Radiations from Br^{77} and Ni^{57}

ROBERT CANADA AND ALLAN C. G. MITCHELL
Physics Department, Indiana University, Bloomington, Indiana*
(Received May 14, 1951)

The nuclear spectra of Br^{77} (58 hr) and Ni^{57} (36 hr) have been investigated in a magnetic lens spectrograph. Br^{77} decays by orbital electron capture and positron emission to Se^{77}. Br^{77} emits a single positron group of energy 0.336 Mev together with gamma-rays of energy 0.160, 0.237, 0.284, 0.298, 0.520, 0.641, and 0.813 Mev, of which the lines at 0.160, 0.237, and 0.520 Mev are internally converted. Br^{77} is the parent of the metastable state Se^{77m} of 17-sec half-life, and the energy of the gamma-ray associated with this transition is 0.160 Mev.

The radiations from Ni^{57} consist of one positron group whose end point is 0.835 Mev together with one strong gamma-ray of energy 1.375 Mev and two weaker gamma-rays whose energies are 1.91 and 0.128 Mev, the latter being internally converted.

I. INTRODUCTION

THE radiations from Br^{77} and Ni^{57} have been studied with the help of a magnetic lens spectrometer. The spectrum of Br^{77} is of interest because the transition goes to Se^{77}, which contains a metastable state of 17 sec half-life, and, in addition, the spectrum of As^{77}, which also goes to Se^{77}, has been measured. The present experiments have fixed the energy of the transition associated with the metastable state since the short-lived metastable state is in equilibrium with the long-lived parent and measurements can be made at leisure. Measurements on Ni^{57} were undertaken to obtain a more detailed picture of the disintegration scheme than that given by the earlier coincidence experiments published from this laboratory.

II. RADIATIONS FROM Br^{77} AND Se^{77m}

The radiations from the decay of Br^{77} (58 hours) have been shown to consist of positrons, gamma-radiation, and x-rays resulting from the capture of orbital electrons. Woodward, McCown, and Pool[1] found a positron end point of 0.36 Mev by absorption techniques. These investigators report that there is gamma-radiation in addition to annihilation quanta, and also that there are abundant x-rays. They give a value of 20 for the ratio of the number of disintegrations which take place by K-capture to those which go by positron emission. Hopkins and Cunningham[2] are reported to have measured a maximum positron energy of 0.36 Mev and a gamma-ray of 0.7 Mev.

Since no complete spectrometric study of the radiations from this disintegration has been reported, it was decided to study the radiations from Br^{77} with the use of a magnetic lens type beta-ray spectrometer. Since it has recently been shown[3] that the 17-second selenium isomer, Se^{77m}, is not the daugher of As^{77}, it is of particular interest to investigate whether this selenium activity grows from Br^{77}.

The source material for these experiments was prepared by alpha-particle bombardment of arsenic in the Indiana University cyclotron. Metallic arsenic powder was pressed into the grooves of a target plate and covered with aluminum foil to prevent the escape of the bromine. Bombardments of 150 micro-ampere-hours gave sufficient activity to allow the preparation of adequate beta- and gamma-ray sources.

The bromine was separated and purified chemically in the following manner. The target material was dissolved in concentrated HNO_3, care being taken to catch any escaping fumes in a water trap cooled in ice. Carrier amounts of iodine and bromine ion were added. Oxidation and extraction cycles designed to separate the bromine from iodine and other impurities were then repeated several times. The last aqueous solution of Br^- was then made $1N$ in HNO_3 and heated. Upon the addition of $AgNO_3$ the source was precipitated as AgBr in which form it was used in the spectrometer.

The spectrometer used in most of these experiments was a magnetic lens with ring-type focusing. The instrument has been described previously.[4,5] During these investigations the spectrometer was adjusted to give maximum transmission, for which the instrument resolution is 2 percent. The zapon window of the Geiger counter had a low energy cutoff at 11 kev. This window was not supported by any kind of grid.

The beta-ray source was made by allowing a water suspension of AgBr to dry on a zapon backing. Because of the small particle flux from Br^{77} it was necessary to use a source which was quite thick. The source was approximately 10 mg/cm^2 in surface density and was 5 mm in diameter.

The electron spectrum is shown in Fig. 1, in which the number of counts per minute, corrected for decay, is plotted against the magnetic rigidity in gauss-cm. The large peak at 1381 gauss-cm is a K internal conversion line corresponding to a gamma-ray energy of

* Supported by the joint program of the ONR and AEC.
[1] Woodward, McCown, and Pool, Phys. Rev. 74, 870 (1948).
[2] H. H. Hopkins, Jr., and B. B. Cunningham, private communication, listed in G. T. Seaborg and I. Perlman, Revs. Modern Phys. 20, 585 (1948).
[3] R. Canada and A. C. G. Mitchell, Phys. Rev. 81, 485 (1951).
[4] Bunker, Canada, and Mitchell, Phys. Rev. 79, 610 (1950).
[5] R. Canada and A. C. G. Mitchell, Phys. Rev. 83, 76 (1951).

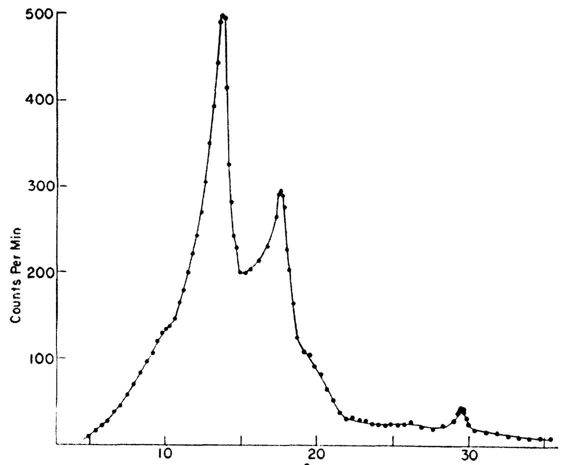

FIG. 1. The electron spectrum of Br^{77}.

0.160 Mev. Similarly the peak at 1756 gauss-cm is a K line for a 0.237-Mev gamma-ray. The L lines are not resolved. There is also a weak internal conversion line at 2946 gauss-cm corresponding to a gamma-ray of 0.521-Mev energy. The positron distribution is somewhat obscured by the two larger internal conversion lines.

For that reason the positron spectrum was measured in a 180° type spectrometer. A plot of the Fermi analysis, using the approximation to the coulomb correction factor given by Bethe and Bacher,[6] yields an end-point energy of 0.336 Mev. There is only one group and the shape indicates an allowed transition. The data from the 180° type instrument shows that the particles causing the continuous distribution beyond 0.336 Mev are negative electrons. They are probably Compton recoils, appearing in some abundance because of the thick source.

The distribution of secondary electrons ejected from a 16 mg/cm^2 lead radiator by the gamma-radiation of Br^{77} was examined with the lens and the result is shown in Fig. 2. The peak at 948.9 gauss-cm (K_1) is the K photoelectron peak corresponding to a gamma-ray of 0.160 Mev. The K and L peaks at 1395 and 1742 gauss-cm (K_2L_2) are due to a gamma-ray of 0.237 Mev. The K and L peaks which appear at 1629 and 1947 gauss-cm (K_3L_3) are due to a 0.284-Mev gamma-ray and the peaks at 1700 and 2039 gauss-cm (K_4L_4) correspond to a 0.298-Mev gamma-ray. The large peak at 2648 gauss-cm (K_5) is the K photoelectron line for a 0.520-Mev gamma-ray and its L line falls at 2918 gauss-cm (L_5). The weaker annihilation radiation rides under this line and, of course, distorts its intensity. The peaks for the photoelectrons for the annihilation radiation come at K_a and L_a. There are small peaks at 3116 and 3753 gauss-cm (K_6 and K_7) which are K lines for 0.641- and 0.813-Mev gamma-rays.

A comparison of the gamma-ray intensities was made using the curves of Gray[7] to obtain the photoelectric efficiencies of the various gamma-rays. The results are shown in Table I.

It should be emphasized that, since the intensity of most of the lines is quite weak, the relative intensities given in Table I may contain large errors. They can serve only as a guide to a proposed scheme.

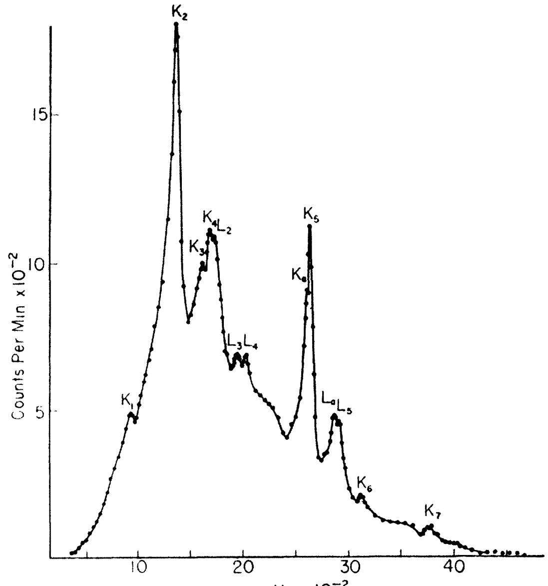

FIG. 2. The distribution of secondary electrons ejected from lead by the gamma-radiation of Br^{77}.

IIa. The Isomer Se^{77m}

In order to investigate whether Se^{77m} is a daughter of Br^{77} a rapid chemical procedure was developed which would separate any selenium from the Br^{77} source material quickly enough to allow a measurement of a very short half-life. Upon the performance of this experiment a 17.5-second selenium activity was found to grow from the Br^{77}. This experiment has been described in detail elsewhere.[8] Since others have measured a gamma-ray of about 0.15 Mev,[9–11] associated with the decay of Se^{77m}, it seems probable that the 0.160-Mev gamma-ray is associated with the 17.5-second Se^{77m} isomeric transition.

IIb. Discussion of the Br^{77}-Se^{77} Decay

The energies and intensities of the gamma-rays observed are given in Table I. From a purely energetic standpoint it will be seen that the gamma-rays have

[6] H. A. Bethe and R. F. Bacher, Revs. Modern Phys. 8, 194 (1936).

[7] L. H. Gray, Proc. Cambridge Phil. Soc. 27, 103 (1931).

[8] Canada, Cuffey, Lessor, and Mitchell, Phys. Rev. 82, 750 (1951).

[9] J. A. Arnold and N. Sugarman, J. Chem. Phys. 15, 703 (1947).

[10] Gideon, Miller, and Waldman, Phys. Rev. 75, 329 (1949).

[11] E. der Mateosian and M. Goldhaber, Phys. Rev. 82, 115 (1951).

energies which suggest that they can be fitted into a decay scheme. Thus the energies of the lines at 0.237 and 0.284 Mev add together to give an energy of 0.521 Mev which agrees with the observed line at 0.520 Mev. In addition the sum of the energies 0.520 and 0.298 Mev gives 0.818 Mev, and that of 0.160 and 0.641 gives 0.801, in reasonable agreement with the observed line at 0.813 Mev. This suggests that the energy relations are given by the decay scheme shown in Fig. 3. In order to explain the relative intensities of the various lines it is necessary to suppose that orbital electron capture takes place to the three levels at 0.237, 0.520, and 0.813 Mev.

The pair at 0.641 and 0.160 Mev, which have been put in series, deserve some special discussion. Since the line at 0.641 Mev has a relative intensity of approximately 8 and that at 0.160 Mev approximately 0.6, it would appear at first sight that these two lines cannot be in series. However, the line at 0.160 is highly internally converted and comes from a metastable state. According to the shell model[12] this line is a transition between a $g_{9/2}$ and a $p_{1/2}$ configuration and the polarity of the radiation should be magnetic 2^4, and N_e/N_γ should be approximately[13] 6. The corrected intensity of this line would then be approximately 4, which is in reasonable agreement with that of the 0.641-Mev line.

Finally, the positron transition is assumed to take place between the ground state of Br^{77} and the ground state of Se^{77}. This is done for several reasons. In the first place, the ratio of the number of internal conversion electrons in the line at 0.160 Mev to the total number of positrons is approximately 0.3. If the character of the 0.160-Mev transition is magnetic 2^4-pole, one would expect about 0.9. Secondly, the shell model predicts that the ground state of both As^{77} and Br^{77} is $p_{3/2}$, and for this reason it would be very difficult to understand why the metastable state is not excited in the As^{77} decay and is excited from Br^{77}. However, if this state is excited via orbital electron capture followed by cascade gamma-rays, as indicated above, the configurations of the ground states of As^{77} and Br^{77} can both be $p_{3/2}$ and that of the ground state of Se^{77} can be $p_{1/2}$, as indicated by the work on As^{77}. In addition the value of $\log_{10}ft$ for the transition from Br^{77} has been calculated and is approximately 5, indicating an allowed transition.

III. THE RADIATIONS FROM Ni^{57}

Absorption and coincidence experiments of Maienschein and Meem[14] showed that Ni^{57} (36 hours) decays by the emission of a 0.725-Mev positron followed by gamma radiation. They showed that at least two gamma-rays are present in cascade and that the energy of the most energetic gamma-ray is 1.97 Mev.

[12] M. Goeppert-Mayer, Phys. Rev. **78**, 16 (1950).

[13] P. Axel and R. F. Goodrich, Internal Conversion Data, University of Illinois (unpublished).

[14] F. Maienschein and J. L. Meem, Jr., Phys. Rev. **76**, 899 (1949).

TABLE I. Relative intensities of the gamma-rays.

Gamma-ray energy	Relative intensity	Remarks
0.160±0.001	0.64	*K* photoelectron line, I.C. (strongly)
0.237±0.002	20.	*K*, *L* photoelectron lines, I.C.
0.284±0.003	0.22	*K*, *L* photoelectron lines
0.298±0.003	0.25	*K*, *L* photoelectron lines
0.520±0.002	100.	*K*, *L* photoelectron lines, I.C.
0.641±0.003	8.6	*K* photoelectron line
0.813±0.005	25.	*K* photoelectron line

Friedlander, Perlman, Alburger, and Sunyar[15] examined the radiations from this nuclide using absorption, coincidence, and scintillation techniques as well as a magnetic lens type spectrometer. They found the positron spectrum to be simple, of an allowed shape, and to have an end-point energy of 0.845±0.01 Mev. The electron spectrum showed a weak line of internal conversion electrons corresponding to a 0.120-Mev gamma-ray. They reported that the gamma-ray intensity was too small to allow the determination of the energies of the quanta by examining the secondary electron distribution in the spectrometer. Lead absorption experiments indicated the occurrence of 1.9-Mev gamma-radiation, annihilation radiation, and 0.120-Mev quanta. They state that the presence of other low-energy components of the gamma-ray spectrum cannot be excluded. These investigators found that the radiations from Ni^{57} produce photoneutrons in Be but not in deuterium. This shows that there must be a gamma-ray present with energy between 1.7 and 2.2 Mev. Comparison measurements with a variably biased scintillation counter gave a gamma-ray energy of 1.9±0.1 Mev. Their coincidence experiments showed that there is hard gamma-radiation in series with the beta-rays and also that the hard gamma-radiation is in coincidence with quanta having energy of less than 0.5 Mev.

The source material used in the present experiments was prepared by bombarding chemically pure iron with

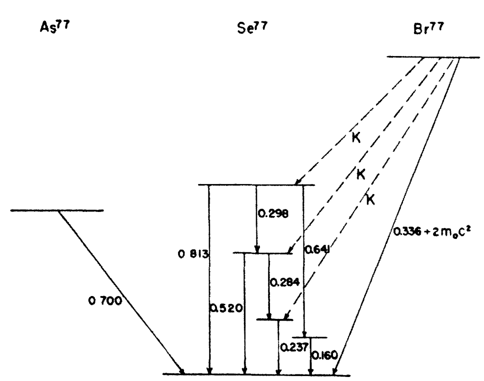

FIG. 3. Suggested decay scheme for Br^{77}.

[15] Friedlander, Perlman, Alburger, and Sunyar, Phys. Rev. **80**, 30 (1950).

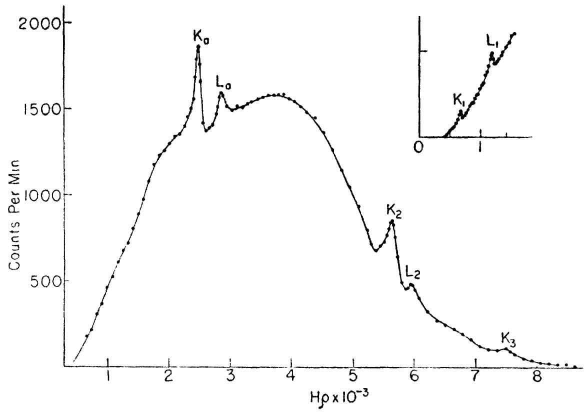

FIG. 4. Spectrum of secondary electrons ejected by gamma-rays of Ni^{57}.

alpha-particles in the Indiana University cyclotron. The iron was in the form of a thin sheet which was hard-soldered to the end of the copper probe. Bombardments of 40 micro-ampere-hours produced enough Ni^{57} activity to allow the examination of both the beta- and gamma-ray spectra in the spectrometer.

The nickel activity was separated and purified chemically by a procedure essentially the same as that described by Friedlander[15] *et al*, the nickel being finally precipitated as the dimethylglyoxime salt. The nickel dimethylglyoxime was used as source material for the study of the gamma-radiation. For the beta-ray sources the material was converted to nickel sulfide and deposited on zapon from a water suspension.

The gamma-rays emitted by Ni^{57} were investigated by examining the momentum distribution of the secondary electrons ejected from a radiator. Figure 4 shows the spectrum of the photoelectrons produced from a uranium radiator of considerable thickness (50 mg/cm²). The strong line at 5651 gauss-cm (K_2) corresponds to a gamma-ray of 1.375-Mev energy converted in the K shell of uranium. The L line for this gamma-ray is at 5945 gauss-cm (L_2). The peaks at 2493 gauss-cm and 2861 gauss-cm ($K_a L_a$) are photoelectron lines for annihilation radiation. There is an indication of a small peak at 7500 gauss-cm (K_3) which corresponds to a K photoelectron line for a 1.914-Mev gamma-ray.

A later experiment in which a lead foil of 16 mg/cm² surface density was used as a radiator showed weak lines at 680 gauss-cm and 1190 gauss-cm ($K_1 L_1$) which indicate a gamma-ray of 0.128-Mev energy. These lines are shown in the inset of Fig. 4. All parts of the gamma-ray spectrum appeared to decay with the same 36-hour half-life.

A comparison of gamma-ray intensities, using Gray's[7] formula for the photoelectric cross-section shows that the ratio of the intensity of annihilation radiation to that of the 1.375-Mev gamma-ray is 0.69. The 1.375-Mev line is approximately six times as intense as that at 1.91 Mev.

The positron spectrum of Ni^{57} has been reported previously[15] and will not be discussed here in detail. The present experiments show that the positron distribution is simple with an end point at 0.835±0.010 Mev. A weak internal conversion line, which corresponds to a gamma-ray energy of 0.128 Mev, was found.

IIIa. Discussion of the Ni^{57} Experiments

The strongest line in the Ni^{57} spectrum is the gamma-ray at 1.375 Mev. From the coincidence experiments of Maienschein and Meem[14] it is clear that this state is fed by the positron disintegration whose end-point energy is 0.835 Mev. Since the ratio of the number of annihilation quanta to the number of 1.375-Mev quanta is 0.69, it follows that this state is also fed directly by orbital electron capture. The state at 1.9 Mev, from which the line of energy 1.9 Mev arises, is produced entirely by orbital electron capture. The weak internally converted line at 0.128 Mev is probably in parallel with the 1.9-Mev line and in series with the 1.375-Mev line, since gamma-gamma coincidences have been found. It is necessary to assume that the states at 1.9 and 1.50 Mev are populated by orbital electron capture since the positron spectrum is simple. The state at 1.375 Mev is populated both by positron emission and orbital electron capture. Since no other gamma-rays were found besides those mentioned, it would appear that the state at 1.9 Mev loses its activation almost entirely through the emission of the 1.9-Mev gamma-ray to the ground state with very little, if any, emission to the states at 1.50 and 1.375 Mev. This no doubt comes about through the action of selection rules. The decay scheme shown in Fig. 5, while incomplete, is in agreement with all of the information which is available to date on Ni^{57}.

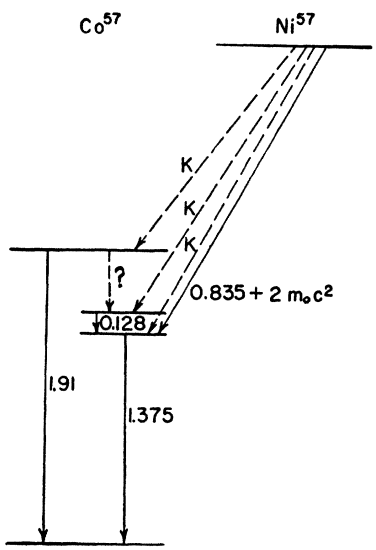

FIG. 5. Proposed disintegration scheme for Ni^{57}.

According to the shell model,[12] the ground state of

Ni^{57} should have the configuration $p_{3/2}$ and that of Co^{57} $f_{7/2}$. The present experiments are in agreement with this prediction, since there is no positron decay to the ground state. Since the positron transition to the 1.375-Mev state of Co^{57} is allowed, the configuration of this state is probably $p_{3/2}$. In addition, since the $p_{3/2}$ and $f_{5/2}$ states have nearly the same energy in this region, it is probable that the state at 1.50 Mev has the configuration $f_{5/2}$.

The authors are indebted to Dr. M. B. Sampson and the cyclotron crew for making the bombardments, to Mr. Arthur Lessor for making the chemical separations, and to Dr. R. G. Wilkinson and Mr. Harvey Israel for help with the investigation of the positron spectrum.

PHYSICAL REVIEW VOLUME 83, NUMBER 5 SEPTEMBER 1, 1951

Z Dependence and Angular Distribution of Bremsstrahlung from 17-Mev Electrons*

L. H. LANZL† AND A. O. HANSON
Department of Physics, University of Illinois, Urbana, Illinois
(Received April 16, 1951)

The relative bremsstrahlung cross section for the upper portion of the spectrum as a function of Z, for 17-Mev electrons from a 22-Mev betatron, has been measured. The radiation was detected by means of the $Cu^{63}(\gamma,n)$ induced activity, which has a 10.9-Mev threshold. The effect of atomic screening is small for the quantum energies to which this detector responds, but was taken into account. The results are in agreement with the Bethe-Heitler theory for electron-nuclear interactions within 1 percent. Electron-electron interactions give 0.75 times the intensity for electron-proton interactions, as measured with a copper detector.

The total cross section for radiative energy loss of electrons has been measured with an ionization chamber. The experimental Z dependence of the relative cross section indicates that the yield from gold for a given $N(Z^2+Z)$ is somewhat less than that from low Z elements. This discrepancy might be accounted for by improved corrections for screening, and by more accurate consideration of the radiation produced by electron-electron impacts. Rough measurements of the absolute cross section are in agreement with the Bethe-Heitler theory.

The intrinsic angular distribution of bremsstrahlung, produced in a small amount of cellophane and air, was measured by film and ion chamber, and was found to fit a $1/[1+(E\theta/\mu)^2]^2$ distribution. The angular distribution was measured with three detectors, for one Be and several Au targets. The results are in agreement with calculations in which the above intrinsic distribution and Molière's multiple scattering theory are used.

The central intensity of bremsstrahlung as a function of target thickness, measured with a small ion chamber, is in approximate agreement with a calculation in which the energy loss of the primary electrons has been taken into account.

INTRODUCTION

THE amount of energy radiated during the passage of electrons through matter has been studied by two methods: (1) by measuring the electron energy before and after passage through a given material, the difference in energy being a measure of the total energy loss, which is caused mainly by ionization or excitation, and by radiation; (2) by measuring the bremsstrahlung itself. This latter method was the one used in the experiments to be presented in this paper, the electron source being a betatron.

Blackett[1] and Anderson and Neddermeyer[2] performed cloud-chamber experiments in which the total energy loss of cosmic-ray electrons in lead was determined by the first method. Some typical results obtained by Anderson and Neddermeyer near 30 Mev were about 16 percent lower than predicted by the Bethe-Heitler theory.[3] Although a number of experiments on energy loss have been performed with β-rays, those at energies below about 9 Mev are of little use in a direct check of the theory because of the multiple scattering which the electrons undergo.[4] Results for β-rays of 9 to 13.5 Mev indicate energy losses of about 1.4 times the theoretical values.[5–7]

The electrostatic generator was used by Ivanov *et al.*[8] for calorimetric measurements of the radiation output from a thick lead target, with results lower than given by the Bethe-Heitler theory for bremsstrahlung production and by that of Bloch[9] for collision loss. Buechner and Van de Graaff[10] found experimentally, with 2-Mev electrons from a Van de Graaff generator, and by using a very thick calorimeter, that no energy is carried away by any means other than radiation, e.g., in the form of neutrinos.

Van Atta, Petrauskas, and Myers[11] measured the

* This work was assisted in part by the joint program of the ONR and AEC.
† Now at Argonne Cancer Research Hospital, University of Chicago, Chicago, Illinois.
[1] P. M. S. Blackett, Proc. Roy. Soc. (London) **165**, 11 (1938).
[2] C. D. Anderson and S. H. Neddermeyer, Phys. Rev. **50**, 263 (1936).
[3] H. Bethe and W. Heitler, Proc. Roy. Soc. (London) **146**, 83 (1934); see also H. Bethe, Proc. Cambridge Phil. Soc. **30**, 524 (1934).
[4] M. M. Slawsky and H. R. Crane, Phys. Rev. **56**, 1203 (1939).
[5] W. A. Fowler and J. Oppenheimer, Phys. Rev. **54**, 320 (1938).
[6] A. J. Ruhlig and H. R. Crane, Phys. Rev. **53**, 618 (1938).
[7] J. J. Turin and H. R. Crane, Phys. Rev. **52**, 63 (1937).
[8] Ivanov, Walther, Sinelnikov, Taranov, and Abramovich, J. Phys. (U.S.S.R.) **4**, 319 (1941).
[9] F. Bloch, Z. Physik **81**, 363 (1933).
[10] W. W. Buechner and R. J. Van de Graaff, Phys. Rev. **70**, 174 (1946).
[11] Van Atta, Petrauskas, and Myers, Am. J. Roentgenol. Radium Therapy **50**, 803 (1943).