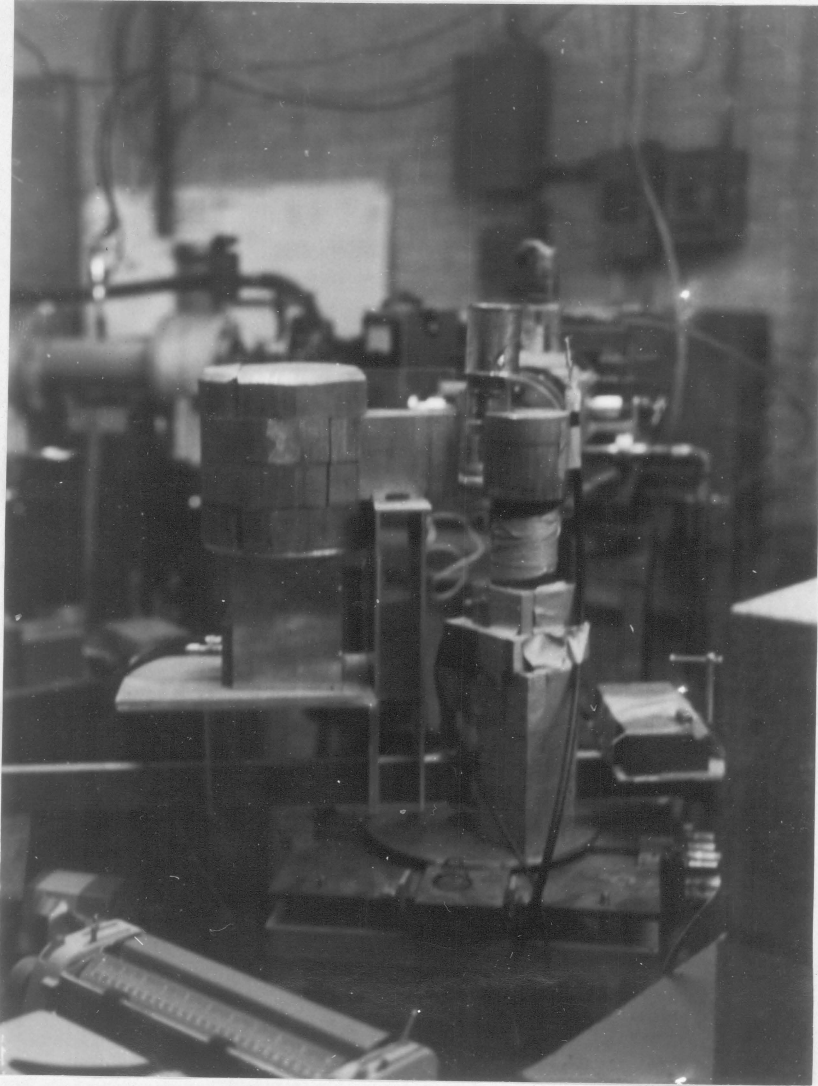


Figure 6. Gamma ray selector

IV. PROCEDURE

Since the counting rate in this experiment was extremely low, background was an important consideration. Background runs were taken at frequent intervals using the same spectrometer settings that were used during actual data taking. Figure 7 is a typical background run. No significant changes were observed. Background runs with beam on target and the slit filled with lead were also taken and were not significantly different.

To facilitate analysis each setting of the angle bar was run with beam on target for one hour. Then the setting was changed to a new angle. This procedure was repeated until there appeared to be a reasonable count accumulated for each setting. Figure 8 is a typical spectrum as seen at one of these positions in a one hour run as recorded on the oscilloscope read out of the 512 channel analyzer.

A relatively high counting rate spectrum with a gamma ray of energy comparable to that of the ground state gamma investigated in the experiment is shown in figure 9. The upper end of this spectrum fit very nicely the upper end of the spectrum from the aluminum

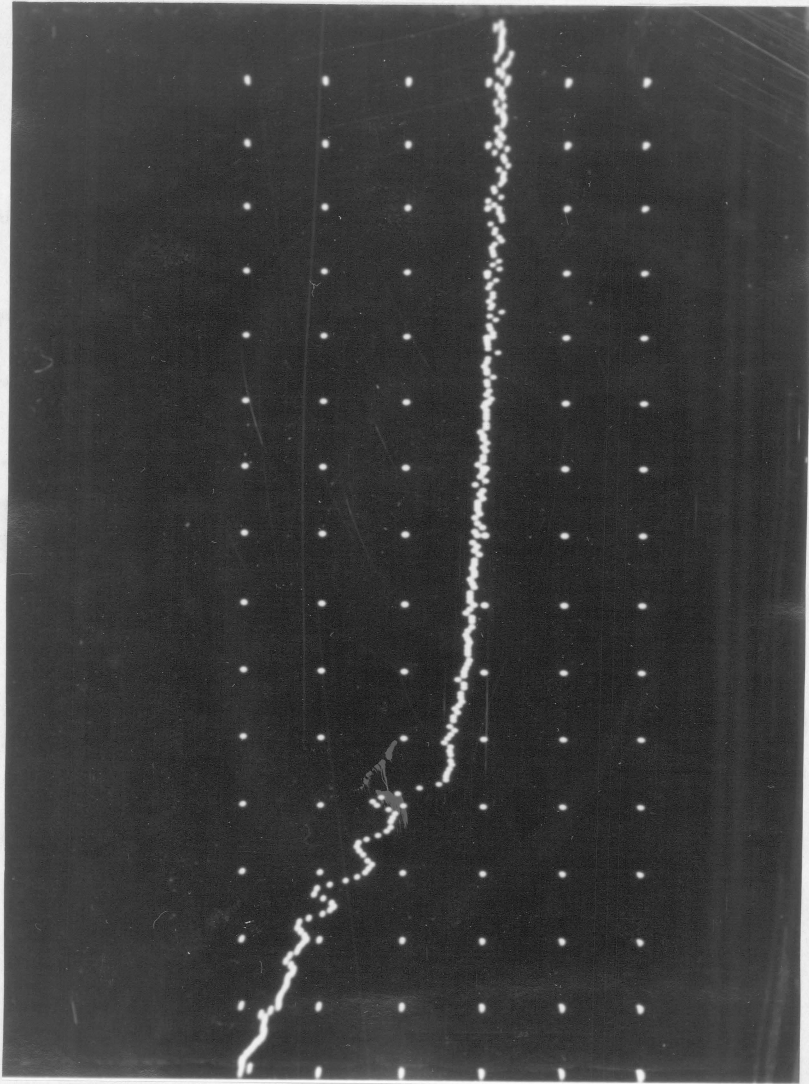


Figure 7. Typical background run

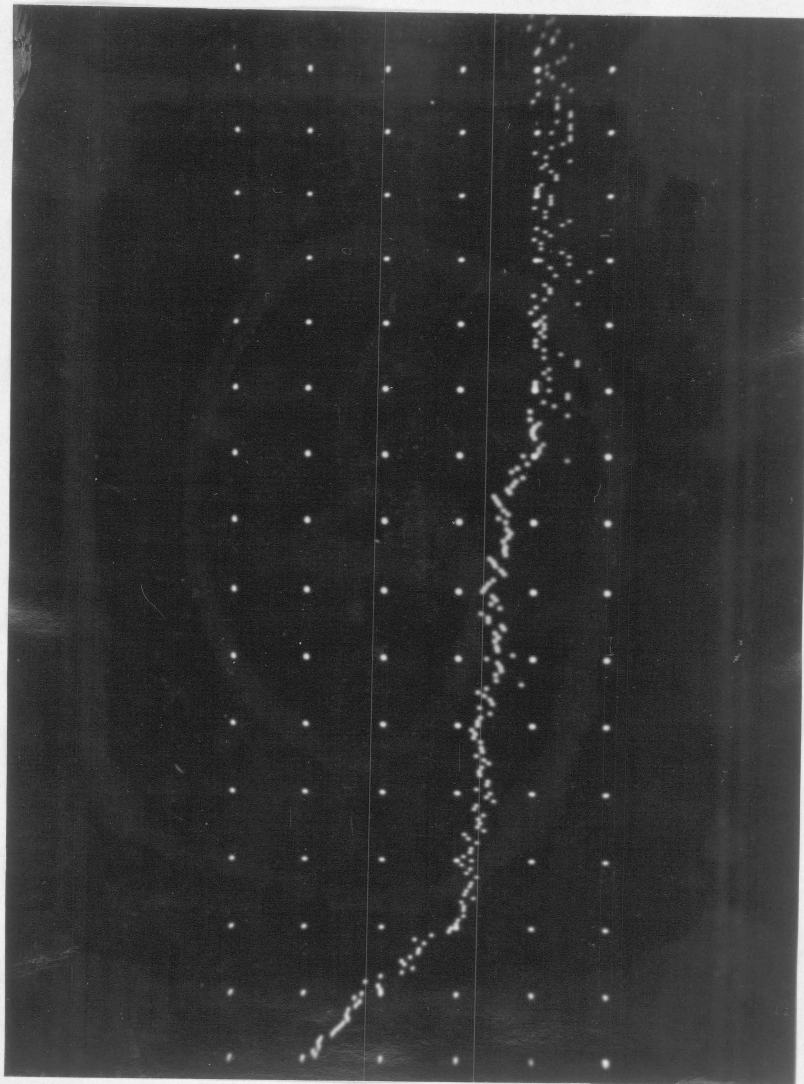


Figure 8. Typical spectrum for one hour run

MILLERS FALLS

OLD DEERFIELD BOND

50% COTTON CONTENT

SPECTRUM FROM $B^{11}(P, \alpha)C^{12}$

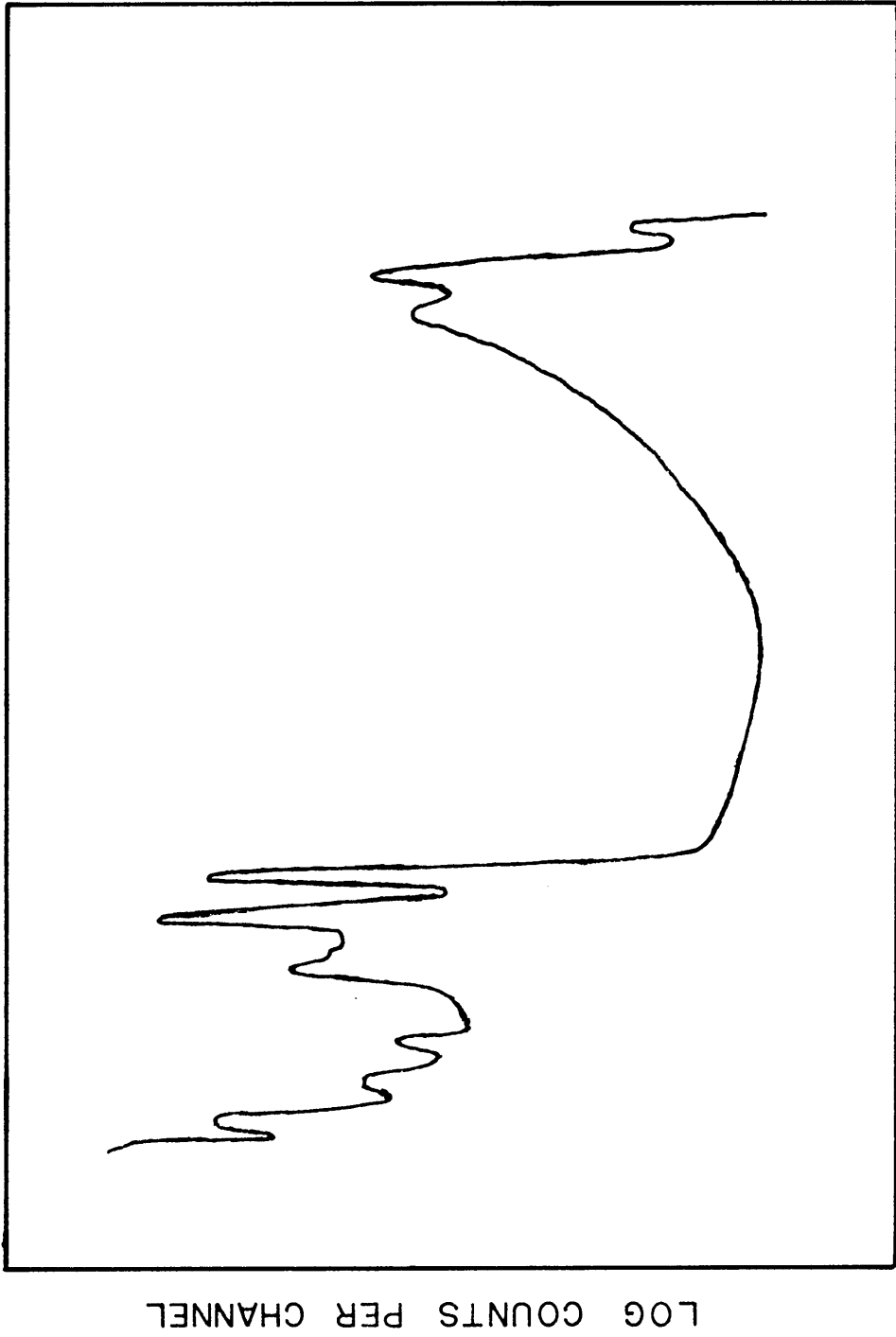


Figure 9. Gamma ray spectrum of $B^{11}(P, \alpha)C^{12}$

reaction (bare counter). This is used as a standard spectrum in analyzing the data.

Due to the fact that the beam current is never exactly constant some method of normalizing the results must be employed. Using a current integrator for this purpose is not very satisfactory because of the difficulty of keeping a constant calibration over a long period of time. A monitor counter has a better chance of maintaining a stable operation but discriminator drifts are still a problem. Furthermore any difference of the position of the beam on target will lead to a difference in monitor reading. Such effects can be minimized by judicious positioning of counter and target. Since these effects must be minimized for the main counter little help is left for the monitor.

Indeed stability problems exist for the main counter too. Even with the most stable of electronic systems temperature changes in the crystal itself will result in gain shifts. This is particularly troublesome when the counting rate is low and the entire experiment cannot be performed in a short time.

These problems were avoided by a process of self monitoring. That is, the number of high energy ground state gammas passing through the window was normalized to the number of lower energy gammas passing through the window at the same setting. In addition to these problems this method avoids those seen by Smith and Endt¹³, a depression of one side of the curve by geometric factors.

V. ANALYSIS

The data resulting from the experiment were put into a form acceptable to an IBM 1620 computer and the computer was programmed to perform the following operations on each set of data, i.e. each hour's run.

1. Subtract the background spectrum.
2. Make a rough plot of the resultant spectrum.
3. Fit the high end of the spectrum to the standard spectrum using a least squares criterion.
4. Make a slight scale change and repeat 3.
5. Perform 4 a preset number of times.
6. Choose the best fit found in 5.
7. Subtract this best fit from the spectrum obtained in 1.
8. Integrate under the best fit curve.
9. Integrate under a selected region of the remainder curve.

The computer was also programmed to collate these results. The numbers from step eight above for each run at the same position were added together. The numbers from step nine above for each run at the

same position were added together. The ratio between the sum of step eight and the sum of step nine was taken for each position. A probable error was computed for each such ratio.

Step two permitted a quick visual check for dropped channels.

Step six allowed for possible differences in gain over the total data taking period.

Since such shifts were not large the selection of the number for step five was only a matter of covering the necessary range.

The result of step nine is proportional to the number of events which could produce ground state gammas.

The result of step eight is proportional to the number of ground state gammas which passed through the window and escaped absorption in the silicon. Thus the ratio is a measure of the transmission of the silicon for gammas of the particular energy determined by the angular position of the window.

VI. RESULTS

The resultant ratios are seen in figure 10 with the straight line representing the average drawn through them. The separation between positions is one third of a degree. It can be seen that the straight line is a rather poor fit to the data. No absorption dips with widths large compared to the separation between positions are evident. A fit of a gaussian to the largest dip was performed with least squares criterion. This resulted in very little improvement in the fit. The number of points lying on the dip was so small that such a fit is of questionable value at best. In any event one dip that far from the center of the distribution would be difficult to explain.

Figure 11 shows the points plotted against difference in energy from the point of zero energy separation as given in equation (8). The upper portion is for increasing energy and the lower portion is for decreasing energy. The zero position was assumed to be between positions 33 and 34 as seen in figure 10.

RESONANT ABSORPTION

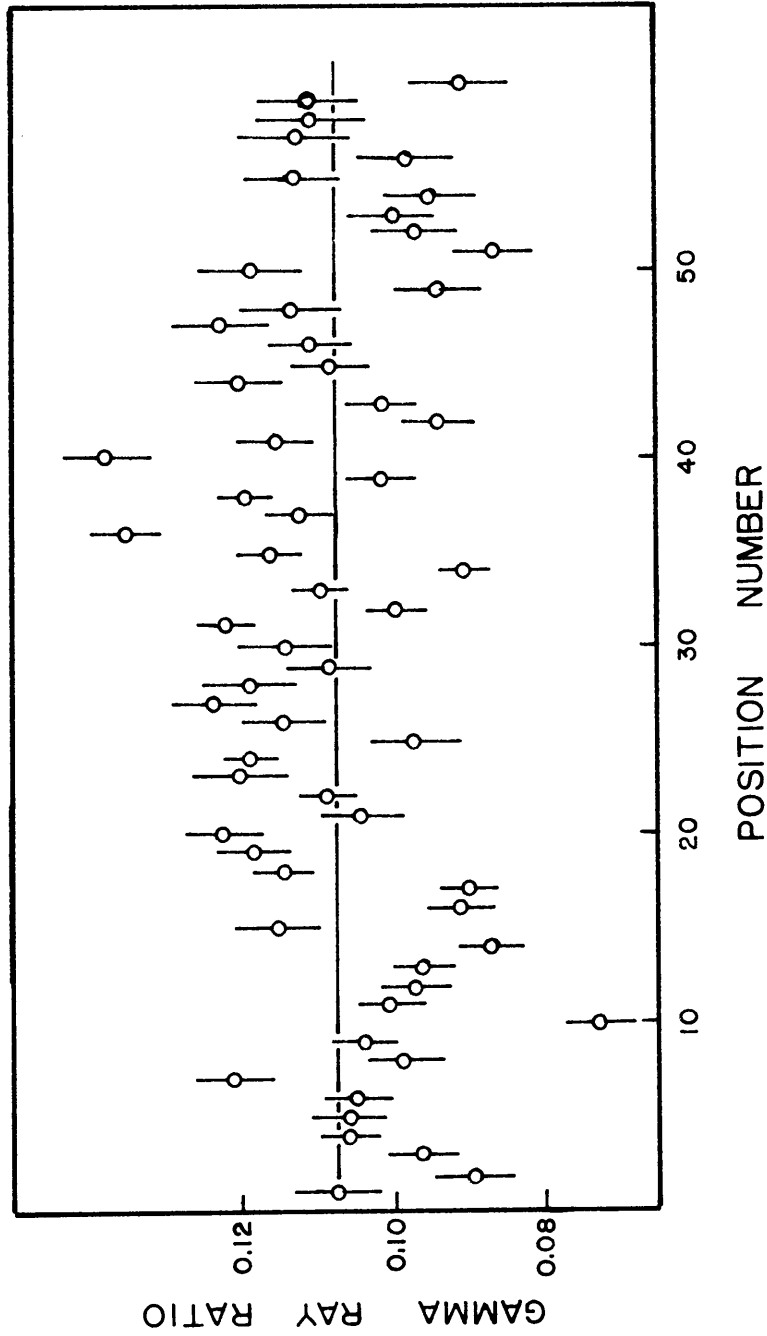


Figure 10. Resonant absorption I

RESONANT ABSORPTION

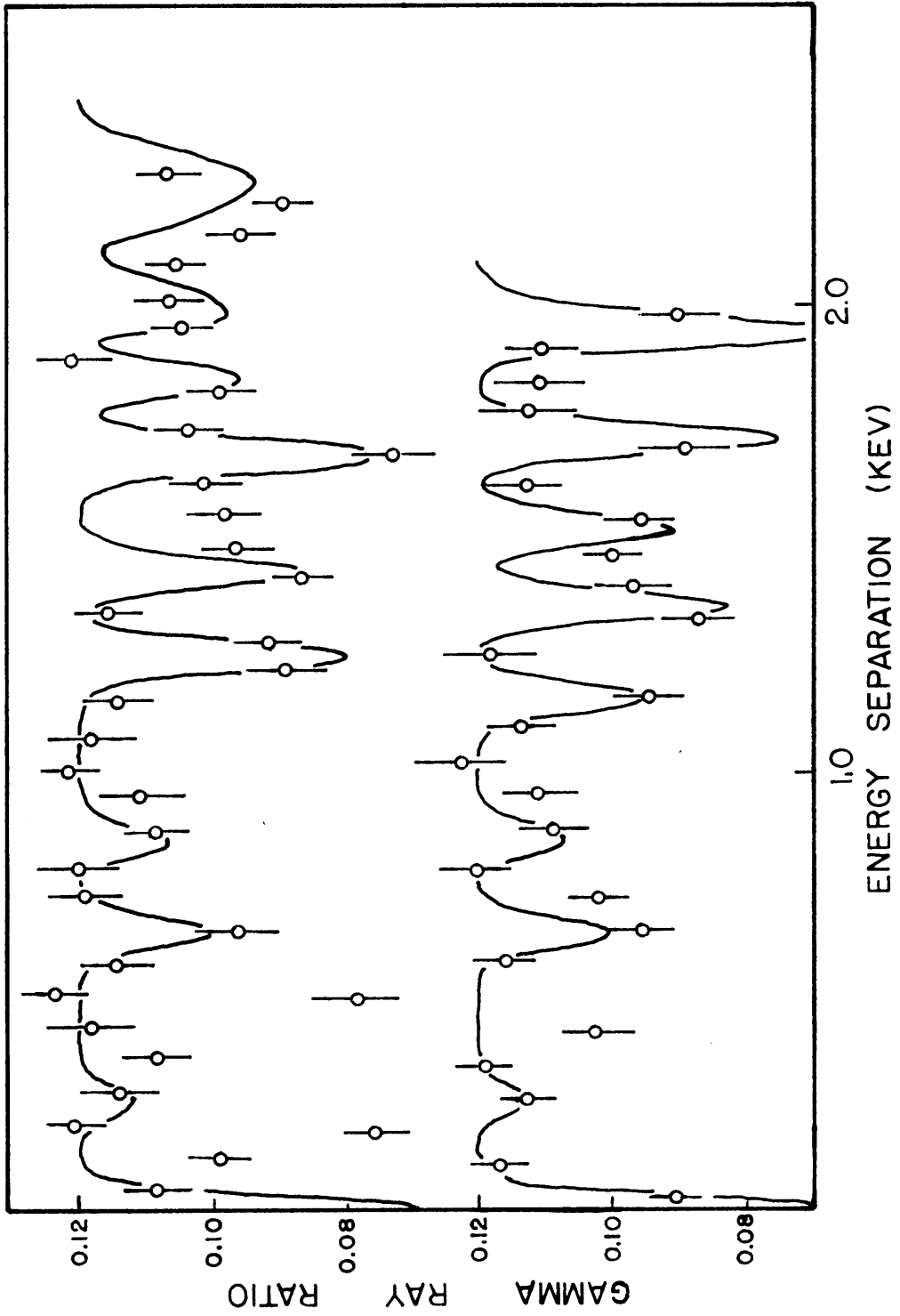


Figure 11. Resonant absorption II

The curve shown is that which would be expected if the levels shown in figure 12 existed. The dips are gaussian of width at half maximum of 77 ev. This sets an upper limit for the width of any such levels. For this analysis the sum of the squares of the deviations from the curve is 0.004096 whereas this sum for the straight line is 0.009460.

It was assumed that the central three levels were the only ones which produced 12 Mev gammas in sufficient quantity to show absorption effects. This produces the assymetry evident in the curves. Several possibilities exist for explaining such a situation. The outer levels might not be in Si^{28} but rather in Si^{29} , Si^{30} , or some contaminant such as Na. The fact that this is an absorption process and the great bulk of the absorber is certainly Si^{28} makes this possibility highly unlikely. These levels could have such a long lifetime that the gammas are not emitted until after motion of the emitting nucleus has ceased. Availability of competing modes of decay itself seems the most likely explanation. That is the 12 Mev gammas are produced from these levels but in such small quantities that they cannot be seen.

ENERGY LEVELS

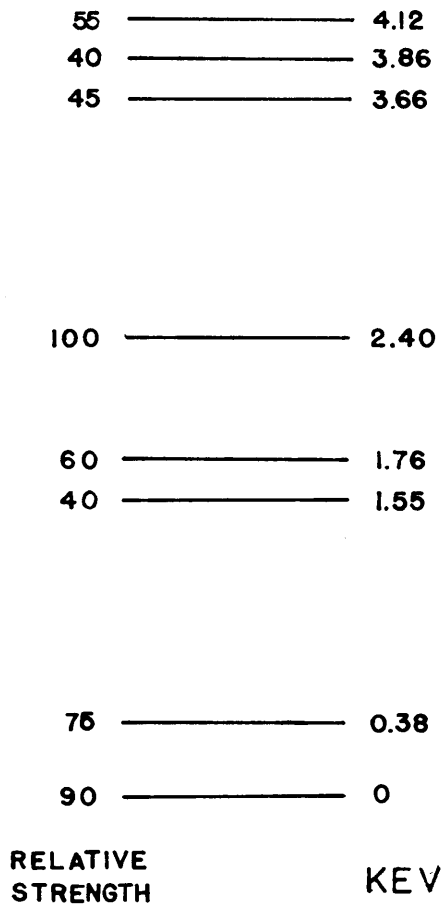


Figure 12. Energy levels

Since all the absorption dips used have the same width this would indicate that the governing factor was the experimental width and due to the few points available to each dip an examination of absorption integrals in an effort to determine level widths would not be significant.

The above analysis of the data is open to some criticism. It has been constructed to fit these particular data, using a rather larger number of parameters. No other evidence of such "fine structure" has been seen. An unknown source of random error would produce deviations from the straight line and this is regarded as the most probable explanation.

VII. ACKNOWLEDGMENTS

The author wishes to express his thanks to Dr. T. M. Hahn who provided opportunity, encouragement, and assistance in the initiation of this work. He is indebted to Dr. W. B. Payne for suggesting the general type of experiment. He thanks Dr. J. A. Jacobs for continued support and encouragement. The support of the entire staff and faculty of the department of physics of Virginia Polytechnic Institute is highly appreciated.

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ABSTRACT

The doublet level at $E_p = 504$ keV excited in the reaction $Al^{27}(p,\gamma)Si^{28}$ was investigated using a technique of nuclear resonance fluorescence. A silicon absorber was placed in a collimated beam of gamma rays from the reaction. The direction of collimation with reference to the direction of the bombarding protons governs the exact energy of the ground state gammas available for absorption. The energy deficit which appears in emission and absorption is made up by the kinetic energy of the compound nucleus recoiling from the proton bombardment. Variation of the angle between the collimator and the proton beam allows the measurement of the transmission of the absorber as a function of energy. Though the energy variation is small absorption by excitation of the energy levels mentioned was covered in the range of angle chosen.

For the above transmission experiment measurement of the ratio of the number of transmitted ground state gamma rays and of the number of decaying nuclei is necessary. This was accomplished in one counter. The entire spectrum from the reaction was observed at each angle. The number of ground state gammas was stripped

from each such spectrum and the number of gammas decaying to excited states thus determined. Thus the number of ground state gammas was normalized to the number of lower energy gammas. The low cross section of the reaction, the collimation and absorption all lead to an extremely low counting rate even though a thick target with proton energy just above resonance was used.

The V.P.I. Van de Graaff was used as a source of protons. Detection of gammas was by a 3 x 3 Na I crystal giving spectra on a 512 channel analyzer. The analysis of the data was accomplished on an IBM 1620 computer.

The resulting transmission versus energy data were fit to a straight line (i.e. no resonant absorption) and a more complicated assumption of some eight closely spaced levels. The straight line fit is considerably poorer but a result of no resonant absorption seems the more likely.