Gamma-Ray Yield Curve of Aluminum Bombarded with Protons

K. J. BROSTRÖM AND T. HUUS
Institute for Theoretical Physics, University of Copenhagen, Denmark

AND

R. TANGEN
Physical Institute, University of Oslo, Norway

(Received January 29, 1947)

The gamma-ray yield from Al^{27} bombarded with 0.5 to 1.4 Mev protons has been investigated with a sensitive G.M. counter. By introduction of a "cutter" device which automatically stopped the measurements when the voltage deviated more than a certain amount from the desired value, a resolving power of 4 kev was obtained. Under this condition a number of previously known peaks have been resolved into groups of narrow lines. In the investigated region the proton width has been estimated to be less than 1 kev, and a rough estimate of the efficiency of the gamma-ray counter gave a radiation width of the order of 1 ev.

INTRODUCTION

THE reaction $Al^{27}(p, \gamma)Si^{28}$ was first investigated by Herb, Kerst, and McKibben.[1] Using a thick target, they found a number of steps, which indicated the existence of resonance effects. Gentner[2] found two sharp resonances at 425 and 560 kev. Plain, Herb, Hudson, and Warren[3] made a detailed investigation of the excitation curve up to 2.6 Mev, using a thin target. They found a multitude of resonances. Hole, Holtsmark, and Tangen[4,5] have found four weak resonances between 220 and 500 kev.

Starting the work with the newly built Van de Graaff generator of the Institute for Theoretical Physics, Copenhagen, we intended to make a study of the excitation curve of this reaction, with the combined aim of matching the voltage scale with the results of the investigations mentioned above, and of finding new resonances with improved technique of detection.

EXPERIMENTAL

Generator

The pressure-insulated Van de Graaff generator was built with a grant from the Carlsberg Foundation to Professor Bohr. It is of the Lauritsen[6] type and will be described in greater detail at another occasion. The plans were made in 1940, and the collaboration of Dr. T. Lauritsen who at that time worked at this institute was of invaluable help in the design and construction.

The dimensions of the tank are 4.35×2.40 meters, and the maximum pressure is 7 atmospheres. The two belts are 50 cm wide. They have independent motors and spray volt plants. There are 52 corona rings, and 26 sections in the acceleration tube. The ion source is of the capillary

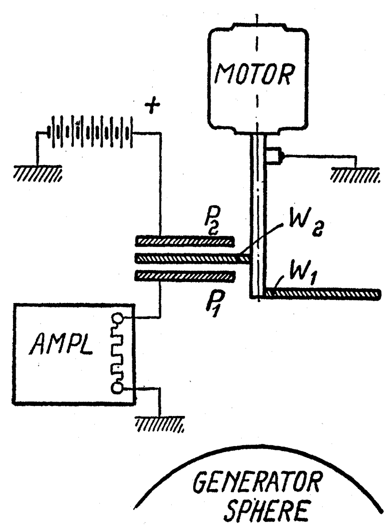

FIG. 1. Rotating compensation voltmeter.

[1] R. G. Herb, D. W. Kerst, and J. L. McKibben, Phys. Rev. **51**, 691 (1937).
[2] W. Gentner, Zeits. f. Physik **107**, 354 (1937).
[3] G. P. Plain, R. G. Herb, C. M. Hudson, and R. E. Warren, Phys. Rev. **57**, 187 (1940).
[4] N. Hole, J. Holtsmark, and R. Tangen, Zeits. f. Physik **118**, 48 (1941).
[5] R. Tangen, Thesis, Trondheim, 1947 (to be published).
[6] T. Lauritsen, C. C. Lauritsen, and W. A. Fowler, Phys. Rev. **59**, 241 (1941).

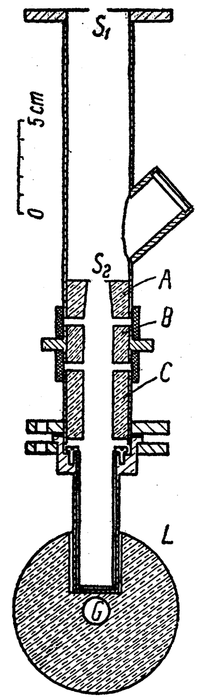

FIG. 2. Target arrangement.

type. The accelerated beam is analyzed magnetically.

A potential of approximately 1800 kv has been obtained with air at 6 atmospheres in the tank.

Voltmeter

The conventional rotating voltmeter measures the charging current of a disk, which is alternately exposed to and shielded from the electrostatic field of the generator dome. The current is directly proportional to the voltage of the generator, but its measurement depends on the reliability of an amplifier or rectifier.

This procedure has been changed into a compensation method using two plates P_1 and P_2 (Fig. 1). When the grounded wings W_1 and W_2 can be rotated without changing the potential of P_1, which is grounded through a resistance, the generator voltage must be strictly proportional to the positive potential of P_2, which is easily measured, being of the order of 1000 volts.

If the compensation is not perfect, P_1 will have a small a.c. voltage. This voltage is amplified and indicated on a small neon lamp of the type used as tuning indicators in wireless sets. The amplified signals from P_1 are also fed to the voltage stabilizer, which is of the McKibben type,[7] and to the "cutter," which blocks both gamma-ray counter and beam integrator when the voltage of the generator deviates more than a prescribed amount from its proper value.

The voltmeter is calibrated by means of the resonance in aluminum at 503 kev, which Tangen[5] has measured with high accuracy, both by comparison with the 440-kev resonance in lithium, and by an independent calibration of his voltage scale. The expected linearity is ascertained by measuring the 503-kev resonance with both protons and the molecular ions H_2^+ and H_3^+.

Beam and target arrangement

The ions were focused to a beam of 3 mm diameter and the current generally used was 1 to 2 μA protons. The current integrator is of the type used by Tangen.[5] It consists of a recorder which counts the pulses in a neon lamp, discharging a condenser constantly charged by the current.

The target arrangement is seen in Fig. 2. S_1 and S_2 are stops of tungsten foil. A, B, and C are lead cylinders, which serve to shield the gamma-ray counter against x-rays from the generator. The bore of these cylinders is greater than the diameter of the stop S_2, so that every ion coming through S_2 must strike the target. B is kept negative in relation to A and C, so that no secondary electrons from S_2 can pass to the target and *vice versa*.

The lowest part of the target tube can be removed for change of target. The target tube can be separated from the main vacuum system by a valve. The target was cooled by securing a good thermal contact between the target disk and the bottom of the lead box L.

The lead box contained a single G.M. counter placed as near to the target as possible. A small tube is preferable in the detection of weak radiation,[5] and a tube of 10-mm diameter and 40-mm length, was used. It was connected to a scale-of-32.

Preparation of targets

Targets were prepared by evaporation of aluminum in vacum on disks of copper or silver,

[7] D. B. Parkinson, R. G. Herb, E. J. Bernet, and J. L. McKibben, Phys. Rev. 53, 642 (1938).

which had been given a fresh and clean surface by being turned carefully with a perfectly clean tool.

As a multitude of targets of different thicknesses had to be used, we have investigated the preparation of targets of known thicknesses in some detail. Because of the smallness of the resonance width, the resonances come out as approximately rectangular curves when the stopping power of the target is much greater than the inhomogeneity in proton energy, and the breadth of this rectangle immediately gives the stopping power of the target. We found the target thickness to be proportional to the amount of aluminum evaporated, so that targets of desired thicknesses could be produced with fairly good accuracy.

In order to estimate cross section values we also determined directly the amount of aluminum in a 25-kev target, and found a specific stopping power of about 250 kev per mg/cm² at 0.5 Mev-proton energy, in accordance with Parkinson, Herb, Bellamy, and Hudson.[8]

The aluminum had a specified purity of 99.998 percent. The targets will of course have an oxide cover, but all measurements of peak heights have been made on 10-kev targets, which we suppose to consist for the most part of metallic aluminum.

MEASUREMENTS

In determining the yield of the gamma-radiation over the energy interval examined, a great number of targets had to be used, since the targets were worn out after 2 to 3 hours of bombardment, even for a proton current of only 1 to 2 μA.

As a standard a target of about 1-kev stopping power at 500-kev proton energy was chosen. Targets of this type were used for all measurements on strong resonances (of intensities above 0.5 in the curve), whereas regions of no, or weak, radiation were searched with targets of about 4-kev stopping power. Finally a number of peaks throughout the spectrum were examined with targets thick enough (about 10 kev) to give saturation intensities. By these measurements the intensities obtained with the thinner targets, which could not be produced with exactly equal thicknesses, were brought to a common scale. The relative intensities of peaks are estimated to be reliable within 20 percent.

In most measurements the cutter was adjusted to allow voltage fluctuations of ± 1.5 kv. With this voltage definition a 1-kev target gives about $\frac{1}{3}$ of the saturation intensity.

The measurements on the 10-kev targets were also used for the establishment of the exact

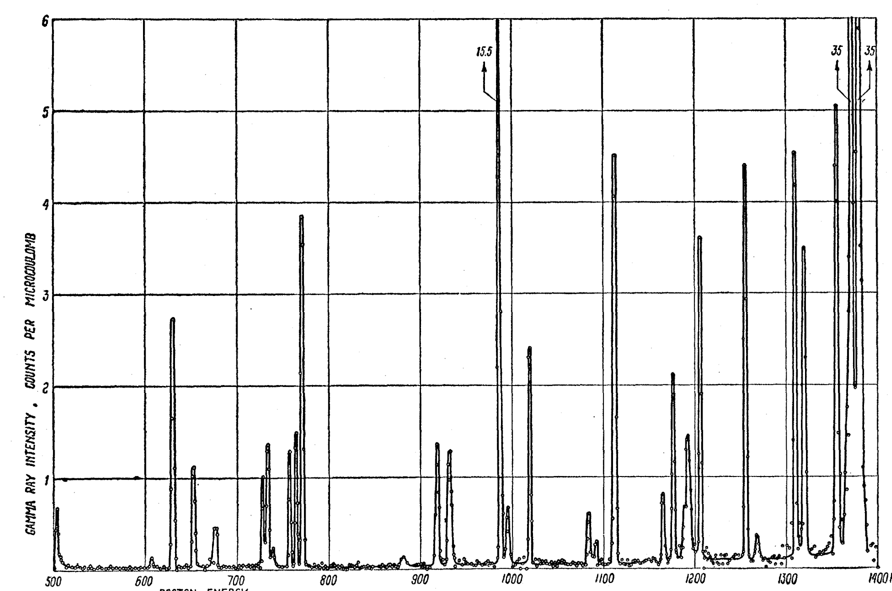

FIG. 3. Yield curve of aluminum bombarded with protons. All peaks have been plotted with the intensities found with the standard targets of about 1-kev stopping power ($\frac{1}{3}$ of saturation intensity), whereas the background has been plotted with the intensities found with 4-kev targets. The natural counting rate has not been subtracted.

[8] D. B. Parkinson, R. G. Herb, J. C. Bellamy, and C. M. Hudson, Phys. Rev. 52, 75 (1937).

TABLE I. The first column gives the energy E in kev of the incident protons at resonance, while the second column contains the directly measured thick target yield N in counts per microcoulomb. The last column gives the quantity $\omega\gamma$ from formula (1), where ω generally is of the order $\frac{1}{2}$, and where γ, except for the weaker resonances, deviates only slightly from the radiation width, when the proton energy exceeds $E\sim 600$ kev.

E kev	N Counts per μC	$\omega\gamma$ ev
225*	0.005	0.4×10^{-3}
295*	0.015	1.3×10^{-3}
325*	0.080	6.0×10^{-3}
404*	0.30	25.0×10^{-3}
443*	0.050	5.0×10^{-3}
503	2.0	0.20
609	0.4	0.05
630	8.2	1.0
652	3.3	0.40
677	1.3	0.15
728	3.0	0.40
733	4.2	0.55
738	0.7	0.10
757	3.8	0.50
764	4.5	0.60
771	11.5	1.6
880	0.5	0.07
918	4.1	0.60
932	3.9	0.60
986	47.0	7.0
994	2.0	0.30
1018	7.2	1.1
1083	1.5	0.25
1091	0.8	0.12
1112	13.5	2.1
1165	2.4	0.40
1176	6.5	1.0
1192	complex	
1205	11.0	1.8
1255	13.0	2.1
1268	1.0	0.15
1309	14.0	2.3
1320	10.5	1.7
1355	15.0	2.5
1372	105.0	17.0
1379	105.0	17.0

* Measured by Tangen[5] and matched to our yield for the 503-kev resonance.

resonance voltage. A simultaneous check of the voltmeter scale was made on the 503-kev resonance with H_1^+, H_2^+, and H_3^+ ions. The voltages given are supposed to be correct within 0.2 percent on our voltage scale, which depends on Tangen's value for the 503-kev resonance.[5]

A survey of the results is given in Fig. 3 and in Table I, where the last column refers to the discussion below. Only the range from 500 up to 1400 kev is covered, since, owing to a breakdown of the belts, the measurements above 1400 kev are so far incomplete.

The curve shows 31 prominent peaks, 16 of which are found in the curve of Herb *et al.*[3] The resonance at 862 kev, which Herb ascribes to fluorine, has not been found, even though only weak background radiation is present in that region. As no considerably stronger fluorine lines exist in the examined voltage region, the curve can therefore not be influenced by fluorine contamination. The complex peak at 1192 kev seems to consist of three lines at 1189, 1192, and 1195 kev, but nothing definitely can be said.

The gradual rise of the background with increasing voltage is mainly due to radiation from the silver disk. Copper gives considerable radiation above 1000 kev and has therefore not been used as target support at higher voltages.

DISCUSSION

According to the general scheme for nuclear reactions, the observed resonances correspond to stationary states of the compound nucleus Si^{28} formed and excited to about 12 Mev by the impact of a proton on a nucleus of Al^{27}, which is the only isotope present in natural aluminum. In the present case, where neutron escape is excluded for energetic reasons, and where the emission of an α-particle is very improbable because of the large barrier, the final result of the collision will depend on a competition between the re-emission of a proton and radiation processes leading to a final capture of the proton.

The yields of such resonances depend on the probabilities for these competing processes, specified by the so-called widths Γ_p and Γ_r for proton emission and gamma-radiation, respectively, which are simply the probabilities measured in energy units by multiplication by Planck's constant over 2π. According to the well-known formula of Breit and Wigner, the cross section for (p, γ) processes integrated over one of the narrow lines will be given by

$$\sum=\frac{h^2}{4ME}\omega\gamma;\quad \gamma=\frac{\Gamma_p\Gamma_r}{\Gamma_p+\Gamma_r},\tag{1}$$

where E is the resonance energy of the proton and M its mass, while ω is a spin weight factor which, because of the high spin 5/2 of Al^{27}, will be of the order $\frac{1}{2}$, although, for large angular momenta of the protons, it may deviate appreciably from this value.

The thick target gamma-ray yield of a single resonance, i.e., the fraction Y of the incident protons finally captured through the radiation processes, will therefore be given by the expression

$$Y=\frac{\sum}{sMA}=\frac{s_0\omega\gamma}{sAE}, \tag{2}$$

where A is the mass number and s the specific stopping power of the target material, while s_0 is an abbreviation for $h^2/4M^2$ and equal to 2.5 kev per mg/cm^2.

For the specific stopping power of aluminum we have used the values given by Herb *et al.*,[8] which for 500 kev agree with our measurements.

By comparing the yield from fluorine with the absolute yield given by Lauritsen *et al.*,[9] and by van Allen and Smith,[10] we find the efficiency of the counting arrangement to be 0.12 percent for 6 Mev quanta. This corresponds approximately to 0.2 percent for the aluminum radiation. The estimate of the efficiency is rather rough and constitutes the main source of uncertainty in the values, given in Table I, of the quantity $\omega\gamma$ calculated by means of Eq. (2).

From Eq. (1) it is seen that γ will be of the same order of magnitude as the smallest of the two partial widths Γ_p and Γ_r. In the low voltage region where, due to the influence of the barrier, Γ_p is very small compared with Γ_r but increases rapidly with the proton energy, we should therefore, according to Eq. (2), expect the resonances to rise gradually in strength with increasing energy E.

In the high voltage region we may, of course, still find small values of Γ_p corresponding to the impact of protons with high angular momenta, but the value of Γ_p for zero angular momentum should be large compared with Γ_r. On entering this region the general increase in the resonance strength should therefore be expected to stop, since the radiation width is normally assumed to be approximately constant.

Such a dependency on the proton energy is also indicated by the general trend of the yield curve (Fig. 3). The transition region between "low" and "high" energies appears to be situated in the vicinity of 600 kev. Below this energy the values given in the third column of Table I should thus represent $\omega\Gamma_p$, while for higher energy they should represent $\omega\Gamma_r$, except in cases where we have to do with comparatively large angular momenta of the incident protons.

Since ω will on the average be about $\frac{1}{2}$, one finds values of Γ_r of the order of magnitude of 1 ev, in accordance with general theoretical estimates. For the three very strong levels at 986, 1372 and 1379 kev it seems necessary, however, to assume excessively large values of Γ_r, which might perhaps be caused by some specific character of the excitation states favorable for radiative transitions.

As regards the order of magnitude of the proton width, we may assume that for zero angular momentum it will rise rapidly from about 1 ev for $E\sim600$ kev, to values of about 1 kev at 1400 kev, as estimated from the penetrability of the barrier. Thus, for none of the resonances is the natural width, which is the sum of the partial widths, revealed by the measurements, but still the slope of the foot of the strong double-line at 1372 and 1379 kev may give an indication of the actual width. In fact, by comparing the shape of the curve in this region with the foot of an ordinary dispersion line with the given area, one arrives at a total width of just about 1 kev.

It need hardly be added that the "foot" might originate from one or more weak lines which have escaped detection by the present resolution, but there is reason to believe that the cutter arrangement is sufficiently reliable to prevent any appreciable influence from the central part of the line at the distance in question, and this interpretation is also confirmed by the sharpness of the strong line at 986 kev for which, with the estimated much smaller proton width, no measurable foot should be expected.

In the region from 600 to 1400 kev the mean distance between resonances is seen from Table I to be about 30 kev. The lines are within this region fairly evenly distributed, but there is a remarkable grouping and perhaps some regularity in the spacing of the levels of each group (e.g., the three lines at 757, 764 and 771 kev), although, it cannot be excluded that some of the coincidences are of a more accidental character. Still, especially in the case of the two very strong lines at 1372

[9] J. F. Streib, W. A. Fowler, and C. C. Lauritsen, Phys. Rev. **59**, 253 (1941).

[10] J. A. van Allen and N. M. Smith, Jr., Phys. Rev. **59**, 501 (1941).

and 1379 kev, it is difficult to escape the impression of the presence of a typical fine structure.

In a forthcoming publication from this institute it is planned to give a more detailed discussion of the characteristics of the spectrum.

The authors wish to express their thanks to Professor Niels Bohr for offering them the facilities to carry out this work, and for his valuable help with the discussion of the results. One of us (R. T.) is also indebted to "The Foundation for Danish-Norwegian Co-operation" and the Norwegian "Foundation of 1919 for Scientific Research" for grants enabling him to take part in the work in Copenhagen.

PHYSICAL REVIEW VOLUME 71, NUMBER 10 MAY 15, 1947

Interference Phenomena of Slow Neutrons

E. Fermi and L. Marshall
Argonne National Laboratory and University of Chicago, Chicago, Illinois

(Received February 7, 1947)

Various experiments involving interference of slow neutrons have been performed in order to determine the phase of the scattered neutron wave with respect to the primary neutron wave. Theoretically this phase change is very close to either 0° or 180°. The experiments show that with few exceptions the latter is the case. The evidence is based on the following types of measurements: (a) measurement of the intensities of Bragg reflection of various orders of many crystals, and comparison with the theoretical values of the form factor; (b) total scattering cross section of gas molecules for wave-lengths long compared with the molecular dimensions; and (c) determination of the limiting angles for total reflection of neutrons on various mirrors. The elements Ba, Be, C, Ca, Cu, F, Fe, Mg, N, Ni, O, Pb, S, and Zn were found to scatter neutrons with 180° phase difference; Li and probably Mn scatter with zero phase difference. The five elements I, Br, Cl, K, and Na behave alike and the phase with which they scatter is tentatively identified as 180°. Coherent scattering cross sections have been determined for several elements.

INTRODUCTION

THE scattering processes of slow neutrons are greatly complicated by interference phenomena due to the fact that the de Broglie wave-length is comparable with interatomic distances. The general pattern of interference phenomena of slow neutrons is similar to that of x-rays, since both the wave-length and the scattering cross section of x-rays are comparable to those of neutrons. On the other hand there are considerable differences due to several factors. Among them is the fact that the scattering of x-rays varies regularly with atomic number while that of neutrons is a rather erratic property. Furthermore, in the case of neutrons the phase difference between scattered and incident wave may be either 0° or 180° as will be discussed in Section 1. For x-rays instead, it is always 180° because x-ray energies are larger than most electronic resonance energies. Also, the absorption properties of neutrons differ markedly from those of x-rays.

The main purpose of this work was the investigation of various interference phenomena in order to determine the phase change of the scattered neutron wave for a large number of elements. Section 1 contains a summary of the theoretical background of this work. Section 2 describes the measurements of the intensities of Bragg reflections of various orders and their interpretation. Section 3 is a discussion of some experiments on filtered neutrons. In Section 4, experiments on scattering of neutrons by gas molecules are presented. Section 5 describes measurements of the limiting angle for total reflection of neutrons. The general conclusions are discussed in Section 6.