GAMMA-RADIATION FROM MAGNESIUM²⁶

UNDER PROTON BOMBARDMENT

DISSERTATION

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By

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Approved by:

A handwritten signature in cursive script, reading "John N. Cooper", written over a horizontal line.

Adviser

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GAMMA-RADIATION FROM MAGNESIUM²⁶ UNDER PROTON BOMBARDMENT

I. INTRODUCTION

One of the experiments for which electrostatic generators are particularly well adapted is the study of proton capture reactions in light nuclei. Among the light elements magnesium remains as one in which proton capture reactions have not been investigated thoroughly. In the past the study of these reactions in magnesium has been confined to relatively low energies and has been complicated by the fact that there are three stable isotopes of magnesium, all relatively abundant in natural magnesium. The work done by other investigators in the low energy region indicated that there were resonances in the spectrum that originated in each of the three isotopes. These investigations are discussed in more detail in Section II of this paper.

In natural magnesium the relative abundances of the three isotopes are: Mg^{24} ---77.4%, Mg^{25} ---11.5%, and Mg^{26} ---11.1%. Small quantities of highly enriched isotopes were obtained in 1950 from the Carbide and Carbon Chemicals Division, Oak Ridge National Laboratory, Y-12 Area, Oak Ridge, Tennessee. This has made

possible a more complete study of each isotope by itself. In particular, 0.055 grams of Mg^{26} were received in the form of magnesium oxide (MgO). The delivered material met the specifications shown in Table 1.

Mass Analysis		Spectrographic Analysis	
Isotope	Abundance (%)	Impurity	%
Mg^{26}	95.91 ± 0.06	Al	< 0.08
Mg^{25}	1.56 ± 0.03	Cu	< 0.08
Mg^{24}	2.53 ± 0.06	Fe	< 0.04
		Si	< 0.08
		Ti	< 0.04

Table 1. Specifications of Mg^{26} as provided by the Oak Ridge National Laboratory

Using the values of the atomic masses as given by Bethe¹, the theoretical Q-values for the various proton-induced reactions were calculated and tabulated in Table 2. The (p, γ) reaction is the only one that shows a Q-value of greater than -2.0 Mev and is therefore the only one of the listed reactions which is

possible with protons of the energies available from the Ohio State University Van de Graaff generator. Gamma-rays of low energy might also be produced by inelastic scattering of protons by the Mg^{26} nuclei.

Reaction	Q-Value (Mev)
(p, γ)	+ 7.5 $\pm$ 0.9
(p,n)	- 3.6 $\pm$ 1.7
(p, α)	- 2.0 $\pm$ 0.5
(p,d)	- 9.9 $\pm$ 1.0

Table 2. The Calculated Q-Values for Various Reactions

The compound nucleus formed from Mg^{26} by a (p, γ) reaction is Al^{27} , the only stable isotope of aluminum. The reaction is thus assumed to be:

The source of protons for inducing this reaction was the Van de Graaff generator at The Ohio State University. The energy of the incident protons was varied from 300 kev to 1500 kev and the yield of gamma-rays was measured as a function of the energy

of the bombarding protons.

II. HISTORICAL BACKGROUND

In 1939 Curran and Strothers² studied proton capture reactions in natural magnesium. They used a Philips generator at the Cavendish High Voltage Laboratory as a source of protons with energies up to 1000 kev. The protons were separated from the remainder of the beam by magnetic analysis. Two Geiger-Müller tubes were used in coincidence to detect the gamma-radiation.

Relatively thin targets were made by evaporating pure magnesium metal in a vacuum and thicker targets were prepared by burning magnesium in air and collecting all of the products of combustion on copper backing.

In natural magnesium the following proton capture reactions should be possible:

Curran and Strothers assumed that reaction (A) was not excited. They therefore attributed all gamma-ray resonances that were accompanied by positron activity to reaction (B) and all gamma-ray resonances that were not accompanied by positron activity to reaction (C). The assumption that reaction (A) was not excited was based upon the fact that the isotope Al^{25} was unknown at that time and the observation that all of the half-life measurements gave values approximately equal to the accepted value for the half-life of Al^{26} . The results reported by Curran and Strothers for Mg^{26} are given in Table 3.

Resonance Energy	Gamma-Ray Energy (Endpoint)	Gamma-Ray Energy (Half-Value)
580 kev	4.9 Mev	3.0 Mev
680 kev		
1000 kev		

Table 3. Data on the Reaction $\text{Mg}^{26}(\text{p}, \gamma)\text{Al}^{27}$ by Curran and Strothers².

Unfortunately, the voltage uncertainty in the

beam used by Curran and Strothers was so large and their targets were so thick that it is extremely difficult to correlate their results with those obtained by Tangen³ and with those in the present paper.

In 1946 Tangen published results obtained by the bombardment of thin targets of natural magnesium with protons from a Van de Graaff generator having a maximum energy of 550 kev. He estimated that the thickness of his targets was between 5 and 10 kev.

Tangen counted the gamma-radiation and the positron activity by means of Geiger-Müller tubes. For gamma-ray detection he used anti-coincidence methods so as to be able to detect resonances which had extremely low yields. The proton beam that he used had a maximum current of 11 microamperes.

In a similar manner to that of Curran and Strothers, Tangen attributed all of the gamma-ray resonances that were not accompanied by positron decay to Mg^{26} . However, he did indicate that there was a strong likelihood that two of the positron resonances were the result of proton bombardment of Mg^{24} rather than of Mg^{25} . He arrived at this conclusion through measurements of the energies of the gamma-ray activity.

The work of Tangen is exceptionally good in the

low energy region but is limited to proton energies below 550 kev. Above this relatively low energy, the spectrum has not been explored thoroughly prior to the present experiments undertaken by the electrostatic generator group at The Ohio State University. The results obtained by Tangen for Mg^{26} are given in Table 4.

Resonance	Gamma-Ray Energy	Relative Yield	Resonance Width
290 kev		0.05	
314 kev	4.9 Mev	0.15	
336 kev	4.9 Mev	1.95	< 1 kev
388 kev		0.22	
430 kev		0.45	
451 kev	6.2 Mev	4.05	< 1 kev
494 kev		0.20	

Table 4. Data on the Reaction $\text{Mg}^{26}(\text{p}, \gamma)\text{Al}^{27}$ by Tangen^{3,4}.

III. DESCRIPTION OF EQUIPMENT

General Features of the Van de Graaff Generator

The Van de Graaff generator used for this experiment is a horizontal, pressure-insulated type generator of conventional design. The pressure tank is 20 feet in length and 5 feet in diameter. It is designed to operate at a pressure as high as 150 pounds per square inch. The insulating gas may be pumped into the tank from an outdoors storage tank or circulated through a Pittsburgh Electrodryer, Type AAC, Size 25, and through an F-10 Electrofilter. The gas used has been carbon dioxide, nitrogen, or a mixture of the two.

The accelerating tube consists of 46 glazed porcelain sections separated by steel accelerating plates. The voltage is distributed throughout the length of the accelerating tube by means of a string of corona points. The corona gaps for the first two accelerating sections may be adjusted independently during operation and serve as one of the two main methods of focussing the beam.

The electrostatic charge is supplied at the ground end of the tank by a 40 kilovolt power supply and is sprayed onto the belt from a system of needle

points. An induction-type spray system is employed at the high voltage end to increase the charging capacity. The high voltage electrode is cylindrical with a spherical end. The diameter of the cylinder is 30 inches and the overall length of the electrode is 43 inches.

The proton source used is a conventional source of the type developed by the Westinghouse Research Laboratories using an oxide-coated filament and a plate voltage of 150 volts to maintain an arc in a hydrogen atmosphere. The probe voltage to draw the protons out of the source may be varied from 0 to 5000 volts and provides the second method of focussing the beam.

Analyzing Magnet and Voltage Measurement

The analyzing magnet serves two functions as used with the electrostatic generator at Ohio State University. Its primary function is the separation of protons of a desired energy from the remainder of the beam. Its secondary function is that it serves as a means of measuring the accelerating voltage.

The magnet has pole pieces that are 8 inches long, 4.5 inches wide, and are separated by an air

gap of 1.5 inches. The coil on each pole has 5,000 turns of No. 14 copper wire. The magnet is designed to produce a maximum field of 15,000 gauss.

The brass analyzing chamber (shown in Figure 1) has five exit ports for components of the beam. In normal operation the chamber is aligned so that the beam is centered on the central port with the magnet current at zero. When the magnet current is adjusted so that the proton beam is centered in the outer port, the beam consisting of the singly-ionized hydrogen molecules falls on the inner port. A vycor glass window is normally used at the end of the H_2^+ port so that the H_2^+ beam may be visually aligned.

The accelerating voltage is measured in terms of the current flowing in the coils of the analyzing magnet. This current is read by determining the potential difference across a standard one ohm resistance with a Leeds and Northrup Type K potentiometer. The accelerator voltage when read in this fashion is highly reproducible over long periods of time, providing one always remains on the same hysteresis curve. The voltage calibration data are given in Section V of this paper.

A generating voltmeter is used for a rough

reference voltage reading. This voltmeter is mounted in the pressure tank near the high voltage electrode. Its alternating current output is read by means of a Ballentine Voltmeter. This reading varies slightly with pressure and corona conditions inside of the tank and is not accurately reproducible.

Current Integrator

The number of protons per second striking the target is determined during operation by collecting the charge in a Faraday Cage (shown in Figure 1). This charge is drained off through a current integrator and thyatron recorder of the type designed by Dunning⁵. This current integrator was calibrated against a Leeds and Northrup galvanometer which had a current sensitivity of 0.048 microamperes per millimeter deflection.

Gamma-Ray Detection Equipment

The emitted gamma-radiation was detected by means of a Technical Associates Type TA-B1 thin-walled Geiger-Müller tube. Pulses from this tube were re-

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ANALYZING CHAMBER AND TARGET ASSEMBLY
FIGURE 1

corded by a Tracerlab Mark II Autoscaler. The position of the Geiger-Müller tube relative to the target is shown in Figure 1. The tube was enclosed in a 2 inch thick lead box to shield it from extraneous radiation. The normal background count with the generator running, but with the beam not on the target, was about 20 counts per minute.

IV. PREPARATION OF TARGETS

In order to make the targets for this particular experiment there were several special problems that had to be overcome. First of all, the very small quantity of the separated isotope available (0.055 grams) made it extremely vital that the first attempt at making targets should be successful. To accomplish this end the techniques to be employed were carefully tested and perfected with natural magnesium oxide before any experiments were attempted with the separated isotopes.

It was desired to make relatively thin targets of Mg^{26} by evaporation in a vacuum followed by condensation on suitable target backing. One of the most serious problems which had to be overcome before such

plating could be accomplished was brought about by the fact that the separated isotopes were received in the oxide form. MgO has a very high melting point (2500° - 2800° C.). This ruled out the use of any common sort of coated basket to hold the oxide during the evaporation.

Because of this high melting point two methods were tried to reduce the magnesium oxide in a vacuum and thus to evaporate pure magnesium metal. The first method of reduction, which was described by Slade⁶, was to mix powdered carbon with the magnesium oxide. When heated in a vacuum to about 1900° C., magnesium was reported to be released according to the following reaction:

The second method of reduction, described by Matignon⁷, is similar in nature. For this reaction a mixture of powdered calcium carbide and magnesium oxide was heated in a vacuum to about 1400° C. The reaction expected is given in Equation (3).

Both of the above reactions were tried but were only partially successful. In each case it was possi-

ble to plate targets but it turned out that these targets consisted of a compound which proved to be so deliquescent that it was felt that they would be unsatisfactory since they would tend to deteriorate as soon as they were exposed to the atmosphere. It is possible that proper conditions might be found which would allow good targets to be plated by either of these reduction methods.

Another method that was tried and abandoned was the making of magnesium chloride targets. The magnesium oxide was dissolved in hydrochloric acid to form the chloride according to the reaction:

Since the magnesium chloride has a low melting point (708° C.), it was relatively easy to evaporate the chloride in a vacuum to plate the targets. However, the magnesium chloride targets were also much too deliquescent to be used.

A further method that was considered was the electrolysis of fused magnesium chloride to liberate magnesium metal at the cathode. This method was not actually attempted because of the extremely small quantity of the separated isotope that was available.

The method finally settled upon for the actual

preparation of the targets was the decomposition of MgO at high temperatures in a vacuum. In the earlier trials the magnesium oxide was heated in a shallow trough of tungsten that was placed in a vacuum chamber. At the necessary high temperature the tungsten apparently reduced the magnesium oxide since the tungsten trough became pitted and an oxide of tungsten was plated on the targets along with the magnesium. This was somewhat undesirable since the presence of the tungsten would cause the targets to be thicker without increasing the yield. Further experiments with this method led to the use of a tantalum strip instead of the tungsten trough. The tantalum had the advantage that it did not seem to plate an appreciable amount of tantalum oxide on the targets.

The arrangement for the plating of the targets is shown in Figure 2. The tantalum "basket" consisted of a horizontal strip of tantalum, 0.0015" thick, 0.5" wide, and 0.75" long which was fastened between heavy copper electrodes. About 0.015 grams of magnesium oxide was spread in a thin layer on this strip and the target blanks to be plated were placed directly above the basket at a distance of about 2 inches. The tantalum was heated by passing a high current

(about 30 amperes) through it from a low-voltage, high-current transformer. The primary of the transformer was supplied from a variac so that the temperature of the basket could be gradually increased until the evaporation started.

Six target blanks were grouped above the basket so that all six could be plated simultaneously to conserve the separated isotope as much as possible. These target blanks consisted of tantalum disks, 0.005" thick and having a diameter of 0.875". Immediately before they were placed in the vacuum system the blanks were cleaned by being immersed in successive baths of hydrochloric acid, water, and acetone. It was found that the quality of the targets depended strongly upon the cleanliness of the surface upon which they were plated.

The target blanks were mounted on a large sheet of copper which was cooled by circulating water to prevent the target blanks from being unduly heated by the radiation from the incandescent basket.

The vacuum was maintained at approximately 10^{-5} cm. of Hg. during the plating process by means of an oil diffusion vacuum pump (Distillation Products Incorporated, Type Mf-250). The vacuum was monitored at all times by a Distillation Products Incor-

porated VG-1A ionization gauge and associated circuit. It was possible to tell from changes in the vacuum when the actual evaporation started.

From the appearance of the targets and by tests with acids on the substance which plated on the inside walls of the vacuum chamber, it seems certain that the targets were composed primarily of magnesium metal. Whether this is due to the reduction of the oxide by the tantalum basket, decomposition of the oxide upon going into the gaseous state, or a mixture of both processes is not known. No chemical analysis of the targets has been made but there exists a strong possibility that there are small amounts of magnesium oxide and tantalum oxide on the targets along with the metallic magnesium.

V. EXPERIMENTAL RESULTS

Method of Taking Data

The method used in taking the data was the same for the spectrum of lithium fluoride which was taken for voltage calibration purposes and for the spectrum of Mg^{26} . In taking each reading the magnet current

TARGET PLATING APPARATUS

FIGURE 2

was first set to a given value as read on the Type K potentiometer. The accelerating voltage was then adjusted until the proton beam was falling on the target. When this condition was attained, a switch was thrown which simultaneously started the Autoscaler to recording the pulses from the Geiger-Müller tube and the current integrator to recording the number of protons falling on the target. When a predetermined number of Geiger-Müller pulses were recorded by the scaler, it automatically stopped and also stopped the current integrator. The operator then tabulated; (1) the length of time of the run, (2) the number of integrator counts, and (3) the number of counts from the Geiger-Müller tube. The relative gamma-ray yield was then computed from the formula:

$$\text{Relative Yield} = \frac{\text{Geiger-Müller Counts} - \text{Time}/3}{\text{Integrator Counts}} \quad (5)$$

The factor, $\text{Time}/3$, was the average value of the time-dependent background count from the Geiger-Müller tube taken with the Van de Graaff generator running but with the beam not striking the target.

The number of Geiger-Müller counts to be recorded on each run was determined by the amount of activity

of the target at the given accelerator voltage. It was set so that each run would be approximately one minute in length. Each point was repeated several times to improve the accuracy of the data.

The setting of the magnet current was varied by steps of 0.00125 amperes in regions where there was resonant activity and by steps of 0.00250 amperes in regions of no activity. A change of 0.00125 amperes corresponds to an accelerator voltage change of about 2 kev at 800 kev energy.

During the taking of the data the average proton beam current varied from about 0.33 microamperes to 0.60 microamperes, depending upon the voltage region. The method of controlling fluctuations in the voltage was of the most elementary nature. Large voltage fluctuations having a long period were compensated for by manual operation of a potentiometer in the primary of the belt-charging transformer. Small fluctuations having a short period were damped to some extent by a set of grounded needle points which could be lowered inside of the pressure tank to a position opposite the high voltage electrode. These needle points were adjusted for a given voltage range to the position which would give the most stable beam of protons.

Voltage Calibration

The current in the magnetic analyzer was calibrated by means of the relatively accurately known resonances in lithium and fluorine. For purposes of this calibration a thin target of lithium fluoride was used. This target had an energy thickness of about 15 kev for incident protons having an energy of 1 Mev.

For calibration points the lithium resonance level at 440 kev and the fluorine resonance levels at 340, 486, 669, 873.5, 935.3, 1290, 1355, and 1381 kev were used. The energy values assigned to the above resonances are those given by Hornyak, Lauritsen, Morrison, and Fowler⁸. The spectrum from the lithium fluoride target is shown in Figures 3 and 4. For the voltage calibration the square root of the energy of the incident protons is plotted as a function of the magnet current in Figures 5 and 6.

The Spectrum of Mg^{26}

The relative gamma-ray activity from the reaction $Mg^{26}(p,\gamma)Al^{27}$ is plotted as a function of the proton energy in Figures 7 and 8. In Figure 7 the region

GAMMA - RAY YIELD FROM LiF

FIGURE 3

GAMMA - RAY YIELD FROM LiF

FIGURE 4

VOLTAGE CALIBRATION

FIGURE 5

VOLTAGE CALIBRATION

FIGURE 6

between 860 kev and 940 kev has been underscored because the activity in this region is believed to have its origin in small amounts of fluorine contamination on the target. The resonances shown in this region appear on the curves made from all three of the magnesium isotopes and appear to "grow" slightly with time while the targets are being bombarded. Because of this apparent growth, it is felt that this fluorine contamination comes from the vacuum system of the Van de Graaff generator.

In the higher energy portion of the spectrum, shown in Figure 8, the resonance at 1378 kev is underscored for the same reason. It seems probable that this is the strong resonance in fluorine reported at 1381 kev.

The following energies have been assigned to the resonances attributed to the reaction $Mg^{26}(p,\delta)Al^{27}$: 343, 450, 662, 720, 813, 840, 954, 992, 1015, 1056, 1127, 1255, 1295, 1425, and 1464 kev. Tangen³ has previously reported resonances at 336 and 451 kev which are in good agreement with our results. Correlation with the work of Curran and Strothers² is difficult because of the width of the resonances shown in their curves. The resonances shown in their curves have

a width at half-maximum intensity of over 100 kev.

The observed widths of the resonances in Figures 7 and 8 of this paper vary from about 12 kev to 25 kev at half-maximum intensity. Calculations of the target thickness and the energy spread in the proton beam are made in a later section of this paper. Also, an attempt is made to find the natural width of the resonance at 450 kev from a thick target curve which was run in this region on natural magnesium oxide.

The energy assignments for the resonances are not corrected for the thickness of the target. Likewise, the resonances from the lithium fluoride target used for the voltage calibration were not corrected for target thickness. In each case the target thickness was approximately the same so that the error introduced by not correcting for the target thickness is minimized. It is believed that the absolute error in the voltage assignments is less than 10 kev in all cases and that the relative spacing of the levels is correct to within 5 kev in all cases.

Energy of Gamma-Rays

The energies of the gamma-rays emitted from some

GAMMA - RAY YIELD FROM Mg^{26}

FIGURE 7

GAMMA-RAY YIELD FROM Mg^{26}

FIGURE 8

of the resonances which have relatively high yields were measured by two separate methods. These methods are discussed in the order that the experiments were carried out.

The first method attempted was the direct absorption of the gamma-rays by known thicknesses of lead and copper. The apparatus used for this absorption is indicated in Figure 9. Since gamma-ray absorption follows the well-known exponential law, $I = I_0 e^{-\mu x}$, it should be possible to find the absorption coefficient, μ , for a given absorbing material as the slope of a straight line on a plot of $\log I$ versus x . Shown in Figure 10 are the absorption curves of the 6.2 Mev gamma-rays emitted from the 340 kev resonance induced in F^{19} and the 1.16 and 1.33 Mev gamma-ray cascade from a Co^{60} source which were made for reference purposes. Absorption curves were plotted for the resonances at 450, 813, 840, and 1015 kev resonances induced in a Mg^{26} target. Examples of these curves are shown in Figure 11.

If the gamma-ray beam were narrowly collimated, it would be immediately possible to arrive at a good value for the energy of the gamma-rays by finding the energy which corresponds to the observed μ on a set of standard μ versus energy curves. However,

TARGET ASSEMBLY FOR GAMMA-RAY
ABSORPTION MEASUREMENTS

FIGURE 9

the geometry used in this case comes under the classification of "bad geometry". By this it is meant that the collimation was so poor that a very large portion of the scattered radiation was still counted by the Geiger-Müller tube. This has the effect of always making the slope of the observed absorption curves too shallow. Therefore, the observed absorption coefficient, μ_{ob} , will be low as compared to the true absorption coefficient. In fact, μ_{ob} , the observed coefficient, should always fall between the values of μ and $\mu - \sigma_s$, where σ_s is the Compton scattering coefficient.

In interpreting the data the approximation was made that, for gamma-rays of given energy and for a fixed geometry, the same percentage of the scattered radiation from copper and lead absorbers would be counted. On the basis of this assumption, it was possible to make a reasonable assignment of energy to the gamma-rays emitted at the various resonances.

The greatest single difficulty in taking accurate data of this type was due to the fact that only thin targets of Mg^{26} were available. Thus, over extended periods of time it was very difficult to hold the accelerator voltage exactly on the peak of a given

ABSORPTION OF 6.2 MEV GAMMA-RAYS FROM FLUORINE

ABSORPTION OF 1.16 AND 1.33 MEV GAMMA- RAYS FROM COBALT⁶⁰

FIGURE 10

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ABSORPTION OF GAMMA-RAYS FROM 450 KEV RESONANCE INDUCED IN Me^{26}

ABSORPTION OF GAMMA-RAYS FROM 813 KEV RESONANCE INDUCED IN Me^{26}

FIGURE II

narrow resonance. To help minimize this difficulty a wide slit (about 1/8 inch) was employed to allow a relatively large voltage spread in the beam.

Measurements made in this manner indicated that the compound nuclei formed at some or all of the resonances did not go to the ground state by a single transition. If true, this is an important observation. It was felt that measurements made by another method might serve to verify this tentative conclusion and also to improve upon the accuracy of the gamma-ray energy measurements.

The second method for measuring the gamma-ray energies was a coincidence method similar to that employed by Fowler, Lauritsen, and Lauritsen⁹. This method is based on the fact that in order for a Geiger-Müller tube to count a gamma-ray, the pulse must be triggered by some secondary electron, either a photoelectron, a Compton recoil electron, or a member of a pair. Therefore, it should be possible to arrange two Geiger-Müller tubes in coincidence so that a coincidence count would be recorded only when a single secondary electron passes through both tubes. Such an arrangement is shown in figure 12. Two Geiger-Müller tubes were used in parallel instead of a single rear tube to increase the useful solid angle and thus increase

the number of coincidences. To measure the energy of the secondary electrons, thin foils of aluminum were inserted between the front and rear Geiger-Müller tubes.

Counts from the front tube were recorded on a Tracerlab Mark II Autoscaler. The pulses were taken from the amplifier of the Autoscaler and fed directly into one channel of an Atomic coincidence circuit, Model 502. The rear Geiger-Müller tubes were connected in parallel so that the pulses from either of these tubes were fed into an Atomic scaling circuit, Model 1030. Pulses were taken from this scaling circuit and fed into the input of an Atomic pulse amplifier, Model 201A. The output of this amplifier was fed into a second channel of the coincidence circuit. The output of the coincidence circuit was put into a Technical Associates scaling circuit which recorded the coincidences.

In taking the data 4096 counts were recorded by the first Geiger-Müller tube for each thickness of absorber and the number of coincidences was recorded for each run. Then, the number of coincidences was plotted as a function of the absorber thickness.

If the number of counts recorded by the first Geiger-Müller tube remains constant, this method gives

data that are less dependent upon voltage instability in the beam than those obtained by gamma-ray absorption methods. However, the method does require some sort of a calibration since the slope of the curve is quite dependent upon the positions of the target, radiator, and absorbers with respect to the Geiger-Müller tubes as well as upon the complexity of the radiation for the given resonance.

For calibration purposes data were taken using this method on the 6.2 Mev radiation from a fluorine target and the 17.5 Mev radiation from lithium. The resulting absorption curves are shown in Figure 13. From these curves calibration curves were drawn in a manner similar to that employed by Fowler, Lauritsen, and Lauritsen⁹. From the absorption curves of the secondary electrons resulting from the gamma-rays from lithium and fluorine, the values of the absorber thickness are plotted in each case that will reduce the number of coincidence counts to $0.7N_0$, $0.6N_0$, $0.5N_0$, and $0.4N_0$ respectively, where N_0 is the number of coincidence counts with no absorber in place. Through these four sets of points four straight lines are drawn which may then be used to find the energy of any gamma-rays by measuring the absorber thickness

which is required to reduce the number of coincidence counts to any one of the above four values. The calibration curves are shown in Figure 14.

Energy measurements were made using the coincidence method for the gamma-rays emitted from the resonances induced in Mg^{26} by protons of 450, 813, 840, 954, and 1015 kev respectively. Typical absorption curves among these are shown in Figure 15. The summary of the energy measurements from both methods is given in Table 5.

Resonance Energy (kev)	Energy by Absorption of Gamma-Rays (Mev)	Energy by Absorption of Secondaries (Mev)
450	6.0	5.9
813	7.5	7.2
840	5.5	5.3
954		7.3
1015	5.3	5.5

Table 5. Summary of Gamma-Ray Energy Measurements.

It is believed that the values of the energies given are correct to within ± 0.5 Mev in all cases.

COINCIDENCE ARRANGEMENT FOR GAMMA-RAY ENERGY MEASUREMENTS

FIGURE 12

ABSORPTION OF SECONDARY ELECTRONS
FROM LiF

FIGURE 13

CALIBRATION CURVES

FIGURE 14

ABSORPTION OF SECONDARY ELECTRONS
FROM Mg^{26}

FIGURE 15

VI. INTERPRETATION OF THE DATA

Calculation of the Absolute Yield

One of the most important pieces of information that may be obtained from a relative yield curve such as that shown in Figures 7 and 8 is the cross-section at resonance, σ_R . In order to find σ_R it is first necessary to find the absolute yield, Y , which is defined as the number of gamma-rays emitted per incident proton. To compute the absolute yield it is necessary to know: (1) the number of gamma-rays counted during time, t , (2) the number of incident protons during the same time, t , (3) the effective solid angle subtended by the Geiger-Müller tube, and (4) the efficiency of the Geiger-Müller tube for gamma-rays of the given energy.

The number of gamma-rays counted during time t is taken from the relative yield curve. The number of incident protons during this time may be computed from the current integrator count by calibrating the integrator against a sensitive galvanometer. This calibration showed that there are 10.9 integrator counts per micro-coulomb of incident charge. This is then equivalent to 57.3×10^{10} protons per inte-

grator count.

The effective solid angle subtended by the Geiger-Müller tube is difficult to compute because the source of the gamma-rays is so close to the Geiger-Müller tube. The approximate effective solid angle was determined by use of an equation given by Norling¹⁰ for calculating the solid angle subtended by a cylindrical counter with a point source in close proximity to it. This equation is:

$$\bar{\Omega} = \frac{1}{\pi} \tan^{-1} \frac{eR}{\sqrt{a^2 - R^2} \sqrt{e^2 + a^2 - R^2}} + \Delta \bar{\Omega} \quad (6)$$

$$\text{where: } \Delta \bar{\Omega} = \frac{eR^2}{A^{1/2}} \left[\left(\frac{\pi}{4} - \frac{1}{2} \sin^{-1} \frac{a}{R} \right) - \frac{a}{2R} \left(1 - \frac{a^2}{R^2} \right)^{1/2} \left(1 - \frac{9R^2}{2A} \right) + \frac{aR}{A} \left(1 - \frac{a^2}{R^2} \right)^{3/2} \right]$$

where: R = the inside radius of the counter

e = half of the counting tube's effective length

a = the distance from the tube's axis to the source

$$d = \frac{R^2}{a}$$

$$A = e^2 + a^2$$

For the geometry used in this work these variables

had the following values:

$$R = 0.95 \text{ cm}$$

$$\alpha = 0.429$$

$$\bullet = 2.5 \text{ cm}$$

$$A = 10.66$$

$$a = 2.10 \text{ cm}$$

Substitution of the above values into Equation (6) gives the result:

$$\Phi = 0.122 \pm 0.007 = 0.129 \quad (7)$$

Because the resonance at 450 kev is well isolated and has a relatively high yield, it was decided to compute the cross-section for this resonance. The energy of the gamma-rays from this resonance was found to be about 6 Mev. Therefore, the efficiency of the Geiger-Müller tube will be almost the same as its efficiency for the gamma-rays from fluorine which have an energy of 6.2 Mev.

It is possible to arrive at a reasonable figure for the efficiency of the Geiger-Müller tube for 6.2 Mev gamma-rays if one assumes a value of the cross-section for a well known fluorine resonance and then measures the relative yield of this resonance with a target of known thickness. The cross-section used is that given by Hornyak, Lauritsen, Morrison, and Fowler⁸ for the fluorine resonance at 669 kev.

In order to make such a calculation of the efficiency one may use the Breit-Wigner dispersion formula. The absolute yield for a resonance is given by the integral:

$$Y = \int_{E - \varrho}^E \frac{\sigma}{\epsilon} dE \quad (8)$$

where: ϵ = the stopping cross-section for the incident particle per disintegrable nucleus.

ϱ = the energy loss of the beam of protons in passing through the target.

It is assumed that ϵ and ϱ are independent of E across the resonance and therefore:

$$\varrho = n\epsilon \quad (9)$$

where: n = the number of disintegrable nuclei per square centimeter of the target.

In order to integrate Equation (8) it is assumed that σ follows the Breit-Wigner dispersion equation: (See the treatment by Fowler, Lauritsen, and Lauritsen⁹)

$$\sigma = \sigma_R K \frac{\Gamma^2/4}{(E - E_R)^2 + \Gamma^2/4} \quad (10)$$

where: σ_R = the cross-section at resonance

Γ = the full width of the resonance at half-maximum intensity.

E = the proton energy.

E_R = the proton energy at resonance.

K = a function that varies slowly with energy.
For $E = E_R$, $K = 1$ so that for a narrow resonance such as those induced in magnesium, it may be assumed that $K = 1$.

If the above value for σ is inserted in Equation (8), the integration yields:

$$Y(Q) = \frac{\sigma_R}{2\epsilon} \left\{ \tan^{-1} \frac{E - E_R}{\Gamma/2} - \tan^{-1} \frac{E - E_R - Q}{\Gamma/2} \right\} \quad (11)$$

The yield is a maximum when $E = E_R + Q/2$:

$$Y_{\max}(Q) = \frac{\sigma_R \Gamma}{\epsilon} \tan^{-1} \frac{Q}{\Gamma} \quad (12)$$

Equation (12) can be used to calculate the absolute yield of a given fluorine resonance by substitution of the appropriate values for σ_R , Γ , ϵ , and Q . It was decided to calculate the absolute yield for the 669 kev resonance in fluorine in order to determine the efficiency of the Geiger-Müller counter for 6.2 Mev gamma-rays.

Using a value of 1.09 for the stopping power of fluorine and a value of 0.50 for the stopping power

of lithium together with a value of 7.2×10^{-18} kev cm² for ϵ_{air} as given by Livingston and Bethe¹¹, the value for the stopping cross-section per nucleus in lithium fluoride becomes $\epsilon = 5.72 \times 10^{-18}$ kev cm². Since only one out of every two nuclei is a fluorine nucleus, the stopping cross-section per fluorine nucleus is:

$$\epsilon_F = 11.45 \times 10^{-18} \text{ kev cm}^2 \quad (13)$$

From the observed resonance width of the 669 kev resonance in fluorine as taken from Figure 3, the thickness of the fluorine target, φ_F , can be derived by use of the relationship:

$$\Gamma' = (\Gamma^2 + \varphi_F^2 + dE^2)^{\frac{1}{2}} \quad (14)$$

where: Γ' = the observed resonance width.

Γ = the actual resonance width

φ_F = the thickness of the lithium fluoride target.

dE = the energy spread of the beam.

As Γ' taken from the 669 kev resonance in Figure 3,

$\Gamma' = 15$ kev. The actual width for this resonance is given by Hornyak, Lauritsen, Morrison, and Fowler⁸ as equal to 7.5 kev. An expression developed by Smith¹² gives a theoretical value for the maximum

voltage spread of the proton beam for the Van de Graaff generator used in this experiment:

$$dE = \left\{ \frac{2dr}{r} + \frac{2dI}{I} \right\} E \quad (15)$$

where: r = the radius of curvature of the proton beam in the magnetic field of the analyzer.

dr = the increment in r introduced by the width of the defining slit.

I = the magnet current

dI = the maximum fluctuation in the magnet current during normal operation.

For a slit width of 0.4 mm and a maximum fluctuation in the magnet current, $dI = 0.002$ amperes:

$$dE = \left\{ 0.002 + \frac{0.004}{I} \right\} E \quad (16)$$

For the 669 kev resonance in fluorine, $I = 0.725$ amperes. Therefore, at this energy:

$$dE = 5 \text{ kev} \quad (17)$$

Substitution of the above values for Γ' , Γ , and dE into Equation (14) gives:

$$\theta_F = 12 \text{ kev} \quad (18)$$

Using a value of $\sigma_R = 3.2 \times 10^{-26}$ as given by Hornyak-

Lauritsen, Morrison, and Fowler⁸ for this resonance in Equation (12) gives:

$$Y_{\max}(12) = \frac{3.2 \times 10^{-26} \times 7.5}{11.45 \times 10^{-18}} \tan^{-1} \frac{12}{7.5} \quad (19)$$

$$Y_{\max}(12) = 2.1 \times 10^{-8} \text{ gamma-rays/proton.} \quad (20)$$

The relative maximum for this resonance, $y_{\max}$, is shown in Figure 3 to be 60 Geiger-Müller counts/integrator count which is equivalent to 10.7×10^{-11} Geiger-Müller counts/proton. The relative yield is related to the absolute yield by the product of the efficiency of the Geiger-Müller counter and the effective solid angle subtended by it:

$$y_{\max} = k \Phi Y_{\max}(12) \quad (21)$$

$$\text{Therefore: } k \Phi = \frac{10.7 \times 10^{-11}}{2.1 \times 10^{-8}} = 0.0051 \quad (22)$$

But from Equation (7), $\Phi = 0.129$. Therefore, the efficiency of the Geiger-Müller tube for 6.2 Mev gamma-rays is:

$$k = 4.0\% \quad (23)$$

This value agrees well with the value given by Fowler, Lauritsen, and Lauritsen⁹ for a similar type of Geiger-Müller tube.

All of the information necessary to calculate the absolute yield from the thin target for the 450 kev resonance in Mg^{26} is now available. Taking the value of the maximum relative yield, $y_{\max}$, from Figure 7 and converting it to gamma-rays counted per incident proton yields; $y_{\max} = 5.69 \times 10^{-12}$ Geiger-Müller counts per proton. Using the value just found for $k\Phi$ gives:

$$Y_{\max}(\varphi) = \frac{5.69 \times 10^{-12}}{k\Phi} = \frac{5.69 \times 10^{-12}}{5.1 \times 10^{-3}}$$

$$\underline{Y_{\max}(\varphi) = 1.12 \times 10^{-9} \text{ gamma-rays/proton}} \quad (24)$$

Equation (24) gives the calculated value for the absolute yield of the 450 kev resonance in Mg^{26} for the thin target used in taking the data.

Calculation of Cross-Section

It is possible to calculate the cross-section at resonance from the absolute yield by means of Equation (12) providing one knows Γ , the natural width of the level; ϵ , the stopping coefficient per disintegrable nucleus in the target; and φ , the thickness of the target.

One of the ways to find a value for the natural width of the level is to run a thick target curve over the same resonance. Then the energy interval between points at which the yield is 1/4 and 3/4 maximum is a measure of the energy spread of the beam and the natural width of the level according to the relationship:

$$\Delta E = (\Gamma^2 + dE^2)^{\frac{1}{2}} \quad (25)$$

where: ΔE = the energy interval from the curve.

Γ = the natural width of the resonance.

dE = the energy spread of the beam.

With the substitution of the values for a slit width of 0.6 mm in Equation (15), the maximum computed energy spread of the beam at 450 kev energy is: $dE = 4.5$ kev.

Since there was not available sufficient Mg^{26} to prepare a thick target, a thick target of natural MgO was prepared. The resonance in Mg^{26} at 450 kev is sufficiently isolated to make a thick target of the natural magnesium oxide usable. The portion of the thick target curve is shown in Figure 16. For the 450 kev resonance on this curve, $\Delta E = 5$ kev. Therefore:

$$25 = (\Gamma^2 + 4.5^2)^{\frac{1}{2}} \quad (26)$$

GAMMA-RAY YIELD FROM
THICK MgO TARGET

FIGURE 16

From Equation (26):

$$\Gamma = 2 \text{ kev} \quad (27)$$

From the thin target curve shown in Figure 7 the observed width of this resonance is 15 kev. Substituting the above values for Γ' , Γ , and dE in Equation (14) and solving for the thickness of the thin target, φ , yields:

$$15 = (2^2 + \varphi^2 + 4.5^2)^{\frac{1}{2}}$$

From which:

$$\varphi = 14 \text{ kev} \quad (28)$$

If it is assumed that the thin target consists primarily of pure Mg^{26} , the stopping cross-section, ϵ , at 450 kev is $11.81 \times 10^{-18} \text{ kev cm}^2$ as taken from curves by Livingston and Bethe¹¹.

Substitution of the values for $Y_{\max}(\varphi)$, Γ , φ , and ϵ in Equation (12) yields a value for the cross-section at resonance:

$$1.12 \times 10^{-9} = \frac{2 \sigma_R}{11.81 \times 10^{-18}} \tan^{-1} \frac{14}{2}$$

From which: $\underline{\sigma_R = 4.6 \times 10^{-27} \text{ cm}^2} \quad (29)$

In the above computation of the cross-section, the value assigned as the natural width of the level

is by far the most uncertain quantity and is most likely to introduce the largest error. If the true value of Γ is 1 kev instead of the calculated value of 2 kev, the computed value of σ_R is 100% too low. If the true value of Γ is 4 kev, the above value of σ_R is 50% too high. It is believed that the true value of σ_R should fall within these limits of error.

Interpretation of Gamma-Ray Energy Measurements

In a (p, γ) reaction the excited levels of the compound nucleus are given by the relationship:

$$E_n = M_1 + M_p - M_f + \frac{M_1}{M_1 + M_p} E_R \quad (30)$$

where: M_1 = the mass of the target nucleus.

M_p = the mass of the proton.

M_f = the mass of the compound nucleus.

E_R = the proton energy at resonance:

In this particular case the masses as given by Bethe¹ are:

$$M_1 = M_{\text{Mg}^{26}} = 25.9898 \pm 0.005 \text{ mass units}$$

$$M_p = 1.008123 \pm 0.000006 \text{ mass units}$$

$$M_p = M_{Al,27} = 26.9899 \pm 0.0008 \text{ mass units.}$$

When these are converted to energy units and substituted in Equation (30), the energy of the excited levels is given by:

$$E_n = 7.5 \pm 0.9 + 0.96E_R \quad (31)$$

From the spectrum given in Figures 7 and 8 can be computed the excitation levels in Al^{27} . These excitation levels are tabulated in Table 6. Also given in this table are the energies of the gamma-rays emitted at the resonances upon which energy measurements were attempted.

It is obvious from Table 6 that the excited Al^{27} nuclei do not in all cases go to the ground state by means of a single transition. A possible explanation for this may lie in the spins of the nuclei involved. Al^{27} is assigned a spin of $5/2$ as given by Bethe¹. The spin of Mg^{26} is almost certainly zero since this nucleus has an even number of protons and an even number of neutrons. The spin of the compound nucleus is dependent upon the angular momentum of the proton that is captured with respect to the target nucleus. At low energies, the only protons that are likely to be captured are S-wave protons, i. e., those protons that have $\lambda = 0$.

Energy of Protons in Center-of-Mass System (Mev)	Excitation Levels in Al^{27} (Mev)	Gamma-Ray Energies (Mev)
0.326	7.826	
0.432	7.932	6.0
0.633	8.133	
0.691	8.191	
0.780	8.280	7.2
0.806	8.306	5.3
0.916	8.416	7.3
0.952	8.452	
0.974	8.474	5.5
1.014	8.512	
1.082	8.582	
1.205	8.705	
1.243	8.743	
1.368	8.868	
1.405	8.905	

Table 6. The Excitation Levels in Al^{27}

The minimum energy that protons with $Q > 0$ can have and be captured by the bombarded nucleus can be calculated from the relationship:

$$2\lambda \leq 2\pi R \quad (32)$$

where: λ = the deBroglie wavelength of the proton.

R = the radius of the bombarded nucleus.

The values of λ and R may be found from the equations:

$$\lambda = \frac{h}{(2mE)^{1/2}} \quad R = 1.5 \times 10^{-13} \times A^{1/3}$$

where: h = Planck's constant.

m = the mass of the proton.

E = the energy of the proton in the center-of-mass system.

A = the atomic number of the target nucleus.

For this computation the following numerical values of the above constants were used:

$$\begin{aligned} h &= 6.614 \times 10^{-27} \text{ erg sec} \\ A &= 26 \quad A^{1/3} = 2.962 \\ m &= 1.674 \times 10^{-24} \text{ grams} \end{aligned}$$

Substitution of these values into Equation (32) gives:

$$\underline{E^{1/2} \gtrsim 1.023 \text{ (Mev)}^{1/2}} \quad (33)$$

This calculation shows that the minimum bombarding

energy that will give a high probability for the capture of a P-wave ($l = 1$) proton is about 1 Mev. A D-wave ($l = 2$) proton would have to have an energy of about 4 Mev before it would be likely to be captured.

Thus, for bombarding energies of less than 1 Mev, it is highly probable that the captured protons are S-wave protons. A Mg^{26} nucleus which captured an S-wave proton would form a compound nucleus with total spin $1/2$. A single transition from $Al_{1/2}^*$ to $Al_{5/2}$ would involve a total spin change of $\Delta I = 2$. Such a transition does not have a high probability of occurring. A much more likely mode of transition would be a gamma-gamma cascade. For such a cascade to exist, it is necessary that there be intermediate excitation levels in Al^{27} . A survey of the literature shows that such intermediate levels have been reported from a variety of other experiments. Some of the reactions that have yielded information on this subject are: $Al^{27}(p,p')Al^{27}$, $Al^{27}(d,d')Al^{27}$, $Mg^{26}(d,n)Al^{27}$, and $Mg^{24}(\alpha,p)Al^{27}$.

Three strong low-lying levels have been found by several investigators using all of the above methods. The values of these levels as given by Swann, Mandeville,

and Whitehead¹³ are 0.88, 1.92, and 2.75 Mev respectively. These levels were located by the study of the reaction, $Mg^{26}(d,n)Al^{27}$.

Using these three intermediate levels a tentative transition scheme can be devised which falls well within the experimental error. The computations for such a transition scheme are tabulated in Table 7.

Resonance (kev)	Excitation Level (Mev)	Gamma-Ray Energy (Mev)	Excitation Level Minus Gamma-Ray Energy (Mev)
343	7.813	4.9	2.90
450	7.932	6.0	1.93
813	8.257	7.2	1.06
840	8.283	5.3	2.98
954	8.389	7.3	1.09
1015	8.451	5.5	2.95

Table 7. Table Showing the Experimental Gamma-Ray Energy Data.

Comparison with the excitation levels reported by Swann¹³, et al, makes it appear possible that the resonances at 343, 840, and 1015 kev could well make the transition to the 2.75 Mev intermediate level; the 450 kev level could go to the 1.92 Mev intermediate

level; and that the 813 and 954 kev levels could go to the 0.88 Mev intermediate excitation level. Such a transition scheme is shown in Figure 17. The three low-lying excitation levels have been assigned tentative spectrographic notation on the basis of the shell model for a single excited nucleon.

If it is assumed that on the basis of the calculation in Equation (33) all of the captured protons are S-wave protons, then the levels excited in this manner are all $s_{1/2}$ levels. The parity of the s and d levels is even and the parity of the p and f levels is odd. The selection rules, given by Halliday¹⁴, due to spin and parity considerations require that the transitions to the $p_{3/2}$ level would be electric dipole radiation; the transition to the $f_{7/2}$ level would be electric octupole radiation and the transitions to the $d_{3/2}$ level would be magnetic dipole radiation. The proposed transition to the $f_{7/2}$ level is an unlikely transition due to the fact that the probability of electric octupole radiation is rather low.

VII. SUMMARY

The gamma-ray spectrum of Al^{27} was investigated

ENERGY LEVEL DIAGRAM FOR Al^{27}

FIGURE 17

by the bombardment with protons of a thin target of Mg^{26} throughout the energy range between 300 kev and 1500 kev. In this region 15 well defined gamma-ray resonances were found. These resonances were attributed to the reaction:

This reaction has a theoretical Q-value of 7.5 Mev. The capture cross-section at resonance was computed for the resonance induced by incident protons of 450 kev energy and was assigned the value:

$$\sigma_R = 4.6 \times 10^{-27} \text{ cm}^2$$

Energy measurements were made by absorption of the gamma-rays in lead and copper for four of the resonances and by coincidence methods for five of the resonances. The complete results are tabulated in Table 8.

Continuation of this investigation should prove of value. The spectrum could well be continued to higher energies with expectation that more excitation levels exist in this higher energy region. More accurate gamma-ray energy measurements should furnish more complete information on the mode of transition to the ground state of Al^{27} .

Resonances (kev)	Resonances By Other Investigators (kev)	Gamma-Ray Energies (Mev)	Gamma-Ray Energies By Other Investigators (Mev)
343	336 ³		4.9 ³
450	451 ³	6.0	6.2 ³
662	580 ²		4.9 ²
720	680 ²		
813		7.2	
840		5.3	
954		7.3	
992			
1015		5.5	
1056			
1127			
1255			
1295			
1425			
1464			

Table 8. Summary of the Experimental Results.

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IX. AUTOBIOGRAPHY

I, Leonard Nelson Russell, was born in Coldwater, Michigan, January 15, 1922. I received my secondary school education in the public schools of that city. My undergraduate training was obtained at Kalamazoo College, Kalamazoo, Michigan, from which I received the degree Bachelor of Arts, Cum Laude in 1947. I have been in attendance in the graduate school of The Ohio State University since October, 1947. While in residence at The Ohio State University, I held the position of Graduate Assistant in the Physics Department for one year, the position of Assistant in the Physics Department for one year, and the position of Research Assistant on a Research Foundation Project for two and one-half years while completing the requirements for the degree Doctor of Philosophy.