An Investigation of Bremsstrahlung by Means of the Nuclear Isomerism of Indium. II*

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A magnetic deflection technique has been employed in a reinvestigation of the thin target x-ray excitation of In^{115}. The results of this investigation confirm the earlier results of Miller and Waldman. Activation levels have been found at 1.08±0.02 Mev, 1.47±0.02 Mev, and 1.60±0.02 Mev. The latter level is reported for the first time. Above 1.65 Mev the increase in activity can be attributed to a rise in the isochromats and/or many unresolved levels of relatively small cross sections. The over-all cross section (per electron incident on a 30-mg/cm² gold target) is approximately 10^{-34} cm² at 1.4 Mev.

I. INTRODUCTION

THE investigation of bremsstrahlung by means of the nuclear isomerism of indium has previously been reported by this laboratory.[1] The work had as its secondary purpose the determination of low lying energy levels in the In^{115} nucleus. This report describes the application of a new technique to a similar study and is to be regarded as a continuation of the earlier work.

Both theoretically and experimentally, the study of nuclear excitation by x-rays is facilitated by producing the x-rays in thin targets that are bombarded with monoergic electrons. However, most of the electrons pass through the target, giving rise to a combination x-ray electron beam. Such a beam is unsuitable for x-ray excitation investigations inasmuch as direct electron excitation completely masks the effect to be studied.[2] Thus, the removal of the electrons from the composite beam is of primary importance.

In the previous experiment[1] a subtraction process was employed in which a low Z absorber was inserted between the thin target and the indium detector. The absorption produced thick target x-rays which contributed to the total excitation. Hence, two irradiations were performed for each experimental point; one with the target and absorber in place, and the other with only the absorber in place, and the latter effect was subtracted from the former. This necessarily introduced large statistical deviations.

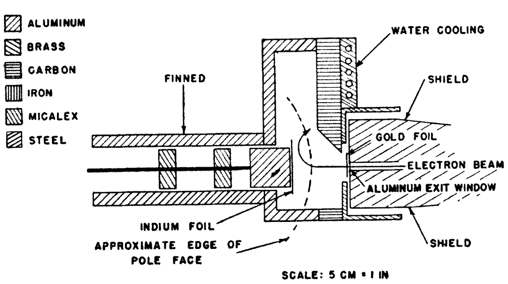

Fig. 1. Target assembly.

The present investigation employed a magnetic deflection technique to remove the electrons from the composite x-ray electron beam.

II. EXPERIMENTAL METHOD

The general problem associated with the magnetic deflection technique is that the electron beam must pass through a region of small magnetic field to a thin target and then must be deflected in a small radius of curvature, preferable through 180°. The electrons must be collected in such a way that the x-rays resulting from the collection should not mask the effect of the thin target x-rays on the indium sample.

A. Electrostatic Generator

The source of the high energy electrons was the Notre Dame electrostatic generator. The voltage was calibrated on the basis of the most recent values for the photodisintegration thresholds of deuterium and beryllium[3] and was stabilized to within 6 kev by use of a partial tank liner.[4]

B. Magnet and Shielding

The strong magnetic field required to deflect the electron beam was produced by a trochoid magnet. Even though this type magnetic field is highly localized, it was necessary to shield the incident electron beam from the stray magnetic field. The iron shield employed was approximately 20 inches long with one-inch wall thickness at the exit end and had a one-half inch inner diameter. The thin gold foil target was placed immediately outside the one-mil aluminum exit window of the shield (see Fig. 1).

C. Electron Collection

The electrons were collected in a Faraday cage. The design of this cage was affected by the following conditions: (1) the geometry was restricted, since the cage had

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[1] W. C. Miller and B. Waldman, Phys. Rev. **75**, 425 (1949).
[2] Waldman, Miller, and Gideon, Phys. Rev. **76**, 181 (1949).
[3] R. C. Mobley and R. A. Laubenstein, Phys. Rev. **80**, 309 (1950).
[4] Miller, Waldman, Noyes, and Van Hoomissen, Phys. Rev. **77**, 758 (1950).

to be inserted between the pole faces, (2) the radius of curvature of the beam had to be small, (3) the electrons had to be stopped when their direction was away from the indium, inasmuch as the x-rays so produced have a predominately forward direction, (4) indium samples had to be readily interchangeable. A Faraday cage can be designed to fulfill these conditions if the path of the beam in the field is known. A determination of this was made by placing a block of paraffin at the end of the shield so that the electron beam struck it at grazing incidence and melted a groove along the path of the beam. The result of this test indicated an average radius of curvature of about one-half inch, for 1.6-Mev electrons. The actual In-Au spacing, however, must be more than twice this because of scattering of the electrons by the gold.

The cage design is shown in Fig. 1. The large parts were constructed of aluminum, while the main collecting block was of carbon. These low Z elements kept thick target x-ray production to a minimum. All sections were insulated from each other and connected to ground through Brown potentiometers.[5] The cage was air- and water-cooled.

D. Foils and Holder

The gold foil used in this investigation was 30 mg/cm^2 thick. The indium foils were circular, 0.01 inch thick and 0.8 inch in diameter. This thickness is greater than the range of the internal conversion electrons from In^{115*}. The foil holder (Fig. 1) could be removed to change indium samples. A constant check of the null current to it was maintained by a Brown potentiometer to insure that direct electron excitation was absent.

E. Angular Distribution

A single In-Au spacing was not feasible. A spacing that would be large enough to prevent high energy electrons reaching the indium would be too great for accurate data at the lower energies, owing to the low intensities in this region. Four different spacings were used over the energy range studied. These positions were determined experimentally, and the data were normalized to constant spacing.

A consequence of relatively large In-Au spacings was the fact that not all of the x-rays produced in the target were incident upon the indium. Thin target x-rays have a predominately forward distribution, the distribution angles varying as a function of electron energy (1 to 2.3 Mev) from about 50° to 30°. These angles are computed on an approximate basis. A first-order correction term has been applied to Heitler's[6] formula for the angular distribution in the extreme relativistic case, so that it would apply at these energies.

[5] These potentiometers provided impedance paths which were less than leakage paths in the cage.

[6] W. Heitler, *The Quantum Theory of Radiation* (Oxford University Press, New York, 1948), second edition, p. 168.

TABLE I. Predicted increase in activity due to the narrowing angular distribution.

Position	In-Au spacing (cm)	Angular size of foil	Energy range (Mev)	Distribution angles	Predicted increase of activity (%)
One	2.70	42°	1.05	49°	14
			1.50	40°	
Two	3.17	36°	1.40	41°	7
			1.60	38°	
Three	4.52	26°	1.55	39°	16
			2.15	33°	
Four	5.08	23°	2.10	33°	6
			2.30	31°	

For any given spacing, activation of the indium should increase as energy is increased because of the narrowing of the cone of x-rays. This behavior depends upon the assumption that every x-ray energy in the continuous spectrum has the same angular distribution. The effect, on this basis, gives rise to an inherent difficulty with the experiment. The magnitude of the effect has been computed in Table I. It is to be noted that the investigation of energy levels is independent of this difficulty. A rise in the activity due to the narrowing of the x-ray distribution should affect only the study of the isochromat theory. Table I also lists the angular distributions for the limiting energies at each indium position and the angles subtended by the foils at these spacings.

A more serious effect, although not inherent, was the possibility that the angle of incidence of the electrons on the gold could vary with energy because of imperfect magnetic shielding. The cone of x-rays reaching the indium is strongly dependent upon the angle of incidence of the electron beam upon the gold target. A deviation of the beam from normal incidence could cause this cone to miss partially the indium. To keep the angle constant the magnetic field was varied with energy, so as to keep the radius of curvature constant over the regions covered by each indium position.

One other important parameter with regard to the distributions was the point at which the electron beam impinged upon the gold. The experimental procedure was designed to keep this point fixed for each indium position.

F. Irradiation

For all irradiations it was necessary to align the shield along the beam. This condition was fulfilled when the current to the shield was a minimum. This minimum represented back-scattered electrons from the gold target. The percentage magnitudes of this current ranged from 3–4 percent at 2.3 Mev to 9–10 percent at 1.2 Mev. A record of the total current was obtained by switching the currents from the various parts of the cage and shield onto a Brown strip-chart recorder. A periodic check of the current to the shield was kept,

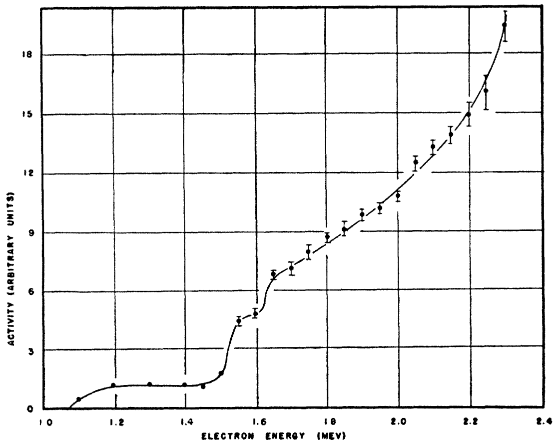

FIG. 2. Thin target x-ray excitation curve of In^{115}. To convert *activity* to *over-all cross section* multiply ordinate by 10^{-34} cm^2 for 30-mg/cm^2 gold target.

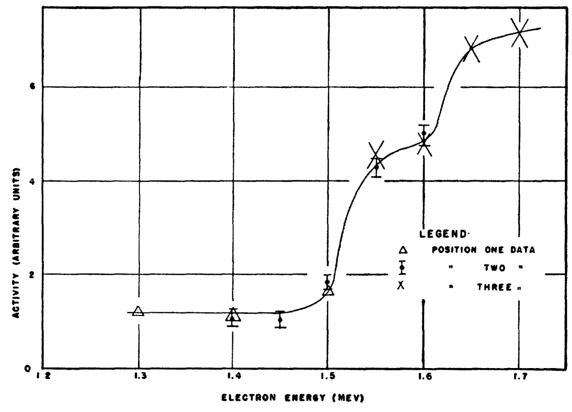

FIG. 3. Thin target x-ray excitation curve of In^{115}. Normalization of the first three positions.

and any run in which the percentage exceeded back scattering was discarded.

Irradiations were made with currents ranging from 60 to 200 microamperes. Most runs were for 1000 seconds, although, because of low intensities, irradiations at the lower energies were for longer periods. Two or more irradiations were made at each voltage.

G. Counting

An Amperex end-window (1.4 mg/cm^2) G-M counter was used to detect the internal conversion electrons from In^{115*}. All samples were counted for 1000 seconds.

III. RESULTS AND DISCUSSION

The results of this investigation are presented in Fig. 2. This curve is a compilation of the data taken at the four indium positions. Figure 3 is presented to indicate the method of normalization and to investigate more closely a newly resolved energy level. The over-all cross section (i.e., per electron incident on a 30-mg/cm^2 gold target) at 1.4 Mev is of the order of 10^{-34} cm^2.

The series of sharp thresholds and subsequent plateaus is a confirmation of our earlier work[1] and Guth's isochromat theory.[7]

The energy levels at 1.08 ± 0.02 Mev and at 1.47 ± 0.02 Mev are those reported previously.[8] The level at 1.60 ± 0.02 Mev is reported for the first time and is believed to be real, inasmuch as the percentage increases in activity in this region are as follows: 400 percent from 1.45 to 1.55 Mev, about 10 percent from 1.55 to 1.60 Mev, and 40 percent from 1.60 to 1.65 Mev.

With the exception of the two end points, every point of Fig. 2 is an average of at least three irradiations. An average of seven runs was made at all points in the region around 1.60 Mev.

The possibility of a step in the curve between 2.00 and 2.05 Mev has been considered, but it is believed that the evidence is insufficient. The rise in activity between these points is 16 percent. In view of the fact that the standard deviations of individual points in this region are about 8 percent, no step has been drawn.

Several conclusions can be drawn from analysis of the data above 1.65 Mev. The increase in slope can be attributed to one or more of four factors:

(1) the increase in percentage of the x-rays incident upon the indium caused by the narrowing of the angular distribution,

(2) the increase in thick target x-rays from the sides and base of the Faraday cage,

(3) a possible rise in the 1.08-Mev isochromat and rises in the 1.45- and 1.60-Mev isochromats,

(4) the existence of many closely spaced energy levels of relatively small cross sections.

Factor (1) can be eliminated. In the energy region between 1.55 and 2.15 Mev, studied with spacing "three," the increase in activity due to the narrowing angular distribution should be about 16 percent (see Table I). However, the same effect in the region between 1.05 and 1.50 Mev, obtained with spacing "one," should have given an increase of about 14 percent. Since no such rise in activity was observed in the lower energy region, one cannot use this mechanism to explain the observed rise in the higher energy region. The validity of the assumption that every x-ray energy in the continuous x-ray spectrum has the same angular distribution is questionable.

Factor (2) can be eliminated. The thick target x-rays are produced in both the aluminum side walls and the carbon block (see Fig. 1). From the geometry of the Faraday cage, one can show that the gold target scatters about 4 percent of the beam into the aluminum side walls at 1.65 Mev. At 2.15 Mev, the scattering to the walls decreases by a factor of two. From our earlier work[1] one finds that the thick target x-ray excitation

[7] E. Guth, Phys. Rev. **59**, 325 (1941).

[8] The difference between these values and those of reference 1 can be attributed to a change in voltage calibration. This calibration is based on the photodisintegration thresholds of beryllium and deuterium (see reference 3).

increases by a factor of about two in going from 1.65 to 2.15 Mev. Thus, the contribution from this effect is approximately constant over this energy region and would not account for the observed rise in activity.

Irradiations made at 1.60 Mev with the gold target removed produced no measurable indium activity due to x-rays from the carbon. At most, this negligible activity could be doubled in the energy interval between 1.60 and 2.15 Mev. This would not account for the observed rise in activity.

The observed rise in activity above 1.65 Mev must be due to a rise in the isochromats or unresolved energy levels or both.

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Photoproton Emission*

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Protons from (γ,p) reactions produced by betatron bremsstrahlung with a maximum energy of up to 50 Mev have been studied with a scintillation counter telescope. Activation curves in Al and Pb showed threshold and resonance characteristics similar to the corresponding curves for the photoneutron processes. The integrated (γ,p) cross section in Al was found to be $\sim 10^{-26}$ Mev cm^2 for 50 Mev bremsstrahlung. For the eleven elements investigated the integrated cross section was roughly proportional to the atomic number. Absorption studies of the protons revealed a high energy component extending up to about 20 Mev which amounted to a few percent of the total number of protons emitted from Al and Pb. For 50 Mev bremsstrahlung the relative photoproton emission at 90° and at 120° to the x-ray beam was measured for Al and Pb. The protons above about 15 Mev were found to come out preferentially at 90° for both elements.

INTRODUCTION

THE protons emerging from nuclei as a result of bombardment with electromagnetic radiations have been studied by several experimenters using counters to record the induced activities,[1] nuclear emulsions,[2] or counters for the photoprotons.[3]

Various theories of the nuclear gamma-absorption have been proposed.[4,4a] Of these, the most satisfactory hypothesis seems to be that the excitation takes place as a result of an interaction between the x-rays and the individual protons in the nucleus.[4a] At low excitation energies ($\lesssim$10 Mev above the threshold), there is greater probability for the energy to be statistically distributed in the nucleus and consequently for protons to come out with low energy and spherical symmetry. At higher energies, however, the protons have increasing probability to come out before their energies have been shared among the other nucleons. These protons emerge preferentially in the direction of polarization of the primary x-ray beam.

In the present experiments the photoprotons from a number of elements have been studied with a scintillation counter telescope in an attempt to attain a better understanding of the phenomenon.

EXPERIMENTAL

Bremsstrahlung from the University of Chicago betatron, operated up to a maximum energy of 50 Mev, was collimated to 1.5 cm at 4 meters from the target with lead and concrete. The photoprotons were gener-

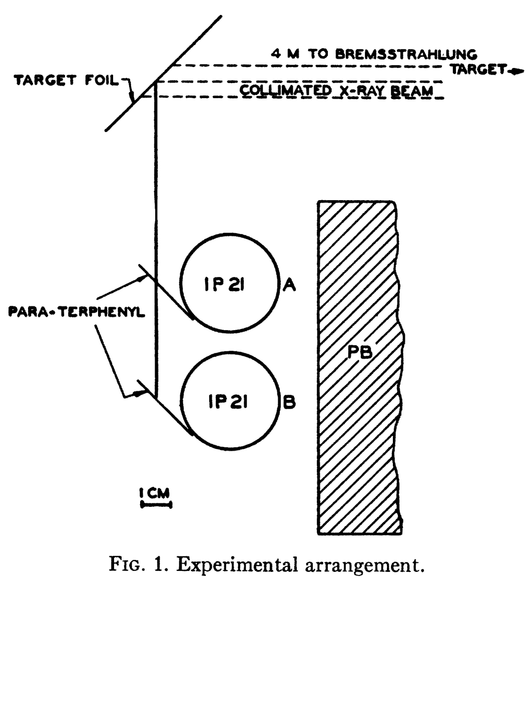

FIG. 1. Experimental arrangement.

* This work was supported by the joint program of the ONR and AEC.

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[2] Curtis, Hombosted, Lee, and Salant, Phys. Rev. **77**, 290 (1950); B. C. Diven and G. M. Almy, Phys. Rev. **80**, 407 (1950); Toms, Halpern, and Stephens, Phys. Rev. **77**, 753 (1950).

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[4] M. Goldhaber and E. Teller, Phys. Rev. **74**, 1046 (1948).

[4a] L. I. Schiff, Phys. Rev. **73**, 1311 (1948); E. D. Courant, Phys. Rev. **74**, 1226 (1948); J. S. Levinger and H. A. Bethe, Phys. Rev. **78**, 115 (1950) (extensive bibliography).