ponents transformed into momentum-space and reduced to a description in spin sub-space as was done in the previous example, it will be seen that these even parts of the direct interaction terms accomplish spin transitions.[6]

The writer gratefully acknowledges his indebtedness to Dr. Leslie L. Foldy for suggesting this problem, and for his invaluable advice and criticism throughout the course of the work.

[6] A related paper by S. Tani, Prog. Theoret. Phys. **6**, 267 (1951), has recently been published. In this paper, Tani employs the transformation for a detailed elucidation of the physical significance of the operators commonly occurring in theories of fermions interacting with fields in the single particle formalism.

PHYSICAL REVIEW VOLUME 86, NUMBER 3 MAY 1, 1952

Radioisotopes of Bromine

S. C. FULTZ* AND M. L. POOL
Ohio State University, Columbus, Ohio
(Received December 31, 1951)

Selenium metal enriched with Se^{76} was bombarded with 7.3-Mev protons. A new 17.2-hour activity in bromine was observed and is assigned to Br^{76}. The radiations of Br^{83}, Br^{80}, Br^{77}, Br^{76}, and Br^{75} have been examined by use of a 180° focusing spectrometer and coincidence methods. Br^{83} emits a simple negatron spectrum with a maximum energy of 0.94±0.02 Mev. The ground state of Br^{80} emits a complex negatron spectrum with components: 1.97±0.03 Mev (80 percent), 1.1 Mev (11 percent), 0.7 Mev (9 percent). The gamma-rays of Br^{77} are associated with the K-capture process. The ground state of Br^{76} emits positrons having a complex spectrum with components 3.57±0.07 Mev (46 percent), 1.7 Mev (10 percent), 1.1 Mev (11 percent), 0.8 Mev (14 percent), 0.6 Mev (19 percent). Gamma-rays identified with Br^{76} have energies of 0.25, 0.33, 0.37, 0.42, 0.68, 0.75, 0.96, and 1.2 Mev. The ground state of Br^{75} decays by emission of positrons having a complex spectrum with components 1.70±0.02 Mev (46 percent), 0.8 Mev (20 percent), 0.6 Mev (15 percent), 0.3 Mev (19 percent).

INTRODUCTION

RADIATIONS from several radioisotopes of bromine have been studied by use of the beta-ray spectrometer and by absorption and coincidence measurements. The radioisotopes were obtained by proton and deuteron bombardments on selenium metal. Decay of their activities was followed with the aid of a Wulf electrometer filled with freon to a pressure of about 2 atmospheres. A magnetic field was used to separate positrons and negatrons, thus enabling decays of the activities giving rise to these particles to be determined separately by use of a G-M counter.

The spectrometer employed was of the 180° focusing type with a trajectory radius of 16 cm. The slits were made long in the direction of the magnetic field in order to obtain maximum possible intensity[1] for a predetermined resolution of about two percent. The spectrometer source consisted of fine particles of activated selenium metal evenly spread on a thin ribbon of Zapon and held in place by a thin layer of collodion. The density of the source and backing was about 10 mg/cm². The thickness of the G-M counter window was 2.5 mg/cm².

THE 17.2-HOUR Br^{76}

Two types of samples of selenium metal were bombarded with protons of 7.3-Mev energy. One type contained the natural isotopic mixture of stable selenium isotopes, while the other type contained Se^{76} enriched from 9.0 to 41.5 percent. In addition to the well-known bromine activities of 4.4-hour Br^{80}, 36-hour Br^{82}, and 2.4-day Br^{77}, a new activity of 17.2 hours was observed. Some evidence for the existence of a 15.7-hour activity had been observed previously[2] and early results for the work discussed below have already been reported.[3] Recently J. Hollander of the University of California privately communicated that a 16-hour bromine activity has been obtained by bombardment of arsenic with alpha-particles.

In Fig. 1 are shown decay curves obtained for the total activity and for the electromagnetically separated particles emitted from a Se^{76} enriched sample of selenium metal which was bombarded with protons of 7.3-Mev energy. Five components are present in the decay curve for the total activity. Their relative contributions to the total activity at the beginning of the measurements can be read from the intercepts of the straight lines. Similar sets of curves were obtained for samples of natural selenium bombarded in the same manner.

In Table I is given activity data obtained from three bombardments. The bottom row contains activities obtained when the bromine was chemically separated from the selenium metal. The activity values listed have been adjusted to take into account differences in

* Fellow, National Cancer Institute of the National Institutes of Health, Public Health Service, Federal Security Agency, Bethesda, Maryland.
[1] G. E. Owen, Rev. Sci. Instr. **20**, 916 (1949).
[2] G. T. Seaborg and I. Perlman, Revs. Modern Phys. **20**, 585 (1948).
[3] S. C. Fultz and M. L. Pool, Phys. Rev. **83**, 875 (1951).

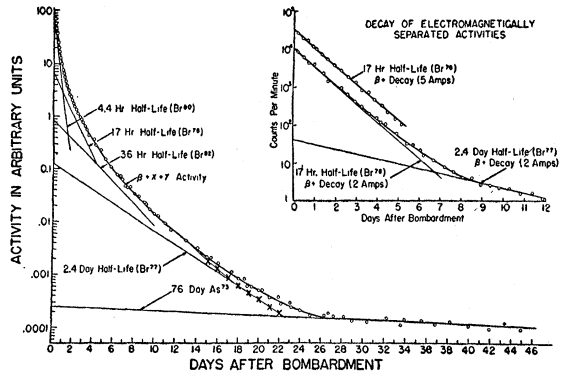

FIG. 1. Decay curves for bromine activities obtained by bombardment of Se^{76} with protons. The 17.2-hour activity is most distinct in the curves on the right for the magnetically separated components.

the cyclotron beam during the separate bombardments. In making these adjustments the 36-hour Br^{82} activity was chosen as a reference standard because it was produced by only a (p,n) reaction. The adjustment was achieved by equating the 36-hour activity to the isotopic abundance of Se^{82} for each type of sample. The 17.2-hour bromine activity may now be traced to the particular selenium isotope from which it was formed through proton bombardment by comparing the relative change in 17.2-hour bromine activity with the relative change in the isotopic abundance of each particular selenium isotope. As is seen in Table I such a comparison strongly favors the isotope Se^{76}. Hence it is concluded that the 17.2-hour bromine activity arises from the isotope Se^{76} under bombardment with 7.3-Mev protons.

Taking the 36-hour Br^{82} activity as a reference, as before, the ratio between the adjusted Br^{77} activities obtained from the enriched and natural samples of selenium is 0.79, which compares favorably with the isotopic abundance ratio of 0.90, for Se^{77}. However, if appreciable $Se^{76}(p,\gamma)Br^{77}$ reaction occurred, this ratio of adjusted activities would be greater than 0.90 because of the increase of Se^{76} relative to Se^{77}, in the enriched sample. Thus it is seen that within the limits of experimental error, no evidence for a (p,γ) reaction exists. Hence it is concluded that the 17.2-hour activity arises from Se^{76} by (p,n) reaction only, and is therefore assigned to Br^{76}.

RADIATIONS OF Br^{76}

Br^{76} disintegrates by emission of positrons, x-rays, and gamma-rays. A magnetic field was used to remove the positrons, and a decay curve was obtained for the x-rays. Using the activity value at the intercept of this curve, the ratio of the number of x-rays to number of positrons was estimated to be 0.7.

The Kurie plot for Br^{76} positrons, shown in Fig. 2, was obtained by use of the Coulomb correction given by Bethe and Bacher,[4] and checked with tables issued by the National Bureau of Standards.[5] It is evident that the spectrum is complex and that the highest energy component has the shape of an allowed spectrum. Results of analysis indicate that the spectrum may be composed of five groups having end-point energies and relative contributions of: 3.57 ± 0.07 Mev, 46 percent; 1.7 Mev, 10 percent; 1.1 Mev, 11 percent; 0.8 Mev, 14 percent; 0.6 Mev, 19 percent. The $\log(ft)$ values for the partial spectra therefore are 7.85, 7.1, 6.5, 6.1, and 5.8, respectively. The spectrum is also shown in Fig. 2.

Spectrometer measurements were also made on the internal conversion electrons and photoelectrons obtained from lead and uranium radiators. The activities available, however, were weak, so a statistical method was used to establish the small peaks. Bombardment conditions and isotopic ratios were changed in order to enhance some peaks at the expense of others. For each sample bombarded the negatron spectrum was scanned in detail several times to examine reproducibility and decay of the peaks. From the results of eight bombardments, a large number of gamma-rays were identified, some of which belonged to Br^{77} [6] and Br^{82}.[7] The following gamma-rays were attributed to Br^{76}: 0.25, 0.33, 0.37, 0.42, 0.68, 0.75, 0.96, and 1.21 Mev. Errors in energies are about 5 percent. From lead-absorption curves averaged gamma-ray energies of 0.6 and 1.4 Mev were obtained.

Coincidence measurements were made on Br^{76} positrons, which were selected by use of a magnetic field. Absorbers were used to eliminate all positrons except those from the high energy partial spectrum, and decay curves verified that the positrons selected belonged only to the 17.2-hour activity. The source and the beta- and gamma-counters were placed in a triangular arrangement such that the counters were on opposite sides of the source. About four inches of lead was then placed

TABLE I. Percent abundances and intensities.

Mass number	82	80	78	77	76	74	
				Percent abundance			
Enriched Se	5.0	30.2	16.1	6.8	41.5	0.5	
Natural Se	9.2	49.8	23.5	7.58	9.02	0.87	
Activities	Br^{82} 1.46 days	Br^{80} 4.4 hr		Br^{77} 2.4 days			17.2 hr
				Intensity of activity in arbitrary units			
Enriched Se	5.0	482	···	7.94	···	···	37.4
Natural Se (no chem.)	9.2	710	···	10.1	···	···	9.9
Natural Se (chem.)	9.2	872	···	···	···	···	8.3

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

[5] Fermi Function Table, preliminary copy, issued by the Computation Laboratory of the National Bureau of Standards. I. Feister, Phys. Rev. **78**, 375 (1950).

[6] R. Canada and A. C. G. Mitchell, Phys. Rev. **83**, 955 (1951).

[7] Siegbahn, Hedgran, and Deutsch, Phys. Rev. **76**, 1263 (1949).

between the counters. Radiations from the source could thus reach either counter, but annihilation radiation created in the beta-counter could not reach the gamma-counter. Thus a cause of false coincidences was eliminated. No true beta-gamma coincidences were recorded in a series of runs extending over a period of 96 hours or about six half-lives. It was therefore concluded that the high energy positrons of Br^{76} are transitions to the ground state of Se^{76}.

Br^{80}

Br^{80} was obtained by proton and deuteron bombardments of natural selenium. The negatron spectrum of the 18-minute isomer was examined while in equilibrium with the 4.4-hour parent isomer. The spectrum and its Kurie plot are shown in Fig. 3. The spectrum was analyzed into three groups having end-point energies and abundances of 1.97±0.03 Mev, 80 percent; 1.1 Mev, 11 percent; 0.7 Mev, 9 percent. The log(ft) values are: 5.48, 5.3, and 4.7, respectively. Coincidence measurements showed that the 1.97-Mev particles are emitted in a transition to the ground state of Kr^{80}.

Br^{77}

The radiations of Br^{77} have been examined previously by use of absorption methods[8] and more recently, with the aid of spectrometers.[6] The negatron spectrum was examined, and four internal conversion peaks were observed which decayed with a half-life of 2.4 days. The corresponding gamma-energies were 160±3, 234±3, 299±3, and 521±4 kev.

Coincidence experiments were conducted in two ways. First, coincidences were sought between positrons and gamma-rays. No true coincidences were found when

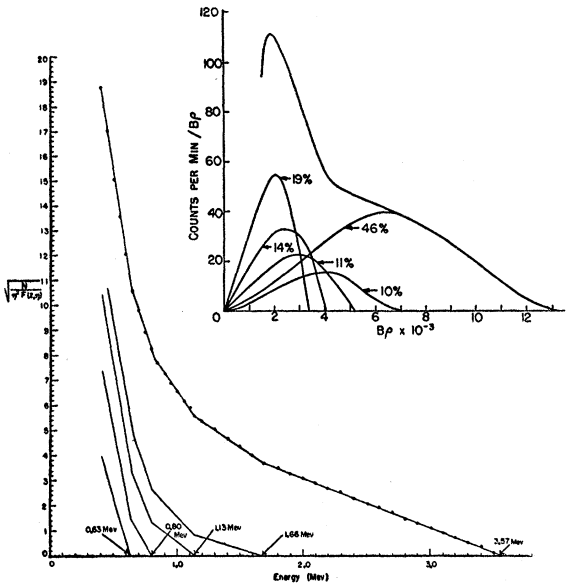

FIG. 2. (Above) Spectrum and partial spectra for Br^{76} positrons. (Below) Kurie plot for Br^{76} positrons showing end-point energies of partial spectra.

[8] Woodward, McCown, and Pool, Phys. Rev. 74, 870 (1948).

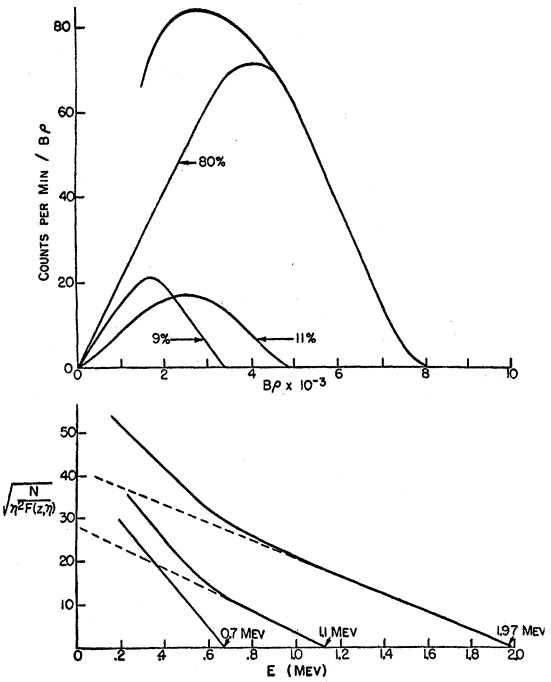

FIG. 3. (Above) Spectrum and partial spectra for Br^{80} negatrons. (Below) Kurie plot for Br^{80} negatrons showing end-point energies of partial spectra.

a wide range of positron energies were examined, so it was concluded that the positrons are emitted in a transition to the ground state of Se^{77}.

Second, coincidences between x-rays and gamma-rays were measured for various thicknesses of lead placed in front of the gamma-counter. The results of these measurements indicate that gamma-rays are emitted in the process of K-capture, and the energy of the unresolved gamma-rays, as given by the coincidence-absorption curve is 0.7 Mev, which is in agreement with the results of lead-absorption measurements previously made.[8] It is therefore evident that the gamma-rays emitted by Br^{77} occur during the K-capture process. The above information on the radiations of Br^{77} confirms two of the assumptions made in the proposed decay scheme of Canada and Mitchell.[6]

Br^{83}

Br^{83} was obtained by bombardment of selenium with deuterons. The negatrons were examined in the spectrometer and corrections were made for presence of other activities as well as its own decay. A Kurie plot indicated that the spectrum is simple and allowed, having an end-point energy of 0.94±0.02 Mev. This is in agreement with the value 0.94±0.01 Mev obtained by Duffield and Langer.[9]

Br^{75}

Br^{75} was obtained by proton bombardment of selenium metal enriched with Se^{74}. The positron spec-

[9] R. B. Duffield and L. M. Langer, Phys. Rev. 81, 203 (1951).

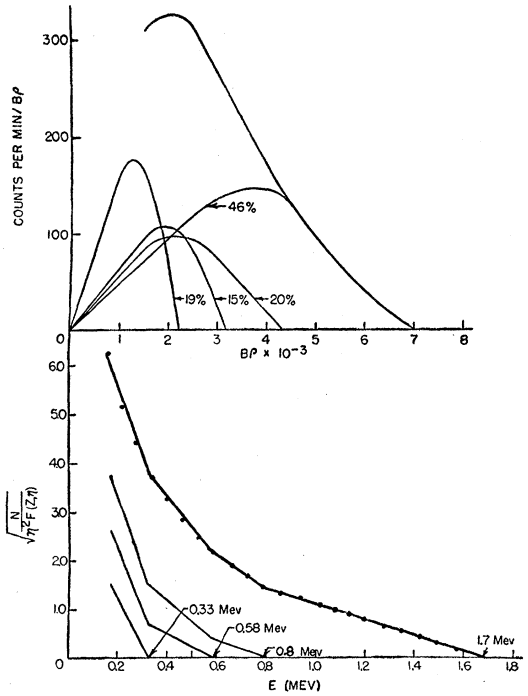

FIG. 4. (Above) Spectrum and partial spectra for Br^{75} positrons. (Below) Kurie plot for Br^{75} positrons showing end-point energies of partial spectra.

trum was examined in the spectrometer and was found to be highly complex. The spectrum and its Kurie plot are shown in Fig. 4. The spectrum has been analyzed into four partial spectra having end-point energies and abundances of 1.70±0.02 Mev, 46 percent; 0.8 Mev, 20 percent; 0.6 Mev, 15 percent; 0.3 Mev, 19 percent. The high energy component has the shape of an allowed spectrum. Assuming that the observed 1.7-hour half-life[8] is that of the ground state of Br^{75}, the log(ft) values are 5.6, 4.9, 4.7, and 4.7, respectively. The lead-absorption method gives an averaged gamma-ray energy of 0.61 Mev.

DISCUSSION

The negatron spectrum of Br^{80} had previously been classified as first forbidden[10,11] according to its log(ft) value. However, the Kurie plot for Br^{80}, as shown in Fig. 3 above, indicates that the negatrons are emitted by allowed transitions. The log(ft) values fall into the allowed group specified by more recent classification.[12,13] As deduced from the shell model[14] and the rules outlined by Nordheim[13] for odd-odd nuclei, the ground state of Br^{80} would be included in the following combinations of spin and parity:

(1)	$p_{3/2}+g_{9/2}$	6 (max)	odd
(2)	$f_{5/2}+p_{1/2}$	3 (max)	even
(3)	$f_{5/2}+g_{9/2}$	2	odd
(4)	$p_{3/2}+p_{1/2}$	1	even

Since Kr^{80} is even-even, its ground state is expected to have zero spin and even parity. Hence the selection rules for an allowed transition are obeyed only if the combination $p_{3/2}+p_{1/2}$ describes the ground state for Br^{80}. The 4.4-hour isomeric level[15] would be expected to be associated with the higher spin states.[11]

Br^{76} is an odd-odd nucleus which disintegrates by positron emission to the ground state of the even-even nucleus Se^{76}. The ground state of Br^{76} is included among the above combinations of spin and parity. The selection rules for the observed allowed beta-transition are again obeyed only for the combination $p_{3/2}+p_{1/2}$. However, the high log(ft) values obtained for Br^{76} are not consistent with the allowed positron spectra. This discrepancy might be explained by attributing the 17.2-hour half-life to an isomeric level which arises from the higher spin states.

The authors wish to acknowledge help received from the Development Fund of the Ohio State University, and financial assistance received by one of them (S.C.F.) from the National Institutes of Health. They also wish to thank Major C. Scoville, U.S.A.F., and Major D. Jones, U.S.A.F., for help in making some of the measurements.

[10] E. J. Konopinski, Revs. Modern Phys. **15**, 222 (1943).
[11] E. Segrè and A. C. Helmholz, Revs. Modern Phys. **21**, 271 (1949).
[12] C. S. Wu, Revs. Modern Phys. **22**, 386 (1950).
[13] L. W. Nordheim, Phys. Rev. **78**, 294 (1950).
[14] M. G. Mayer, Phys. Rev. **78**, 22 (1950).
[15] A. H. Snell, Phys. Rev. **52**, 1007 (1937).