Gamma-Rays from Sodium Bombarded by Protons

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The intensity of the γ-radiation emitted by sodium under proton bombardment has been studied as a function of the energy of the bombarding protons up to 1.9 Mev. Protons were accelerated by a 2-Mv pressure-insulated electrostatic generator, and were incident on a thin evaporated film of metallic sodium. The γ-ray intensities were measured by means of the counts produced by recoil electrons entering a single glass Geiger-Müller counter which actuated a scale-of-16 and mechanical recorder. Generator voltages were measured by a generating voltmeter, which was calibrated by means of the 0.862-Mev resonance in the F(*p*, γ) reaction. The yield curve shows 21 well-defined resonances, whose half-widths (with one exception) are probably experimental.

INTRODUCTION

THE intensity of the γ-radiation emitted by sodium under proton bombardment has been studied as a function of the energy of the bombarding protons by Herb, Kerst, and McKibben;[1] Gentner;[2] and Curran and Strothers.[3] From Barkas' values of the atomic masses,[4] the only known proton reactions that are energetically possible (for incident protons of less than 2-Mev energy) are the radiative capture

$$Na^{23}\ (p, \gamma)\ Mg^{24},$$

in which 11 Mev are liberated, and the (*p*, α) reaction, in which the available energy is 1.4 Mev. That the (*p*, γ) reaction is responsible for the observed radiation is shown by the fact that measurements by Curran and Strothers,[3] of the absorption of the recoil electrons, indicate a quantum energy of the order of 10 Mev, which is several times as great as the energy that could be liberated in the (*p*, α) reaction.

The present paper is a more detailed study of the yield of γ-rays from a thin target of metallic sodium as a function of the proton energy, and covers the range of energies up to 1.9 Mev.

APPARATUS

Protons were accelerated by a two-million-volt pressure-insulated electrostatic generator.[5] The voltage was measured by means of a generating voltmeter of the type described by Parkinson, Herb, Bernet, and McKibben.[6] This was calibrated against the 0.862-Mev resonance in the F^{19} (*p*, γ) reaction by using as a target a thick calcium fluoride crystal covered by nickel gauze.[7] The voltage of the fluorine resonance depends, in turn, upon that of the 0.440-Mev resonance in the lithium (*p*, γ) reaction measured by Hafstad, Heydenburg, and Tuve.[8]

The arrangement of the target chamber and recording counter is shown in Fig. 1. Protons, separated from molecular and other ions by a magnetic analyzer, enter the target chamber through a $\frac{7}{32}$-inch defining aperture in a tantalum sheet (*A*). The $\frac{1}{8}$-inch thick copper strip *T*, which served to cool the target by conduction, was faced on both sides with tantalum (used because of its low γ-ray yield under proton bombardment), and could be rotated through a ground brass joint. One of these faces was coated with a thin film of metallic sodium by evaporation from the Nichrome wire *W*, and the other was used to check background counting rate. During the preparation of an evaporated sodium film, the target was rotated into a horizontal position above the wire *W*.

Recoil electrons produced in the aluminum top of the target chamber by the γ-radiation, were recorded by means of the single glass

[1] Herb, Kerst, and McKibben, Phys. Rev. **51**, 691 (1937).
[2] W. Gentner, Zeits. f. Physik **107**, 354 (1937).
[3] S. C. Curran and J. E. Strothers, Proc. Roy. Soc. **A172**, 72 (1939).
[4] W. H. Barkas, Phys. Rev. **55**, 696 (1939).
[5] The generator is to be described in connection with some test work done with it. J. L. McKibben and R. L. Burling in a forthcoming issue of Rev. Sci. Inst.
[6] Parkinson, Herb, Bernet, and McKibben, Phys. Rev. **53**, 642 (1938).
[7] Bernet, Herb, and Parkinson, Phys. Rev. **54**, 398 (1938).
[8] Hafstad, Heydenburg, and Tuve, Phys. Rev. **50**, 504 (1936).

Geiger-Müller counter C, which actuated a scale-of-16 circuit and mechanical recorder. The proton current entering the target chamber was measured by means of the current integrator described by Herb, Kerst, and McKibben.[1] The entry of secondary electrons into the target chamber was prevented by applying a potential of minus 45 volts to it; and the escape of secondaries was prevented by the fact that the solid angle subtended by the opening of the chamber at the target was very small.

Results

The γ-ray yield curves obtained for sodium are shown in Fig. 2 in which γ-ray intensities are plotted against the energy of the incident protons. The abscissas are proton energies in Mev, and have been corrected for the energy imparted by the probe which draws the ions out of the arc source. The ordinates are γ-ray yields in arbitrary units. For curves A, B, and C, the ordinates are the numbers of counts produced in the Geiger-Müller counter for every 2×10^{14} protons incident on the target. In Curve A, which was taken with a single thin film, the

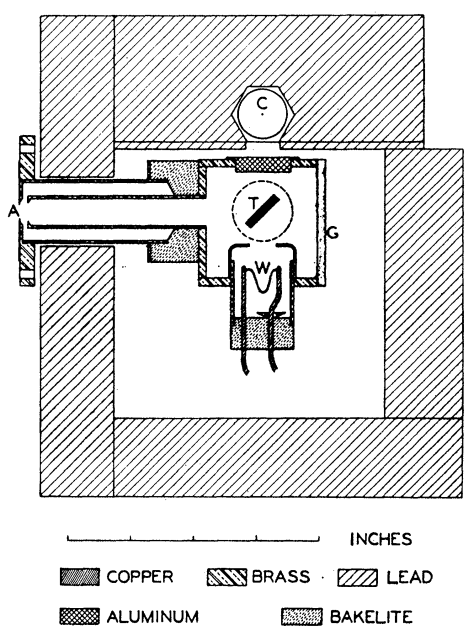

FIG. 1. Target chamber. Protons enter the target chamber through the $\frac{7}{32}''$ defining aperture A. Sodium is evaporated onto the tantalum-faced copper target T from the wire W. γ-rays are detected by the Geiger-Müller counter C. G is a glass window.

ordinate is the actual number of counts recorded at each point, so that it may be used to estimate the probable statistical errors in the data. In curves B and C the actual number of counts recorded at any point was 1, 2, or 5 times as great as the ordinate of the point, the total number of incident protons having been increased for these points. Curve B was taken with two films, each only slightly thicker than that used for curve A, but is less accurate statistically because of the low yield in the low voltage region. Curve C is for a film of about the same thickness as that used for curve A, and is given merely to demonstrate the reproducibility of the data in curve A.

Curve D is for two films, each several times as thick as the films used for the other curves, and shows for this reason wide peaks shifted fifteen or twenty kev toward higher voltage relative to the curves taken with thinner targets. Its ordinates bear no relation to those of curves A, B, and C, since curve D was taken with a different geometrical arrangement of the Geiger-Müller counting tube (as in Fig. 2 of reference 9). For the portion of curve D above 1.1 Mev, the ordinates are actual numbers of counts, but for lower voltages, six times as much proton current was incident on the target, so that the ordinates must be multiplied by six to give the actual number of counts from which the probable statistical errors may be determined.

It was not necessary to extend the thin film data below 0.3 Mev, since a thick target yield curve showed (in agreement with the results of Gentner[2]) a sharp threshold at this energy, thus indicating that there could be no resonances of measurable intensity below this value.

With the same scale as was used for curve A, the yield of γ-radiation from a thick target of sheet Nichrome was 1600 at 1.65 Mev; or only 400 greater than the background yield from a tantalum target. Hence none of the observed resonances could have been due to a contamination from the Nichrome wire from which the sodium was evaporated.

The yield curves show twenty-one well-defined resonances, the approximate voltages of the peaks, listed in order of decreasing intensity,

[9] Plain, Herb, Hudson, and Warren, Phys. Rev. **57**, 187 (1940).

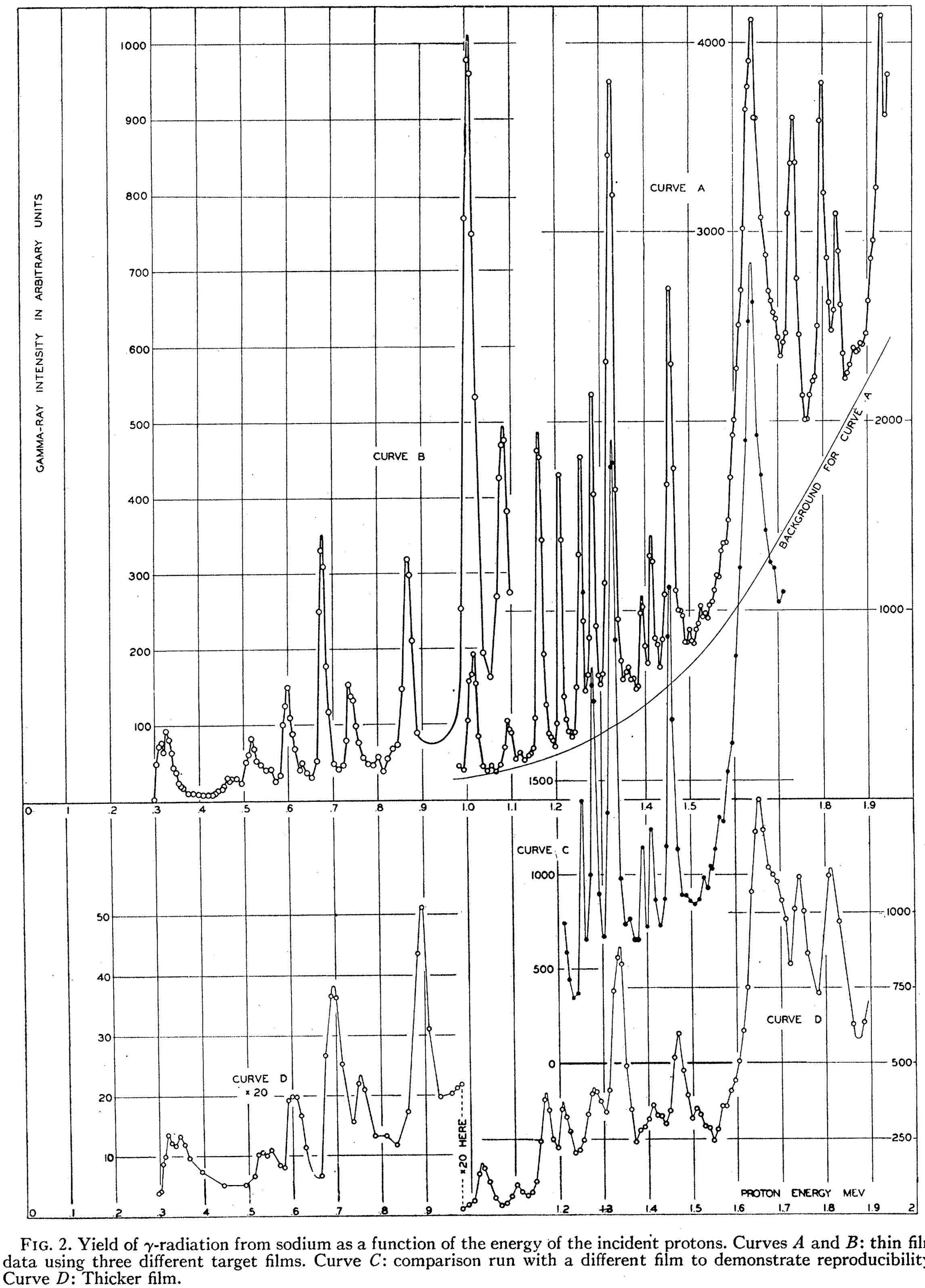

FIG. 2. Yield of γ-radiation from sodium as a function of the energy of the incident protons. Curves *A* and *B*: thin film data using three different target films. Curve *C*: comparison run with a different film to demonstrate reproducibility. Curve *D*: Thicker film.

being: 1.324, 1.638, 1.454, 1.795, 1.732, 1.93, 1.159, 1.281, 1.255, 1.206, 1.829, 1.412, 1.006, 1.392, 1.08, 0.576, 0.867, 0.735, 0.598, 0.31, and 0.515 Mev. These energies are in million electron volts, and have not been corrected for target thickness, so do not represent actual resonance energies. The peak at 0.31 Mev is due to a resonance reported by Gentner,[2] in whose work the resonance is more sharply defined. The resonances between 0.4 and 0.9 Mev have all been reported by Curran and Strothers,[3] although their work does not appear to resolve them as clearly as does curve *B*.

The half-widths of the resonance peaks (with the exception of that at 1.638 Mev) vary from 10 to 25 kev, and are to be regarded as largely experimental, since: (1) the generator voltage fluctuated by 5 or 10 kilovolts during any single observation; (2) there was a spread of energy in the proton beam due to ionization in the probe canal of the ion source and in the accelerating tube; and (3) no corrections have been applied for target thickness. However, the 1.638-Mev resonance has an observed half-width of 70 kev, so that it must be due either to a wide level, or to an unresolved group of closely spaced levels.

ACKNOWLEDGMENTS

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The Paschen-Back Effect

VIII. The Reality of the Distant Components

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The helium line λ7066 has been investigated in order to show that the distant components, whose predicted intensities are extremely small, really do exist. Agreement between theory and experiment, as regards both position and intensities of these components, is excellent.

In all elementary discussions of the Paschen-Back effect, we find statements to the effect that in very strong fields, the Zeeman pattern of a multiplet degenerates into a normal triplet. A more careful analysis of the problem shows, however, that the perpendicular components of this triplet should show structure, each of the lines consisting of a number of components equal to the multiplicity involved in the transition, when we are dealing with *LS* coupling. The reality of this structure has been shown in an earlier communication[1] and by Jacquinot.[2] But in addition to this so-called "normal" triplet, there should also be some components of twice the normal distance (for doublet spectra) and also at three times the normal distance (for triplet spectra). These far distant components have never been separated[3] and it is the purpose of this paper to complete the record. It may be shown quite simply that the most distant component is $\Delta\nu_{\text{norm}}\times$the multiplicity $(2S+1)$ if the full multiplicity of one of the groups of L levels has been reached. We must find the largest value of $(m_S+2m_L)-(m_S'+2m_L')$ subject to the condition that $(m_S+m_L)=(m_S'+m_L')\pm1$ for the perpendicular components. This will obviously be

[1] J. B. Green and R. A. Loring, Phys. Rev. **49**, 630 (1936).
[2] P. Jacquinot, *Verh. Zeeman* (Amsterdam, 1935).
[3] Paschen and Back report weak components in the oxygen triplet, but this is really a quintet spectrum and should have more distant components.