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Observations on the 4.43-Mev Gamma Rays from C^{12}†

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A scintillation spectrometer has been used for "fore and aft" measurements to demonstrate that the 4.43-Mev gamma radiation from $Be^9(\alpha,n\gamma)C^{12}$ exhibits a Doppler shift as the result of motion of the emitting nucleus. This implies a lifetime for the C^{12} excited state less than 3×10^{-13} second. The Compton electron spectrum from a thin converter has been studied in a magnetic lens spectrometer to produce a value for the level excitation of 4.425 ± 0.020 Mev. The spectrum of internal pairs has been found to agree most closely (to 5 percent) with the (known) assignment of the radiation as electric quadrupole.

INTRODUCTION

THE only gamma radiation of substantial intensity produced by the bombardment of beryllium with low-energy alpha particles is the 4.43-Mev line from $Be^9(\alpha,n\gamma)C^{12}$. The excitation energy of the emitting level is well known: 4.432 ± 0.008 Mev is the average of figures quoted by Ajzenberg and Lauritsen.[1] The angular momentum of the level is 2^+: this is the only assignment which is consistent with all of 13 angular distribution and correlation measurements quoted by the above authors as well as the observed branching ratio of the B^{12} beta decay.[2] Such a well-investigated solitary gamma line constitutes a useful standard for the evaluation of techniques of gamma-ray spectroscopy. This paper presents evidence that the line exhibits a Doppler shift due to motion of the emitting nucleus. This is followed by an energy measurement based on the spectrum of Compton electrons from a thin converter, and a multipole-order determination from the internal pair spectrum. Only the first datum provides new information about the excited nuclear state; the others may be regarded primarily as demonstrations of method.

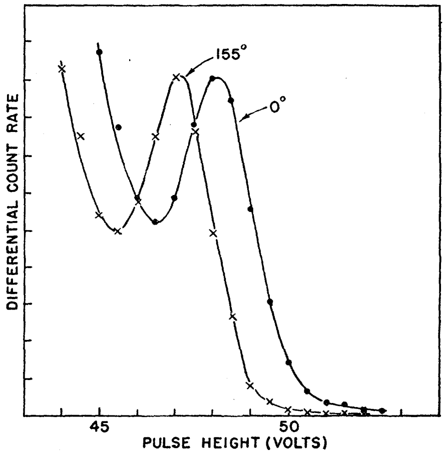

FIG. 1. Pulse-height spectrum in NaI(Tl) from $Be^9(\alpha,n\gamma)C^{12}$ in the region of the "full-energy" peak for the 4.43-Mev gamma radiation. Circles represent readings taken with counter in line with the beam; crosses correspond to 155 degrees. Peak heights have been drawn equal.

DOPPLER SHIFT

This experiment consisted of a measurement of the energy difference of gamma rays emitted at different directions with respect to a beam of He^+ ions from a 3-Mev electrostatic accelerator. Such a difference is expected to be caused by the net forward motion of the emitting nuclei (imparted by the bombarding particles) unless these are stopped before the emission. The beam energy was adjusted by electrostatic analysis to give maximum gamma-ray yield from an 0.09-mg/cm² Be target at a strong resonance[3] at 1.90 Mev. The gamma rays were studied with a scintillation spectrometer employing a cylindrical NaI(Tl) crystal (1.5 in. diam. ×1.5 in. long), a Dumont type-6292 photomultiplier, and a 10-channel pulse analyzer. The counter was placed 15 centimeters from the target, in turn at 0 degrees and at 155 degrees with respect to the beam. At each position, the "full-energy" peak produced by the 4.43-Mev line was studied. The stability of the system was checked frequently by measurements on the 2.62-Mev line from ThD.

One of three sets of spectra is shown in Fig. 1. The average distance between the peaks corresponds to an energy difference of 2.1 ± 0.3 percent of the line energy, or about 93 kev. The maximum shift expected to result from center-of-mass motion, given (to first order) by

$$(v/c)(\cos 0^\circ-\cos 155^\circ),$$

where v/c is the velocity of the center of mass relative to the velocity of light, is 1.88 percent. From this good agreement, it appears that the lifetime of the 4.43-Mev level is less than the stopping time for the recoiling C^{12*} in the tantalum backing, about 3×10^{-13} second. The single-particle model[4] suggests a lifetime of about 1.5×10^{-13} second.

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† Assisted by the joint program of the U. S. Office of Naval Research and the U. S. Atomic Energy commission.

[1] F. Ajzenberg and T. Lauritsen, Revs. Modern Phys. **24**, 321 (1952).

[2] G. Vendryes, Compt. rend. **233**, 391 (1951).

[3] F. L. Talbott and N. P. Heydenburg, Phys. Rev. **90**, 186 (1953).

[4] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1952).

GAMMA-RAY ENERGY

In the following measurements, a magnetic-lens spectrometer was used in a manner described in earlier communications.[5,6] The detector of focused particles was an Amperex type-200C Geiger counter with a 1.2-mg/cm^2 mica end window. The He$^+$ beam energy was set at 2.2 Mev.

Figure 2 shows the spectrum of Compton electrons produced in a 19-mg/cm^2 Be target-converter. The solid curve is a theoretical spectrum expected from gamma radiation of energy 4.465 Mev. It was computed by folding the Klein-Nishina momentum distribution [TL, Eq. (4a)][5] with functions representing the spectrometer window (a Gaussian of width 1.9 percent of electron momentum), energy losses in the converter, and Doppler shift distribution (computed from nuclear motion in the center-of-mass system). The calculations were simplified by approximating the last two functions by Gaussians (widths 0.5 percent and 1.1 percent of electron momentum at 15.3 kilogauss-cm, respectively). The Doppler shift distribution is expected to be uniform, since the gamma emission follows the emission of *s*-wave neutrons (see reference 1), so the approximation is adequate. Account was taken of the variation of the spectrometer window with momentum setting and of the effect of the Compton recoil angle [TL, Eq. (7a)], though the latter correction amounted to less than 1.5 percent over the range covered. Multiple scattering corrections were estimated to be negligible.

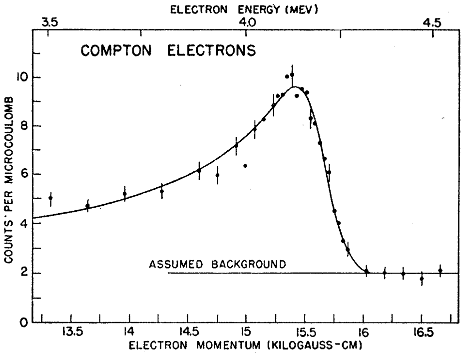

FIG. 2. Spectrum of Compton electrons produced by 4.43-Mev gamma radiation in a 19-mg/cm^2 Be converter. The solid curve represents a theoretical line shape. All points near peak correspond to same total bombardment.

The energy of gamma radiation emitted at 20° with respect to the beam (the spectrometer acceptance angle) is thus found to be 4.465 ± 0.020 Mev. Correcting for the Doppler shift gives as a value for the level excitation 4.425 ± 0.020 Mev, in good agreement with other data. An earlier measurement at this laboratory,[5] made by employing a thick converter, gave a level energy 4.443 ± 0.020 Mev.

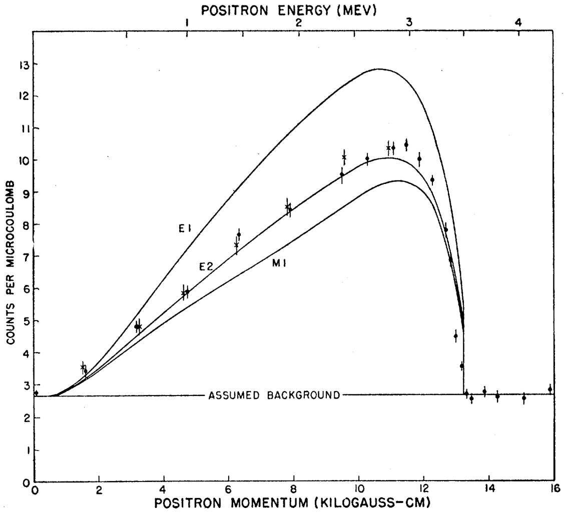

FIG. 3. Positron spectrum. Internal pairs from the 4.43-Mev transition. Solid curves represent theoretical spectra normalized on measured gamma-ray yield. *E*1 represents electric dipole; *E*2, electric quadrupole; etc. Circles represent points taken with a 19-mg/cm^2 target; crosses, those from an 0.25-mg/cm^2 target (arbitrarily normalized at 11 kilogauss-cm).

INTERNAL PAIRS

The same target was used to investigate the positron spectrum (shown in Fig. 3, solid circles). It was then backed with a thick (700-mg/cm^2) Al converter to measure the gamma-ray yield, employing the method[5,6] of comparison of experimental points with a theoretical spectrum. This yield value (uncertain to about 8 percent) was then used to normalize the theoretical positron spectra corresponding to the various multipole orders shown in Fig. 3 (where *E*1 designates the electric dipole curve, etc.). The Born approximation spectra[7] have been corrected at the end point,[8] although the fold with the spectrometer window would largely offset this adjustment.

As a test of the effect of target thickness on the spectrum, the positron measurement was performed on an unbacked 0.25-mg/cm^2 Be target. The points, arbitrarily normalized to match the earlier ones at 11 kilogauss-cm, are shown as crosses in the figure. They show no discernible deviation from the others.

The ratios of the areas under the theoretical curves to the area under the experimental curve (between 2 and 13 kilogauss-cm) give a measure of agreement between data and theory. They are:

$E1$: 1.33 ± 0.12,
$E2$: 0.95 ± 0.09,
$M1$: 0.83 ± 0.08,
Others: $\leqslant 0.78 \pm 0.07$,

where the assigned errors include the yield uncertainty. The comparison shows to what extent assignments

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[5] R. G. Thomas and T. Lauritsen, Phys. Rev. **88**, 969 (1952); this paper will be referred to as TL.

[6] R. J. Mackin, Jr., Phys. Rev. **94**, 648 (1954).

[7] M. E. Rose, Phys. Rev. **76**, 678 (1949); **78**, 184 (1950).

[8] M. E. Rose and G. Uhlenbeck, Phys. Rev. **48**, 211 (1935).

other than $E2$ may be excluded by the present data. The total internal pair coefficient (which is proportional to the area under a curve of counts/momentum) was found to be 4.0 percent greater than that predicted for $E2$ radiation. This is not felt to be as significant as the previous comparison because of the extra weight given the low-momentum points.

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Production of I^{124} by the Deuteron Bombardment of Tellurium

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We have observed a nuclear reaction not previously reported: the production of I^{124} by the deuteron bombardment of tellurium. The I^{124} was identified by decay and gamma-ray pulse-height studies using a well-type scintillation counter. We report also some observations on the relative amounts of the different iodine isotopes produced by the bombardment.

FOR those who are interested in the use of radioactive iodine isotopes, we would like to call attention to a means of producing I^{124}, which apparently has not been reported previously in the literature.[1] We have observed that substantial amounts of I^{124} are produced when ordinary tellurium is bombarded with the deuteron beam of a cyclotron, the reactions presumably being $Te^{124}(d,2n)$ and $Te^{123}(d,n)$.

In our work the tellurium was exposed to a beam of 20-Mev deuterons for 50-microampere hours. The I^{124} was identified by the study of its gamma-ray spectrum with a well-type (2-in. × $1\frac{5}{8}$-in. diameter) NaI scintillation crystal and a single-channel pulse-height analyzer. After five days (during which time the I^{130} component in the product decayed to an insignificant amount) the bulk of the gamma radiation, apart from the contribution from I^{131}, was observed to count in the pulse-height range between 0.50 and 0.75 Mev, while the main I^{124} gamma lines have been reported to be 0.60 and 0.73 Mev.[2] Scintillation pulses were observed in much weaker intensity up to about 2 Mev but not higher, which is consistent with the reported weak gamma rays of 1.7 and 1.95 Mev from I^{124}. Also, decay data taken between eight and thirty days after bombardment gave a half-life for the pulses between 0.75 and 1.4 Mev of 4.6 days, coinciding well with the reported I^{124} half-life of 4.5 days.[3]

In the deuteron bombardment of tellurium, iodine isotopes 124, 126, 130, and 131 are produced. No study was made of the relatively short-lived 130 component, but the relative amounts of the others were obtained from analysis of decay data taken between six and thirty days after bombardment. For I^{126}, whose gamma spectrum and counting efficiency in the crystal are quite similar to I^{131}, we found the activity (extrapolated back to bombardment time) to be 0.4 times the activity of the 131 component. For I^{124}, the counting efficiency in the crystal is quite different, but we estimate the I^{124} activity to be approximately twice the I^{131} activity immediately after bombardment.

The iodine was separated from the tellurium prior to the measurements by chemical procedures which should have precluded the presence of tellurium or any other elements. The fact that all the activity was from iodine isotopes was confirmed by a chemical reaction: When the active material was coupled to antibody protein, its degree of combination was the same as that of I^{131} in the sample.

We wish to thank W. Harris of the Brookhaven National Laboratories for his collaboration in this work.

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[1] The compilation of Hollander, Perlman, and Seaborg, Revs. Modern Phys. **25**, 469 (1953) lists three means of producing I^{124}: the spallation of tin, the alpha-particle bombardment of antimony, and the proton bombardment of tellurium.

[2] The values quoted for the radiations from I^{124} are taken from *Nuclear Data*, National Bureau of Standards Circular No. 499 (U. S. Government Printing Office, Washington, D. C., 1950).

[3] The decay data were taken in this pulse-height band, despite its exclusion of the main I^{124} lines, in order to avoid any counts from the 0.64-Mev gamma line of I^{131}. The observed pulses were from Compton scattering of the high-energy I^{124} gamma rays.