Resonance Scattering of Protons by Aluminum

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The elastic scattering of protons by aluminum at energies near the 985-kev [based on the 440-kev Li(p,γ) voltage scale] resonance has been studied, with the use of the homogeneous proton beam available from the Wisconsin pressure generator equipped with the 90° electrostatic analyzer. The variation in the scattering yield with proton energy agrees qualitatively with the prediction of the Breit-Wigner formula. On the assumption of S-scattering, the data indicate a natural resonance width of the order of 100 volts.

INTRODUCTION

IN the course of tests on the Wisconsin 90° electrostatic analyzer,[1] runs were taken over gamma-ray resonance levels in several elements. The preparation of good thin targets turned out to be the main experimental difficulty, and aluminum targets seemed to be the easiest to make. Because of this, the best data were obtained from the 985-kev $Al^{27}(p,\gamma)Si^{28}$ level, and an attempt was made by Bender, Shoemaker, and Powell[2] to determine the natural width of this resonance. It was necessary to correct for the effect of energy spread in the proton beam and the effect of target absorption thickness. A resonance width of 300 ± 50 volts was obtained on the basis of the following assumptions: (a) the surfaces of the analyzer plates were sufficiently accurate that the energy spread of the proton beam could be calculated from the slit widths, (b) the aluminum target film was perfectly uniform, (c) the effects of oxidation of the aluminum film were negligible, and (d) the effects of straggling in the target film could be neglected. It should be noted that all of the neglected effects would cause the above figure to be larger than the true width, so that this result had to be taken as reliable only as far as the upper limit is concerned.

During a visit to this University in the spring of 1947, E. P. Wigner emphasized the desirability of experimental data on elastic resonance scattering. The Breit-Wigner theory of nuclear resonance predicts a variation from Rutherford scattering near a resonance, in form similar to the optical dispersion near an absorption band. In order that this variation shall not be excessively reduced by averaging over a range of energies, the energy spread of the proton beam and target absorption thickness cannot greatly exceed the resonance width. An aluminum film thin enough for resonance experiments must be supported, and the large number of protons scattered by a heavy backing material, such as is commonly used for gamma-ray work, would completely mask those scattered by the target film. Professor Wigner pointed out that protons scattered into the backward direction from a backing of lower atomic weight than the target would all have lower energy than those scattered by the target, and suggested that it might be possible to make use of this energy difference so that only the desired protons would be recorded.

EXPERIMENTAL METHOD AND RESULTS

The energy difference available for the separation of the scattered protons, of course depends on the atomic weight of the backing material. It would seem that the best choice would be the lightest material available, but, as will be seen later, an aluminum film has a surface film of oxide, so that one must be able to separate the protons scattered by oxygen from those scattered by aluminum. The energy of a proton scattered in the backward direction by an aluminum nucleus is about 86 percent of the bombarding energy, and a proton scattered in the same direction by an oxygen nucleus is about 78 percent of the bombarding energy. Thus, there is a difference of about 9 percent for the separation. This is well within the capabilities of a simple focusing magnetic analyzer.

Figure 1 shows a plan view of the apparatus used. An aperture, $\frac{1}{8}''\times\frac{1}{4}''$, limited the cross section of the incident proton beam, so that the illuminated area on

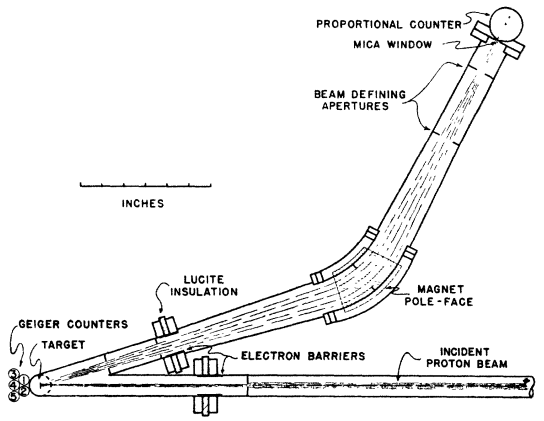

FIG. 1. Plan view of the apparatus used for the resonance scattering experiment. The focusing magnetic analyzer was used to separate the protons scattered by the aluminum from those scattered by the lighter target backing.

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[1] Warren, Powell, and Herb, Rev. Sci. Inst. **18**, 559 (1947).

[2] Bender, Shoemaker, and Powell, Phys. Rev. **71**, 905 (1947).

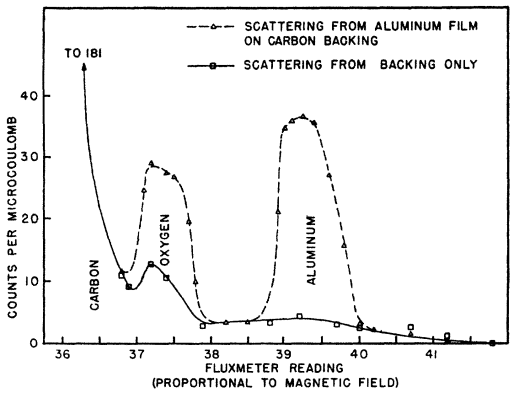

FIG. 2. Momentum spectrum of the scattered protons. The incident proton energy was kept constant at a value well away from the resonance while these data were taken. The three groups of protons were scattered by aluminum, oxygen, and carbon, respectively.

the target formed the entrance slit of the magnetic analyzer. Other apertures were spaced at intervals along the path of the scattered protons to avoid secondary small angle scattering from the walls of the vacuum chamber. The gap between the pole-faces of the magnet was adjusted with iron shims so that the focusing error was less than $\frac{1}{32}''$ in the image plane. The opening into the counter was intentionally made wider than the image formed by the magnet, so that the counting rate would not vary with small fluctuations in the magnetic field.

Scattered protons were counted by a proportional counter consisting of a $1\frac{1}{2}''$-diameter brass tube with a coaxial 0.003-in. molybdenum wire supported at both ends by Stupakoff Kovar-glass insulators. Protons entered through a $\frac{1}{4}\times\frac{1}{2}$-in. opening in the side, made vacuum tight by a 1.6-mg/cm^2 mica window sealed on with a thermoplastic (Gelva V-7, obtained from the Shawinigan Products Company). The counter was filled to a total pressure of 15 cm Hg with tank argon (99.6 percent pure) with 2 percent CO_2 added. The operating potential was 570 volts, which provided a gas amplification of about 20. The proton pulses were amplified by a Los Alamos Model 100 amplifier and were counted by a scale of 64 and mechanical recorder. The pulses were twenty times the noise level, and very uniform in size so that the discriminator on the scaler could be set to give zero background.

Gamma-rays were counted by five Radiation Counter Laboratories Geiger-Mueller tubes connected through a coincidence circuit to another scaler. Referring to Fig. 1, counter (1) was connected in coincidence with (3) and (4), and counter (2) was operated in coincidence with (4) and (5). Coincidences between (1) and (5) and between (2) and (3) were eliminated to minimize the background counting rate. To maximize the counting efficiency, the counters were placed as close as possible to the target, with a millimeter of lead in between.

To provide for beam current integration, the target chamber was insulated from the remainder of the apparatus by Lucite disks to form a Faraday cage. Electrons released by the proton beam striking the target or defining aperture were prevented from passing into or out of the target chamber by guard cylinders maintained 300 volts negative by a battery. The current was integrated by causing it to charge an eight-microfarad polystyrene condenser to a potential of ten volts, measured by a string electrometer. For proton currents of the magnitude used in this experiment, 0.05 to 0.5 microampere depending on the energy spread of the beam, the combination of a short period electrometer and high quality condensers appears to be an unusually reliable and convenient current integrator.

Targets were prepared by evaporating aluminum onto strips of spectroscopically pure carbon, which had been polished by rubbing with another piece of the same material. Beryllium was also tried for target backings, but all available samples had large amounts of heavy impurities, which gave an excessive amount of background scattering. Another advantage of carbon over beryllium as a target backing is that the gamma-ray yield proved to be much lower. Previous results[2] showed that if targets were maintained at a temperature of about 250°C and a liquid air trap was used between the target and oil diffusion pump during bombardment, there was no detectable surface contamination. Accordingly, the targets were mounted on a heated support. This support was arranged so that it could be moved by a rod through a Wilson seal, so that targets could be changed without breaking the vacuum.

Figure 2 illustrates the behavior of the magnetic analyzer. In taking these data, the incident proton

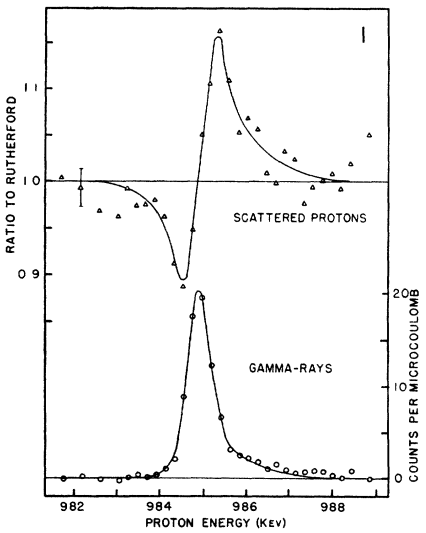

FIG. 3. Data from run *1* showing resonance scattering and absorption of protons by aluminum. The scattered proton yield at energies distant from the resonance was assumed to be Rutherford scattering. The curves were drawn to give an apparent fit with the experimental points without reference to the theory. The absolute energy position is based on the 440-kev Li(p,γ) standard.

energy was kept constant at a value well away from the resonance, and proton counts were recorded as a function of magnetic field. Results of two of these runs are shown, one taken with a carbon-backed aluminum target, and the other using as the target a region on the carbon which had been shielded from the aluminum during the evaporation. On the curve taken with the aluminum target, three groups of protons are evident. The group having the highest energy was scattered by the aluminum. The next group appears at a magnetic field setting corresponding to scattering by oxygen. Since this group has appreciable intensity only in the run taken with the aluminum target, and since it has the character of scattering from a thin target, it is assumed that it is due to oxidation of the aluminum film. The group next lower in energy has a continuous spectrum extending to the low energy limit of the counter, set by the stopping power of the mica window. The upper energy limit and thick target character identify this group as scattered by the carbon backing. For the thinnest targets used, the intensities of the aluminum and oxygen groups correspond to scattering by Al_2O_3, the common oxide of aluminum. Thicker targets show a relatively less intense oxygen group, indicating that these films were not completely oxidized. The curve taken with the bare carbon target shows the presence of heavy impurities, and in addition a slight surface layer of oxygen.

Five runs were made with different target thicknesses and proton beam energy spreads, recording both gamma-ray counts and proton counts as the energy of the incident proton beam was varied. By use of a flip coil and fluxmeter, the field in the magnetic analyzer was kept at the value to accept the protons scattered by the aluminum. Figures 3 and 4 show two of these runs. In plotting these data, a background of about 10 percent, due to heavy impurities in the target backing, was subtracted from the scattered proton yield. Also, a background of about 10 counts per microcoulomb, due to gamma-radiation from the thick carbon target backing, and a time dependent background amounting to around two counts per microcoulomb, were subtracted from the gamma-ray yield. These corrections were measured for every target. The scattered proton yield at energies relatively distant from the resonance was assumed to be Rutherford scattering. The run shown in Fig. 4 was taken with a thicker target and a larger proton energy spread than the one shown in Fig. 3. This shows up in an increased gamma-ray yield, a broader gamma-ray peak, and a relatively smaller effect of the resonance on the proton scattering.

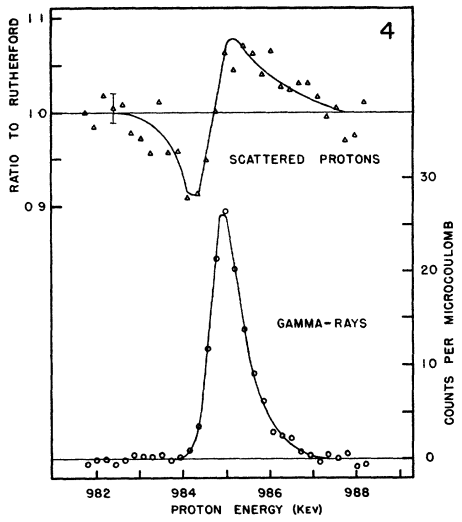

FIG. 4. Data from run *4*. A larger target thickness and proton energy spread were used for this run than for run *1* shown in Fig. 3. Note that the gamma-ray peak is wider and more intense, and that the effect of the resonance on the proton scattering is smaller.

DISCUSSION OF RESULTS

The observed scattering variation has the form predicted by the Breit-Wigner theory. The decrease from Rutherford scattering on the low energy side of the resonance, predicted by the theory, is caused by destructive interference between the coulomb and resonance scattering amplitudes.

An attempt was made to use this data to determine the width of this level. The lack of angular distribution data makes necessary some assumption about the orbital angular momentum of the scattered protons. In this discussion, the assumption is made that only zero orbital angular momentum is important. The formula for the cross section for scattering of particles with spin has been worked out explicitly only for this case. Bethe[3] gives this formula, which, after substituting constants fixed by the experimental arrangement, reduces for this resonance to:

$$\sigma/\sigma_0 = 1+0.078(2J+1)(0.85+2x)/(1+x^2),$$

where σ is the differential elastic scattering cross section, σ_0 is the Rutherford scattering cross section, J is the total angular momentum quantum number for the compound nucleus, $x=2(E-E_r)/\Gamma$, E is the proton energy, E_r is the proton energy for resonance, and Γ is the total width of the resonance. The constants shown in this formula were computed on the assumption that the partial width for proton re-emission is large compared to the width for gamma-ray emission. This assumption is justified by the following argument. Brostrom *et al.*,[4] by measurements of absolute gamma-ray yield, have shown that the smaller of these widths is about 15 volts. If the total width were not very much larger than this, no variation in scattering would have been observed with the resolving power available, so that one of the partial widths must be large compared to 15 volts. If the large one were the gamma-ray width,

[3] H. A. Bethe, Rev. Mod. Phys. **9**, 69 (1937). (Formula 625, p. 176.)

[4] Brostrom, Huus, and Tangen, Phys. Rev. **71**, 661 (1947).

TABLE I. Determination of the natural width of the 985-kev $Al^{27}(p,\gamma)Si^{28}$ resonance (*S*-scattering assumed).

Run	Width of gamma-ray peak (electron volts)	Amplitude of the scattering variation	Natural width (electron volts) $J=2$	$J=3$
1	690	26%	154	103
2	760	21%	120	84
3	810	16%	95	68
4	880	17%	120	86
5	550	25%	103	68
		Averages	118	82

the values of the constants in the above formula would be so small that the variation in scattering, even with perfect resolution, would be smaller than that observed.

When this formula is plotted, it gives a curve similar to the optical anomalous dispersion curve, dipping on the low energy side to 0.64, and rising on the high energy side to 1.83, for $J=3$. For $J=2$, the dip is to 0.74 and the rise to 1.59.

While the variation in scattering near the resonance as shown in Figs. 3 and 4 is of the form represented by this formula, the amplitude is not as large. This is due to the fact that the resolving power was insufficient, resulting in an effective averaging of the scattering over an energy region considerably larger than the resonance width. Therefore, not all of the assumptions made in the analysis of the gamma-ray results in reference 2, as listed in the introduction to this paper, are valid. Among the possibilities for explanation of the invalidity of one or more of these assumptions are: (a) an almost unmeasurable conicity of the electrostatic analyzer deflection plates would increase the energy spread of the proton beam appreciably, (b) the thermal agitation of the atoms in the target[5] assuming Maxwellian motion, would cause a perfectly homogeneous million-volt proton beam to have an effective energy spread of about 140 volts (Note: Because this combines with the energy spread of the proton beam approximately as the square root of the sum of squares, it contributes only from 10 to 20 percent to the energy spreads used.), (c) Figure 2 shows that the targets were oxidized so that their effective thickness was increased by as much as a factor of two, and (d) electron microscope photographs of evaporated aluminum films[6] show a crystalline structure, instead of a uniform distribution, which could increase the energy loss in the target by a completely unknown amount, as one would expect this crystallization to depend on the nature of the backing material.

In view of these uncertainties, the following method was used to estimate the resonance width. For each run a value was found for the energy spread and for the target thickness, which would account for the observed width of the gamma-ray peak if the natural resonance width were 50 volts. This computation was repeated for assumed natural widths of 75 volts, 100 volts, and 150 volts. The method used was essentially that developed by J. L. Powell for the analysis of the gamma-ray work in reference 2. Next, for each of these assumed natural widths, the effect of the corresponding energy spread and target thickness on the amplitude of the scattering variation was calculated, assuming that Bethe's formula would give the correct scattering if the resolving power were infinite. Of course, the gamma-ray data are capable of fixing only one of these experimental parameters, but since the energy spread and target thickness enter symmetrically into both the gamma-ray and scattering calculations, one of them can be assumed to have a reasonable fixed value and the other can then be determined. If the energy spread is assumed to be that given by the electrostatic analyzer slit widths, corrected for the effect of thermal agitation of the target atoms, the target thicknesses required to account for the observed width of the gamma-ray peaks are found to be about twice as large as those calculated on the assumption of a uniform film of aluminum, corrected for oxidation. A comparison of these calculated amplitudes with the observed scattering variation gives, by interpolation, a first approximation to the natural resonance width. These results, combined with Brostrom's[4] measurement of the radiation width, were then used to recompute the constants in the scattering formula. The analysis of the data was then repeated to give a better approximation to the width. This result clearly depends on the angular momentum quantum number of the compound nucleus, which could be either 2 or 3 for *S*-scattering of protons by aluminum. The results are shown in Table I.

The *S*-wave barrier penetrability is 0.005 if 4.5×10^{-13} cm is used for the nuclear radius. Combined with the width indicated by the present data, this gives approximately 15 kev for the width without barrier.

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[5] H. A. Bethe, Rev. Mod. Phys. **9**, 140 (1937).
[6] C. E. Hall, J. App. Phys. **19**, 198 (1948).