It should be pointed out that this measurement and that of Muehlhause[9] are both dependent on the same standard boron cross section, so they only serve to check each other on the boron-to-hydrogen ratio. The standard boron cross section has as yet not been confirmed by other laboratories. Any change in the accepted value of this cross section will, of course, produce a proportionate change in the value of the capture cross section of hydrogen.

Because this experiment seems relatively free of uncertain corrections and the principal source of error appears to be the statistics of the activity ratio measurements of the two solutions, we believe that it would be entirely possible to reduce the error in σ_H to about $\frac{1}{2}$ percent. The effort involved in this would be warranted however only after there was more certainty in the capture cross-section standards.

It is a pleasure to express our gratitude to the following members of this laboratory: Dr. L. A. Turner for several suggestions on the method used in this experiment, to Dr. David Rose for his measurement of the NaI capture cross section, and to Mr. Ralph Bane and Mr. Ralph Telford for their careful boron and iodine analyses.

PHYSICAL REVIEW VOLUME 90, NUMBER 4 MAY 15, 1953

Inner Bremsstrahlung Associated with K Capture in A^{37}†*

CARL E. ANDERSON,‡ GEORGE W. WHEELER, AND W. W. WATSON
Yale University, New Haven, Connecticut

(Received February 2, 1953)

An investigation has been made of the inner bremsstrahlung accompanying K capture in A^{37}. The inner bremsstrahlung energy distribution was examined by absorption and scintillation spectrometer techniques and found to agree with that predicted by theory. A Kurie-type plot showed the maximum energy of the gamma-radiation to be 815±15 kev.

INTRODUCTION

THE theory of inner bremsstrahlung associated with beta-decay processes was extended to the case of K capture by Morrison and Schiff[1] in 1940. More recently, Jauch[2] has reviewed and improved the theory. The first experimental evidence for the existence of this inner bremsstrahlung was found by Bradt *et al.*[3] in the nucleus Fe^{55}. Later investigations on the same nucleus by Maeder and Preiswerk;[4] Jauch;[2] and Bell, Jauch, and Cassidy[5] have confirmed Bradt's conclusions and have also yielded further knowledge of the K capture transition energy and the gamma-radiation energy distribution. Up to the present investigation, Fe^{55} is the only nuclide shown to emit inner bremsstrahlung with K capture.

The theory shows, essentially, that the relative probability of photon emission per K capture is given by

$$\frac{dP}{P_0}=\frac{\alpha}{\pi m^2}\left(1-\frac{\omega}{W_0}\right)^2\omega d\omega \qquad (1)$$

and that the total number of photons emitted per K capture is given by

$$\int_0^{W_0}\frac{dP}{P_0}=\frac{\alpha}{12\pi}\left(\frac{W_0}{m}\right)^2. \qquad (2)$$

Here dP is the probability per unit time for photon emission, P_0 is the probability per unit time for K capture, ω is the energy of the photon, W_0 is the energy available for the transition, m is the rest energy of the electron, and α the fine structure constant. It has also been shown by Jauch[2] that it is possible to write (1) in such a form that a linear plot may be made of the experimental data. That is,

$$N(\omega)d\omega=C(\omega)\frac{\alpha}{\pi m^2}\frac{\omega}{W_0^2}(W_0-\omega)^2d\omega, \qquad (3)$$

where $N(\omega)$ is the number of photons having energy between ω and $\omega+d\omega$, and $C(\omega)$ is a slowly varying function (except at low energies) which is therefore treated as a constant. Upon simplification we have

$$K[N(\omega)/\omega]^{\frac{1}{2}}=W_0-\omega, \qquad (4)$$

where K is a constant. The intercept of this straight line on the energy axis will be W_0, the energy available for the transition.

HALF-LIFE

The A^{37} source was prepared by irradiating enriched argon gas for 30 days in the Brookhaven reactor. The

† This paper is part of a dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Yale University by C. E. A. A preliminary report on the results has appeared in Phys. Rev. **87**, 668 (1952).

* This work was supported by the U. S. Atomic Energy Commission.

‡ Now at the General Electric Research Laboratory, Schenectady, New York.

[1] P. Morrison and L. I. Schiff, Phys. Rev. **58**, 24 (1940).
[2] J. M. Jauch, Oak Ridge National Laboratory Report ORNL 1102, 1951 (unpublished).
[3] H. Bradt *et al.*, Helv. Phys. Acta **19**, 222 (1946).
[4] D. Maeder and P. Preiswerk, Phys. Rev. **84**, 595 (1951).
[5] Bell, Jauch, and Cassidy, Science **115**, 12 (1952).

argon had been enriched by means of thermal diffusion[6] to 96 percent A^{36}, 1 percent A^{38}, and 3 percent A^{40}. The irradiated gas was transferred from a quartz breakseal to a brass chamber having thin (9.7 mg/cm^2) aluminum foil windows. This made it possible to observe the low energy gamma-rays and to be free of activities present in the quartz.

To verify that the observed gamma-ray continuum was indeed due to A^{37}, the half-life of this continuum was determined. The decay curve is shown in Fig. 1. The measured half-life of 32 days agrees, within statistics, with the value of 34.1 days found by Weimar *et al.*[7]

The theory developed by Morrison and Schiff and by Jauch applies only to allowed transitions, and consequently, it is necessary to show that the transition $A^{37}\rightarrow Cl^{37}$ is allowed before making use of the results of this theory. A calculation of the ft value of the process indicates that the transition is indeed allowed. For an allowed transition in this case $f_k^0(\epsilon_0)\cong 0.095$

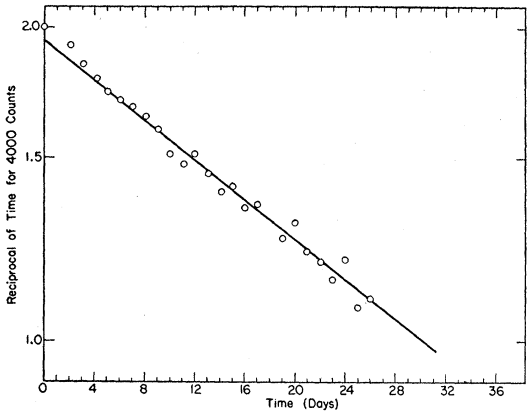

FIG. 1. Gamma-ray continuum half-life curve.

and for a first forbidden transition $f_k'(\epsilon_0)\cong 2.0\times 10^{-3}$. From these f values the predicted half-lives are $t_{\frac{1}{2}}=5.0\times 10^5$ sec and $t_{\frac{1}{2}}=2.4\times 10^9$ sec, respectively. As the half-life is $t_{\frac{1}{2}}=2.8\times 10^6$ sec, the transition falls within the region of allowed transitions.

ENERGY DISTRIBUTION

Absorption Method

The absorption method consists in comparing an observed absorption curve with a curve calculated from the theoretical distribution curve, Fig. 2. To calculate the absorption curve the continuum was approximated by a set of mono-energetic gamma-rays whose intensities are proportional to the area of the energy region they represented. The individual absorption curves of these gamma-rays are then graphically added to obtain the complex absorption curve of the continuum.

[6] A. Zucker and W. W. Watson, Phys. Rev. **79**, 241 (1950).
[7] Weimar, Kurbatov, and Pool, Phys. Rev. **66**, 209 (1944).

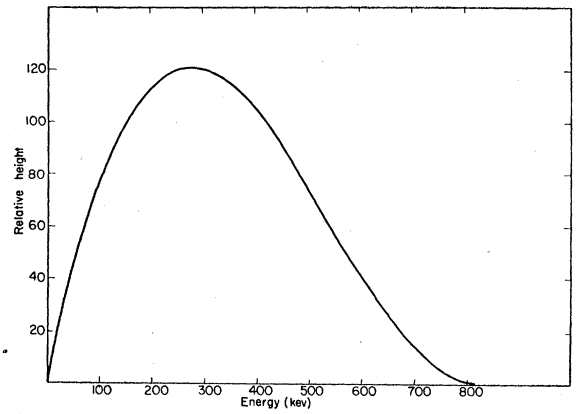

FIG. 2. Theoretical inner bremsstrahlung distribution, $W_0=816$ kev.

The observed absorption curve in lead was taken using an anthracene scintillation counter as detector. The theoretical absorption curve was calculated in the aforementioned manner after modification of the theoretical energy distribution for the variation of detector efficiency with energy (in this case, the percent transmission of the phosphor). The calculated and observed absorption curves are shown in Fig. 3. The agreement is good except at low absorber thickness. This is believed to arise from a compromise made between collimation and counting rate which allowed slightly more high than low energy gamma-rays to enter the detector.

Scintillation Spectrometer Method

Scintillation spectroscopy has been applied successfully to the measurement of continua by Madansky and

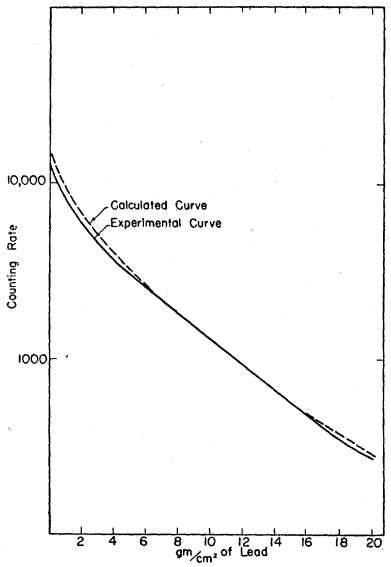

FIG. 3. Absorption curves in lead.

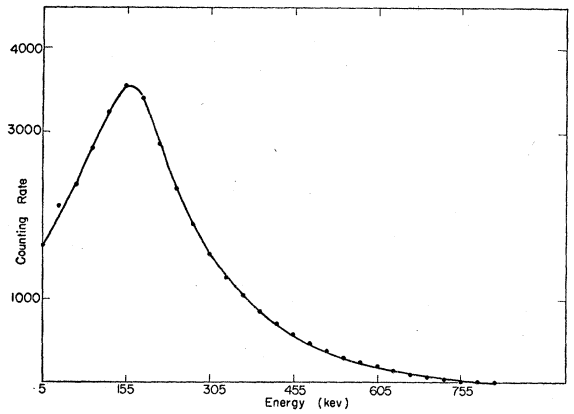

FIG. 4. Pulse-height distribution of gamma-ray continuum.

Rasetti;[8] Jauch;[2] Maeder and Preiswerk;[4] and Bell, Jauch and Cassidy.[5] Following the method used by Madansky and Rasetti, the effect of the finite resolution of the spectrometer was determined. This is done by assuming that only the photoeffect occurred and that the pulse spectrum of a mono-energetic gamma-ray can be represented by a Gaussian function. Therefore, the pulse-height distribution is given by

$$f(s)=(2\pi\sigma^2)^{-\frac{1}{2}}\int_0^1 f(\epsilon)\exp\left[-\frac{(s-\epsilon)^2}{2\sigma^2}\right]d\epsilon, \qquad (5)$$

where $f(\epsilon)$ is $(1-\epsilon)^2\epsilon$, the theoretical distribution, $\epsilon=\omega/W_0$, and σ is a width parameter. Assuming a resolution of 15 percent at 661 kev, we determined $f(s)$. Graphical comparison of $f(s)$ with $f(\epsilon)$ showed that no significant distortion occurred except at the end points of the distribution.

In all of the investigations mentioned above,[2–5,8] the maximum energy was low enough so that only photoelectric conversion was of importance in the phosphor and little distortion occurred from the presence of the Compton effect. This distortion is not readily susceptible to calculation. In the case of A^{37}, W_0 is about 800 kev, and thus significant distortion will occur. We can only say that the result will be to increase the maximum and shift it to lower energy, preventing a direct comparison of the experimental and theoretical distributions. However, by following the method of Jauch it is still possible to determine the maximum energy by means of a Kurie plot, because the distortion is small at the high energy end of the spectrum.

[8] L. Madansky and F. Rasetti, Phys. Rev. **83**, 187 (1951).

The photomultiplier used was an RCA 5819, while the phosphor was a $1\frac{1}{2}$ in. diameter$\times$1 in. thick NaI(Tl) crystal, roughly polished and imbedded in dry MgO powder. This arrangement gave a resolution of 11 percent at 661 kev. The spectrometer was calibrated with the following four sources: Cs^{137} (661 kev), Au^{198} (411 kev), Hg^{203} (285 kev), and W^{185} (135 kev).

The pulse-height spectrum obtained is shown in Fig. 4. This spectrum must be corrected for the variation of the counting efficiency with energy of the spectrometer. We have used as the most reasonable correction factor the variation of the percent absorption with energy of the 1-in. thick NaI crystal. This choice is only an approximation. Of course a very thick crystal would not require any correction. Perhaps a better correction could be deduced for our crystal from an analysis of the pulse-height distribution of a number of mono-energetic gamma-rays.

The corrected spectrum was then used to construct the Kurie plot shown in Fig. 5. For comparison, the

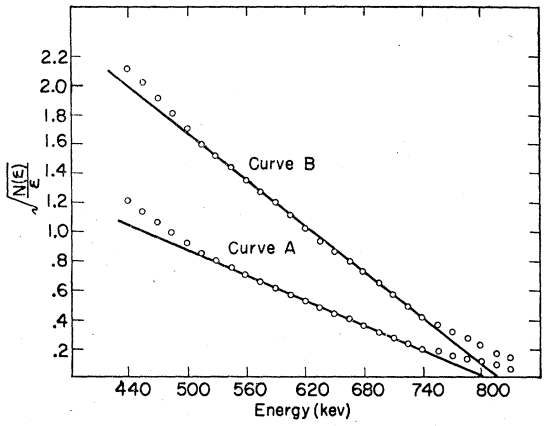

FIG. 5. "Kurie plots," curve A uncorrected data, curve B, after modification of data for detector efficiency.

Kurie plot of the uncorrected data is also shown. The maximum energy W_0 obtained from the Kurie plot is 815 ± 15 kev. This value agrees well with that obtained from nuclear reaction data. Using the Q value of the reaction $Cl^{37}(p,n)A^{37}$, Richards, Smith, and Browne[9] obtain a value of 816 ± 4 kev, while Schoenfeld, Duborg, Preston, and Goodman[10] obtain a value of 816 ± 2 kev.

[9] Richards, Smith, and Browne, Phys. Rev. **80**, 524 (1950).
[10] Schoenfeld, Duborg, Preston, and Goodman, Phys. Rev. **85**, 873 (1952).