The Energy of Gamma-Rays Accompanying the Decay of Be^7

IGNACE ZLOTOWSKI AND JOHN H. WILLIAMS
University of Minnesota, Minneapolis, Minnesota

(Received April 21, 1942)

Coincidence counter measurements have been made on the absorption of secondary electrons produced by the gamma-rays accompanying the decay of Be^7. The gamma-rays from the annihilation of N^{13} positrons were used for calibration of the absorbing system. The maximum ranges in aluminum are respectively 0.86 ± 0.04 mm for the annihilation radiation and 0.77 ± 0.03 mm for that due to Be^7. The energy of the latter was found to be 0.485 ± 0.005 Mev by assuming gamma-rays of 0.510 Mev from N^{13}. The agreement between the experimental result and the low excited level of Li^7 (0.475 Mev) deduced from other reactions confirms the suggestions of previous authors that the observed gamma-rays from Be^7 originate from this excited state of Li^7 which is created by electron capture.

INTRODUCTION

THE 43-day half-life radioactivity observed in lithium targets bombarded with deuterons has been assigned[1] to Be^7 from the reaction $Li^6(d,n)Be^7$. Since no charged particle emission could be detected the radioactivity was explained by the capture of an orbital electron by the nucleus of Be^7 following the equation: $Be^7+e^-\rightarrow Li^7+\eta$, where η denotes the neutrino.[2]

Later Roberts, Heydenburg, and Locher[3] discovered a gamma-ray accompanying the decay of Be^7 and from absorption of this radiation in lead obtained a value of its energy quantum of 0.425 ± 0.025 Mev. A similar result (0.425 ± 0.020 Mev) obtained by using Be^7 from the reaction $B^{10}(p,\alpha)Be^7$ and the cloud-chamber method for determining the secondary electrons spectrum has been reported by Maier-Leibnitz.[4] The observed gamma-rays have been interpreted as an evidence of an excited state in Li^7 produced during the radioactive transmutation of Be^7 : $Be^7+e^-\rightarrow Li^{7*}+\eta$ and $Li^{7*}\rightarrow Li^7+(h\nu)_\gamma$.

As a matter of fact there are several indications of the formation of Li^7 in an excited state at 0.4 to 0.5 Mev. The mean energy separation of the two states of Li^7 as measured from the proton groups occurring during the deuteron bombardment of Li^6 was computed to be $0.455+0.015$ Mev.[5] From the apparent absorption coefficient in lead and aluminum of gamma-rays emitted during the bombardment of separated Li^7 target with protons Fowler and Lauritsen[6] found that the excitation energy was equal to 0.495 ± 0.025 Mev. Hudson, Herb, and Plain[7] obtained a value of 0.459 Mev for the energy of these gamma-rays, due to excitation of Li^7 without capture of the incident proton. From the difference between the energy release of the reaction $Be^9(d,\alpha)Li^7$ deduced from the alpha-particle range and that calculated from the most recent mass determination, the higher energy level in Li^7 was computed to be 0.494 ± 0.016 Mev.[8] The excitation energy deduced from the recent range determination of the two groups of alpha-particles from the reaction $B^{10}(n,\alpha)Li^7$ was 0.470 Mev.[9] And finally the Li^7 excited level calculated from the difference between the energy release value of the latter reaction deduced from the alpha-particle range and that deduced from the exact mass values is estimated to be 0.48 Mev.[10]

Within the limits of experimental error the above results are in good agreement with each other, the mean value being equal to 0.475 ± 0.020 Mev. However, there is an evident discrepancy between this result and the above discussed energy of gamma-rays from Be^7. The question

[1] L. H. Rumbaugh, R. B. Roberts, and L. R. Hafstad, Phys. Rev. **54**, 657 (1938).
[2] R. B. Roberts and N. P. Heydenburg, Phys. Rev. **53**, 929 (1938).
[3] R. B. Roberts, N. P. Heydenburg, and G. L. Locher, Phys. Rev. **53**, 1016 (1938).
[4] H. Maier-Leibnitz, Naturwiss. **26**, 614 (1938).
[5] J. H. Williams, W. G. Shepherd, and R. O. Haxby, Phys. Rev. **52**, 390 (1937); L. H. Rumbaugh, R. B. Roberts, and L. R. Hafstad, reference 1.
[6] W. A. Fowler and C. C. Lauritsen, Phys. Rev. **56**, 841 (1939).
[7] C. M. Hudson, R. C. Herb, and G. J. Plain, Phys. Rev. **57**, 587 (1940).
[8] E. R. Graves, Phys. Rev. **57**, 885 (1940).
[9] M. S. Livingston and J. G. Hoffman, Phys. Rev. **53**, 227 (1938).
[10] J. C. Bower, E. Bretcher, and C. W. Gilbert, Proc. Camb. Phil. Soc. **34**, 290 (1938).

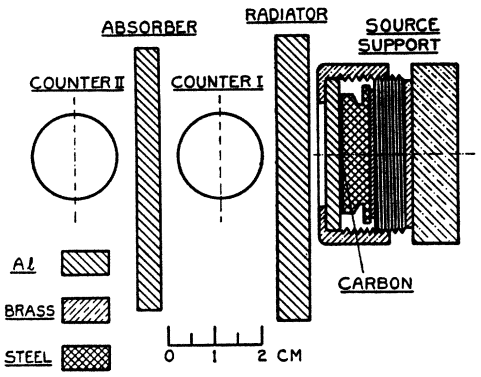

FIG. 1. Counters and source disposition in the absorption experiments.

arises as to whether in both cases one has to do with the same excitation level or with two different energy states if not two different nuclear phenomena.

EXPERIMENTAL METHOD

Since the energy of gamma-rays can be determined with much greater accuracy from the measurement of the range of the recoil electrons projected by incident radiation than from direct measurement of its absorption coefficient, the method used by Rumbaugh, Roberts, and Hafstad, we determined the energy of the Be^7 gamma-rays by measuring the maximum range of Compton electrons in aluminum placed between two Geiger-Müller counters in a coincidence circuit.[11]

We have investigated the gamma-rays from a thick target of LiOH which was previously bombarded with 15 μa-hours of 2.7-Mev deuterons accelerated by the Minnesota pressure Van de Graaff generator.[12]

We used two glass G-M counters filled with a mixture of argon ($p=10$ cm of Hg) and ethyl alcohol ($p=1$ cm of Hg). They were 1.8 cm in diameter and 10 cm long. A thin platinum layer evaporated on the inside of the glass tubes served as the cathode. The effective thin portions of the glass envelopes were 0.12 to 0.16 mm thick. The thickness of the aluminum plate used as a source of secondary electrons was 7 mm. The arrangement of target, secondary radiator, absorbers, and counters was similar to that shown for the case of a N^{13} source in Fig. 1.

The Neher-Harper method of quenching the discharges was used. The pulses from the amplifier were recorded through a scale-of-eight circuit. The threshold for both counters was the same (910 ± 15 volts) and the length of the flat portions of their characteristics about 125 volts. The small regular increase in the single counting rate with counter overvoltage within the flat portion limits never exceeded 0.2 percent per volt. Our coincidence circuit had a resolving time of $3.6\pm0.5\times10^{-6}$ sec. The experimental results collected in Table I show that it was practically independent of the single counting rates in the counters. The gamma-rays from a well-shielded radium source were used in order to get the number of chance coincidences (C_t-C_c) as a function of the single counting rates (s_I and s_{II}). Sufficient precautions were taken with regard to the geometry of the system to exclude the possibility of an error due to the presence of some genuine coincidences. The errors in the table represent the root-mean-square values.

The gamma-rays from the annihilation of N^{13} positrons were first studied to obtain a calibration of our absorbing system in the region of 0.5 Mev. Radioactive nitrogen was prepared by deuteron bombardment of a carbon target prepared by deposition of pure acetylene carbon black onto a sheet of tantalum, a metal giving no products of disintegration with observable gamma-rays. The measurements over an hour gave a value of 10.1 ± 0.2 minutes for the radio-nitrogen half-life, in excellent agreement with some recent evalua-

TABLE I. Counting rates.

Single counts per min. Counter I s_I	Counter II s_{II}	Total coincidence rate per minute C_t	Cosmic-ray coincidences per minute C_c	Resolving time $\tau=\frac{60(C_t-C_c)}{2s_Is_{II}}$ sec.
2760	2810	1.07 ± 0.06	0.09	$3.8\pm0.3\times10^{-6}$
2690	2740	0.99 ± 0.08	0.08	$3.7\pm0.4\times10^{-6}$
1920	2045	0.53 ± 0.04	0.06	$3.6\pm0.4\times10^{-6}$
1309	1428	0.26 ± 0.03	0.07	$3.1\pm0.5\times10^{-6}$
1215	1244	0.24 ± 0.03	0.07	$3.6\pm0.4\times10^{-6}$
1120	1272	0.25 ± 0.04	0.06	$4.1\pm0.8\times10^{-6}$

Mean value $3.6\pm0.5\times10^{-6}$ sec.

[11] For details see: W. Bothe and J. Becker, Zeits. f. Physik **76**, 428 (1932); F. Rasetti, Zeits. f. Physik **97**, 64 (1935); S. C. Curran, P. I. Dee and V. Petržilka, Proc. Roy. Soc. (London) **A169**, 269 (1939).

[12] The experimental arrangement is described in the paper by J. H. Williams, L. H. Rumbaugh, and J. T. Tate, Rev. Sci. Inst. **13**, 202 (1942).

tions.[13] Without attempting to explain why, it is to be noted however that in order to get a regular decay curve it is necessary to heat the carbon target after bombardment for at least three minutes.

Figure 2 shows the absorption curves of the secondary electrons from both kinds of gamma-rays. All data obtained have been corrected for chance coincidences calculated as a function of single counts for each counter and the resolving time of our coincidence circuit. The maximum ranges are, respectively: $(a+0.37\pm0.03)$ millimeters of aluminum for electrons from Be^7 gamma-rays and $(a+0.46\pm0.04)$ millimeters for those from the annihilation radiation. a denotes the absorption power of three counter walls in aluminum equivalent.

CALCULATIONS

For gamma-rays of energy between 0.1 and 30 mc^2, the absorption in aluminum is principally due to the Compton scattering. From the relativistic relation between momentum and energy of an electron projected by a light quantum as a result of a collision, the amount of energy transferred to the electron is given by the formula.

$$E=E_0-E_0\cdot\mu/[\mu+E_0(1-\cos\theta)], \qquad (1)$$

where E_0 is the initial energy of the incident gamma-ray quantum, θ is the angle between the initial and final directions of its momentum and μ denotes as usual the rest energy of an electron.[14] Since the frequency shift of the scattered radiation is maximum for $\theta=180°$, the maximum energy transferred is

$$E_{\max}=2E_0^2/2E_0+\mu.$$

In the case of the annihilation radiation $E_0=\mu$, and

$$E_{\max}=(\tfrac{2}{3})\mu=0.340 \text{ Mev}.$$

The range-energy relation in aluminum for beta-rays between 0.25 and 0.40 Mev is represented in Fig. 3. The curve shows the values obtained by numerical integration from a graph of the reciprocal of $(-dE/dR)$ plotted against E, the average energy-loss per unit of path being calculated from Bloch's equation.[15]

By use of these data the total range of 0.86 $\pm$0.04 mm of aluminum is obtained for the 0.340 Mev beta-rays. Hence the absorption power a of the three counter walls which each secondary electron is passing through in our coincidence set-up is equivalent to: $0.86-0.46\pm0.04=0.40$ ±0.04 millimeters of aluminum. Since the same counter walls acted as an additional absorber in the case of secondary electrons from the Be^7 gamma-rays, it may be readily calculated that

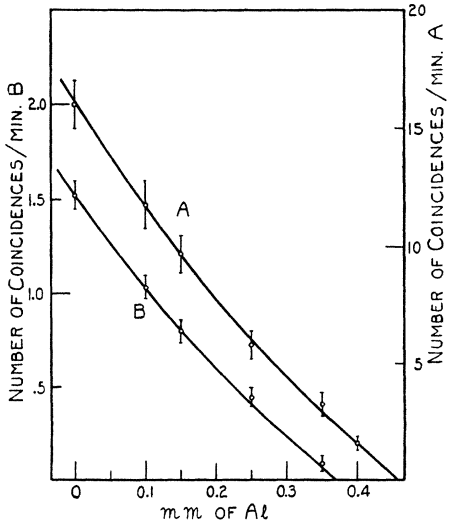

FIG. 2. Absorption curves (in aluminum) of secondary electrons from (A) the N^{13} annihilation radiation and (B) the gamma-rays accompanying the decay of Be^7.

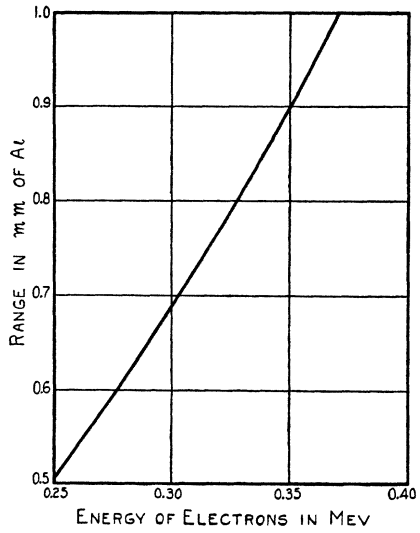

FIG. 3. Range-energy relation in aluminum for low energy electrons.

[13] See: A. G. Ward, Proc. Camb. Phil. Soc. **35**, 523 (1939); G. T. Seaborg, Chem. Rev. **27**, 199 (1940).

[14] W. Heitler, *Quantum Theory of Radiation* (Oxford, 1936), p. 217.

[15] F. Bloch. Zeits. f. Physik **81**, 363 (1933); E. E. Widdowson, Proc. Phys. Soc. (London) **50**, 185 (1938).

the total range of these electrons was equal to $0.40+0.37\pm0.03=0.77\pm0.03$ mm of Al. Their maximum energy computed from the energy-range graph should be 0.320 ± 0.005 Mev. By substituting this value into formula (1) it follows immediately that the initial energy of the gamma-rays accompanying the radioactive decay of Be^7 is 0.485 ± 0.005 Mev.

CONCLUSIONS

It should be mentioned that the presence of 0.28 Mev gamma-rays of N^{13}, reported by several authors,[16] could not affect our calculations based upon the maximum range of secondary electrons from radio-nitrogen gamma-radiation. On the other hand it is apparent from the experimental absorption curve for these electrons that there is a very little if any amount of incident gamma-rays with energy above 0.510 Mev.

[16] J. R. Richardson, Phys. Rev. **55**, 609 (1939); E. M. Lyman, Phys. Rev. **55**, 1123 (1939).

Owing to the large value of the slope of the energy-range curve for soft beta-rays the accuracy of our range determination permits us to evaluate the corresponding energies and therefore the energies of the incident gamma-rays within 1 percent. The reasonably close agreement between our experimental result and the mean value of the low excited level of Li^7 deduced from other reactions provides considerable support for the original suggestion to associate the Be^7 gamma-rays with the energy separation of the two states of Li^7 built up by electron capture from the parent body.

ACKNOWLEDGMENTS

The senior author wishes to thank the Rockefeller Foundation for financial support during the course of these investigations. We are very much indebted to Mr. R. G. Nuckolls for the construction and maintenance of the coincidence circuit used in these experiments.

JULY 1 AND 15, 1942 PHYSICAL REVIEW VOLUME 62

Density of Sodium Chloride

The Atomic Weight of Fluorine by Combination of Crystal Density and X-Ray Data

HERRICK L. JOHNSTON AND DWIGHT A. HUTCHISON
Department of Chemistry, The Ohio State University, Columbus, Ohio

(Received January 5, 1942)

The densities of carefully purified crystals of sodium chloride have been determined by the method of "crystal flotation" in pure ethylene dibromide. The results yield

$$d_{27.634°C}=2.16165\pm0.00002 \text{ g/ml},$$

which reduces to

$$d_{20°}=2.16366\pm0.00003 \text{ g/ml}.$$

It is found that six successive precipitations of NaCl in the manner employed by Richards and Wells in their determination of the atomic weights of sodium and of chlorine are required to effect purification to constant density (± about 4×10^{-6} g/ml), and also that exposure to air produces surface contamination sufficient to cause erratic changes in apparent density that may amount to as much as 5×10^{-4} g/ml within a few minutes. Combination of our value for d_{NaCl} with that of C. A. Hutchison and H. L. Johnston for d_{LiF} and with Straumanis, Ievins, and Karlsons' value for the lattice constant of LiF relative to the Siegbahn value for NaCl yields 0.443640 ± 0.000025 for the ratio of the molecular weights of LiF and NaCl, respectively. With the adoption of 22.997 (International Atomic Weight Committee) for the atomic weight of sodium, this ratio yields 18.994 ± 0.001 for the atomic weight of F. With the adoption of 22.994 (Birge) for sodium, the F atomic weight comes out 18.992. Either of these figures is in reasonable agreement with the value 22.995 ± 0.002, based on densities and lattice constants of fluorite and calcite, and with the gas density determinations for compounds of F, but are somewhat lower than the mass spectrograph value of 18.999 ± 0.001 for F^{19}. It appears that the determination of relative molecular weights by combination of x-ray and density data are as reliable, in favorable cases, as by other standard atomic weight methods. In calcite, fluorite, and rock salt crystals, used to obtain the data underlying these computations, there is no evidence of any appreciable influence of "crystal mosaic" patterns which Zwicky thought might influence crystal densities by as much as 1 percent.

THE most accurate determinations of the density of sodium chloride, reported in the literature, appear to be those of Defoe and Compton[1] and of Tu,[2] made for the purpose of

[1] O. K. Defoe and A. H. Compton, Phys. Rev. **25**, 618 (1925).
[2] Y. Tu, Phys. Rev. **40**, 662 (1932).