Study of the Decay Scheme of Bromine-74†

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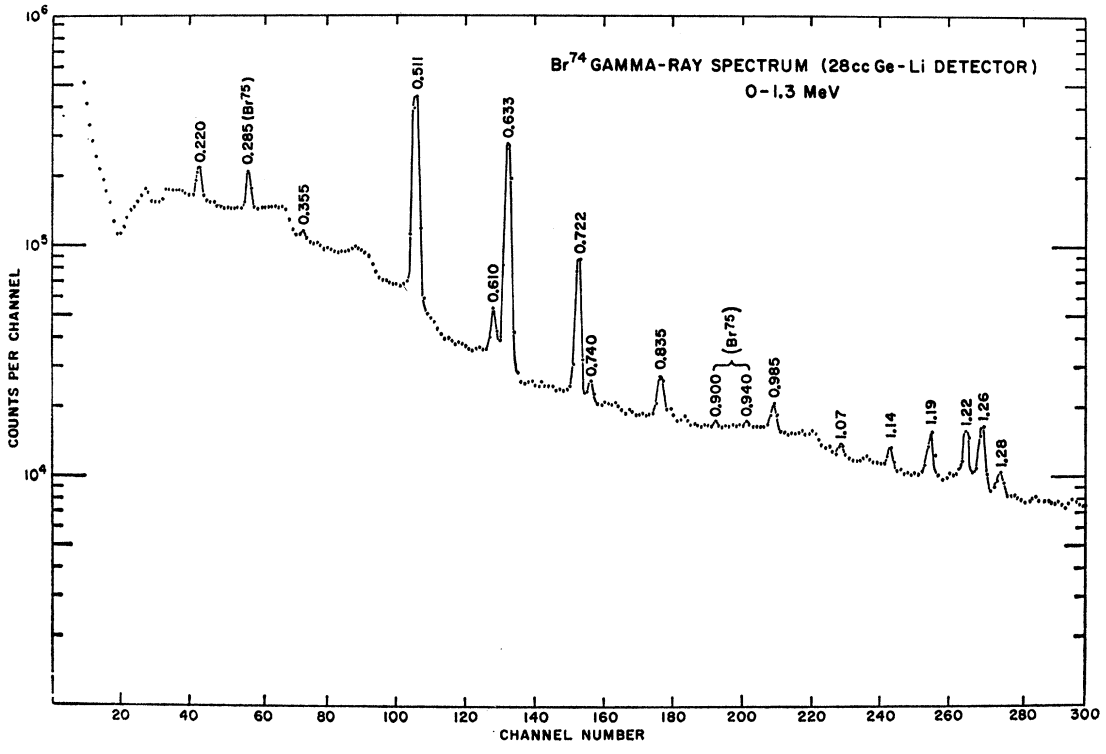
The decay scheme of bromine-74 produced by carbon-12 ions (5.5 MeV/nucleon) on thin copper targets is discussed. The half-life was found to be 38±1 min. The β^+ endpoint energy was measured to be 5.2± 0.1 MeV. For the determination of the γ rays, two Ge(Li) detectors were used and the following γ rays were established: 220±2, 355±2, 511, 610±2, 633±2, 722±2, 835±2, 985±2, 1190±5, 1220±5, 1260±5, 1355±5, (1445 and 1455)±5, 1705±5, 1960±5, 2300±10, 2330±10, and 3950±15 keV. The weaker γ rays are listed in a table. A tentative decay scheme for bromine-74 is given.

I. INTRODUCTION

IN 1953, Hollander[1] produced Br^{74} with C^{12} ions on copper, and in 1956 Beydon *et al.*[2] produced the same isotope with nitrogen ions on copper. The half-life was found to be 42±5 min, and a γ line of 640±10 keV was observed. In 1965, Belyaev *et al.*[3] studied the decay scheme of Br^{74} with NaI(Tl) crystals. They reported a half-life of 36±1 min and γ rays of the following energies: 420±15, 511, 630±5, 720±10, 830±10, 950±15, 1110±50, 1230±10, 1450±30, 1705±30, 1860±50, 2230±20, 2380±50, 2700±100, 3220±20, 3350±50, 3800±20, and 4400±100 keV. Belyaev *et al.* assigned the 630-keV γ line to the first 2^+ excited level,



(a)

FIG. 1. (a) Low-energy part of the Br^{74} γ spectrum accumulated with a 28-cm³ Ge(Li) detector and a Nuclear Data 1024-channel analyzer. (b) Singles γ-ray spectrum of Br^{74} in the region 1.3–2.6 MeV taken with the 28-cm³ Ge(Li) detector. (c) High-energy portion of the Br^{74} γ-ray singles spectrum taken with a 28-cm³ Ge(Li) detector.

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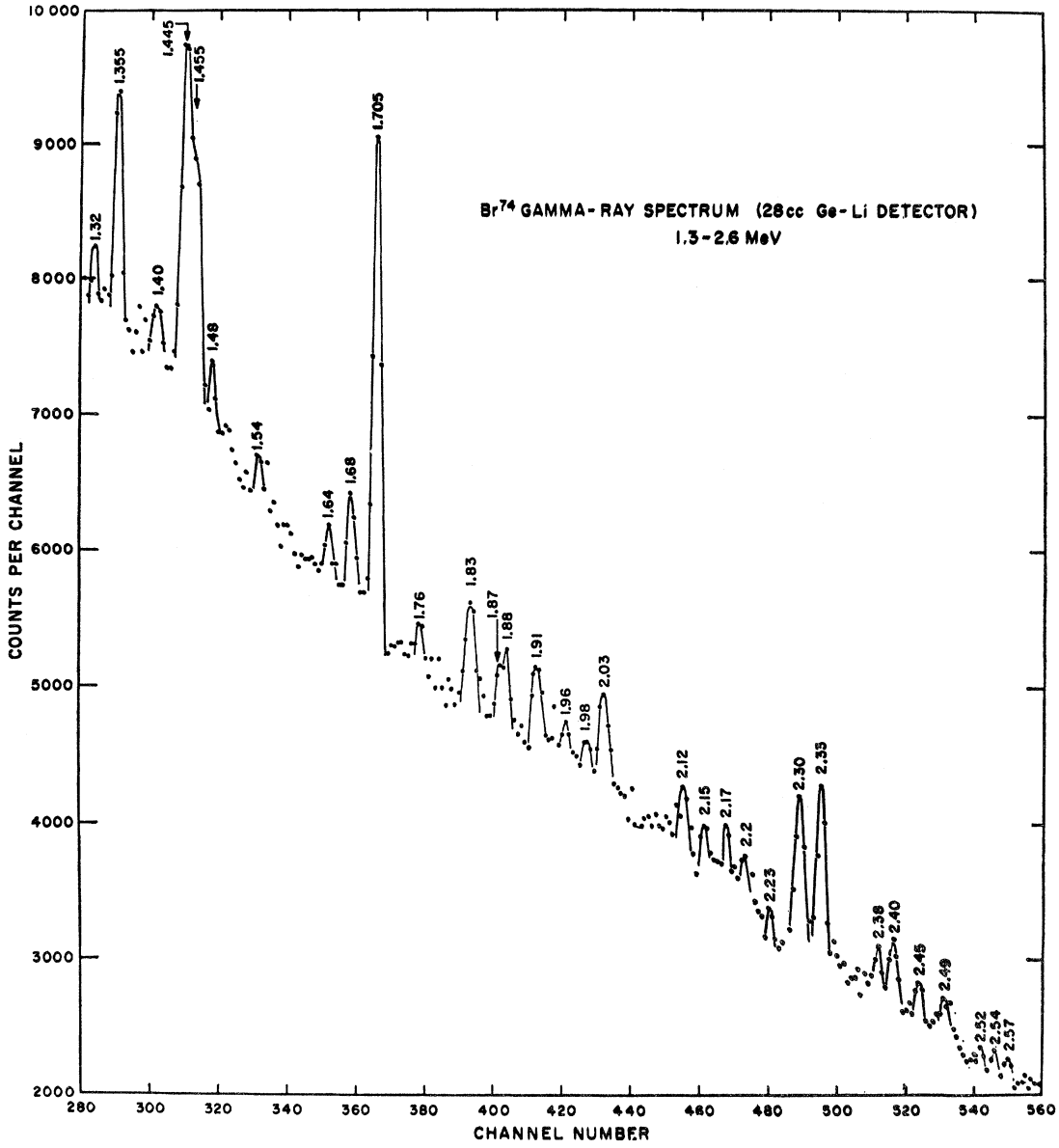
[1] J. M. Hollander, Phys. Rev. **92**, 518 (1958).

[2] J. Beydon, R. Chaminade, M. Crut, H. Faraggi, J. Olkowsky, and A. Papineau, Nucl. Phys. **2**, 593 (1957).

[3] B. N. Belyaev, B. A. Gvozdev, V. I. Gudov, A. V. Kalyamin, and L. M. Krizhanskii, Yadern. Fiz. **3**, 609 (1966) [English transl.: Soviet J. Nucl. Phys. **3**, 446 (1966)].



(b) FIG. 1. (*Continued*).

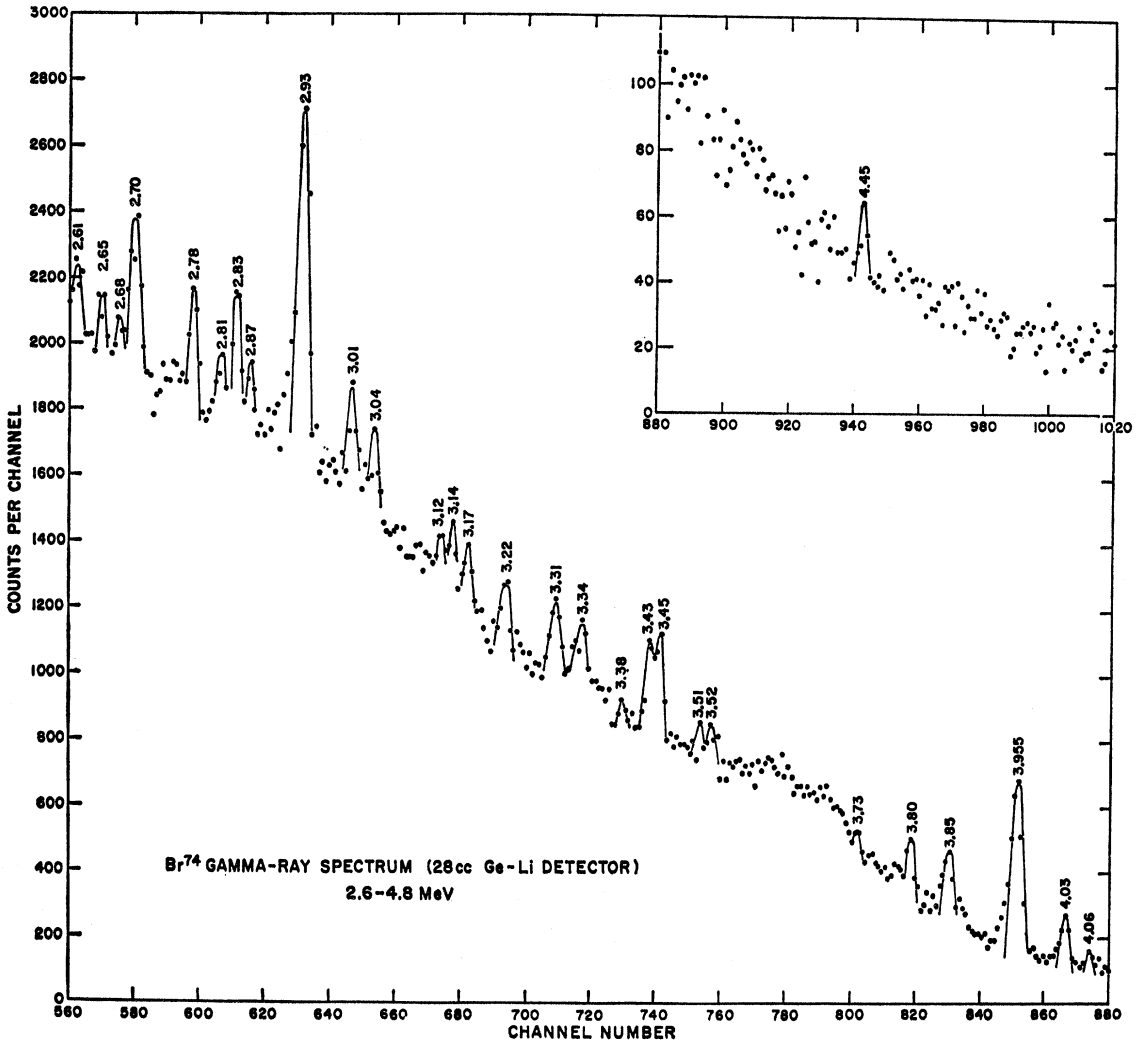
the 1230-keV line to be the second excited 2^+ level, and the 1860-keV the third excited 2^+ level in Se^{74}. The 600-keV γ line from 1230 to 630 keV has not been resolved from the 630-keV line, and therefore was experimentally not found. Other authors[2,4–6] have found that the 1370-keV level is the second 2^+ level in Se^{74}. With the availability of high-energy resolution Ge(Li) spectrometers, it seemed interesting to investigate this matter and clarify it. Furthermore, the availability of C^{12} ion beams at the Yale Heavy Ion Acceleratior made these experiments possible.

II. EXPERIMENTAL

A. Source Preparations

Stacks of thin Al-absorber foils (4.5 mg/cm²) in order to degrade the 10.5 MeV/nucleon carbon ions to 5.5 MeV/nucleon, a natural Cu target (1.5 mg/cm²), and one 4.5-mg/cm² Al catcher foil were bombarded with carbon-12 ions for 40 min. The catcher foil was dissolved in dilute HCl, 20-mg Br carrier was added

[4] F. Butement and G. Boswell, J. Inorg. Nucl. Chem. **16**, 10 (1960).
[5] Y. P. Gangrskii, I. K. Lemberg, Izv. Akad. Nauk. SSSR Ser. Fiz. **26**, 1001 (1962).
[6] D. M. Van Patter, R. Rikmenspoel, P. N. Trehan, Nucl. Phys. **27**, 467 (1961).



(c) FIG. 1. (*Continued*).

as well as 15 ml 1*N* HNO_3. With a few drops of 0.1*N* $KMnO_4$ solution, the bromine was oxydized to Br_2 and extracted five times with 10-ml carbon tetrachloride. The Br_2 was reduced with a $NaHSO_3$ solution, and, after acidifying with HNO_3, the bromine was precipitated as AgBr, washed, dried, and mounted as a source.[7] Such sources were used for all the different measurements. The Br^{75} produced at this C^{12} energy was little compared to the activity of Br^{74}.

B. Counting Techniques

The half-life was established by following the decay of the various γ-ray transitions (up to 1.5 MeV) with both 3×3-in. NaI(Tl) and Ge(Li) detector systems.

For the γ-ray measurements, singles as well as coincidences, a 6-mm thick×6-cm^2 Ge(Li) detector (resolution: 4 keV for the 1.33-MeV Co^{60} photo peak) was used. Several 3×3-in. NaI(Tl) crystals (resolution: 8.5% for the 661-keV photopeak of Cs^{137}) were employed for recording the various single and coincidence measurements simultaneously in connection with several RIDL channel analyzers. The coincidence circuits had a resolving time of approximately $2\tau = 40$ nsec. For the measurements of the positron spectrum, a 1-in. thick× 2-in. diam anthracene crystal coupled to a Dumont 6292 photomultiplier as well as a 3×4 in. plastic crystal were used. The calibration of the β spectrometer was performed with the following standard sources: Cs^{137} (624 keV), Bi^{207} (470 and 970 keV) and Sr^{90} (2.27-MeV endpoint energy).

In all the coincidence measurements, the counters were shielded with sufficient lead from each other to avoid Compton scattering. The two detectors were placed at 90° to each other. In the measurements performed the coincidence counts/random counts ratio was

[7] J. Kleinberg and G. A. Cowen, U.S. At. Energy Comm. NAS–NS 3005, 21 (1960).

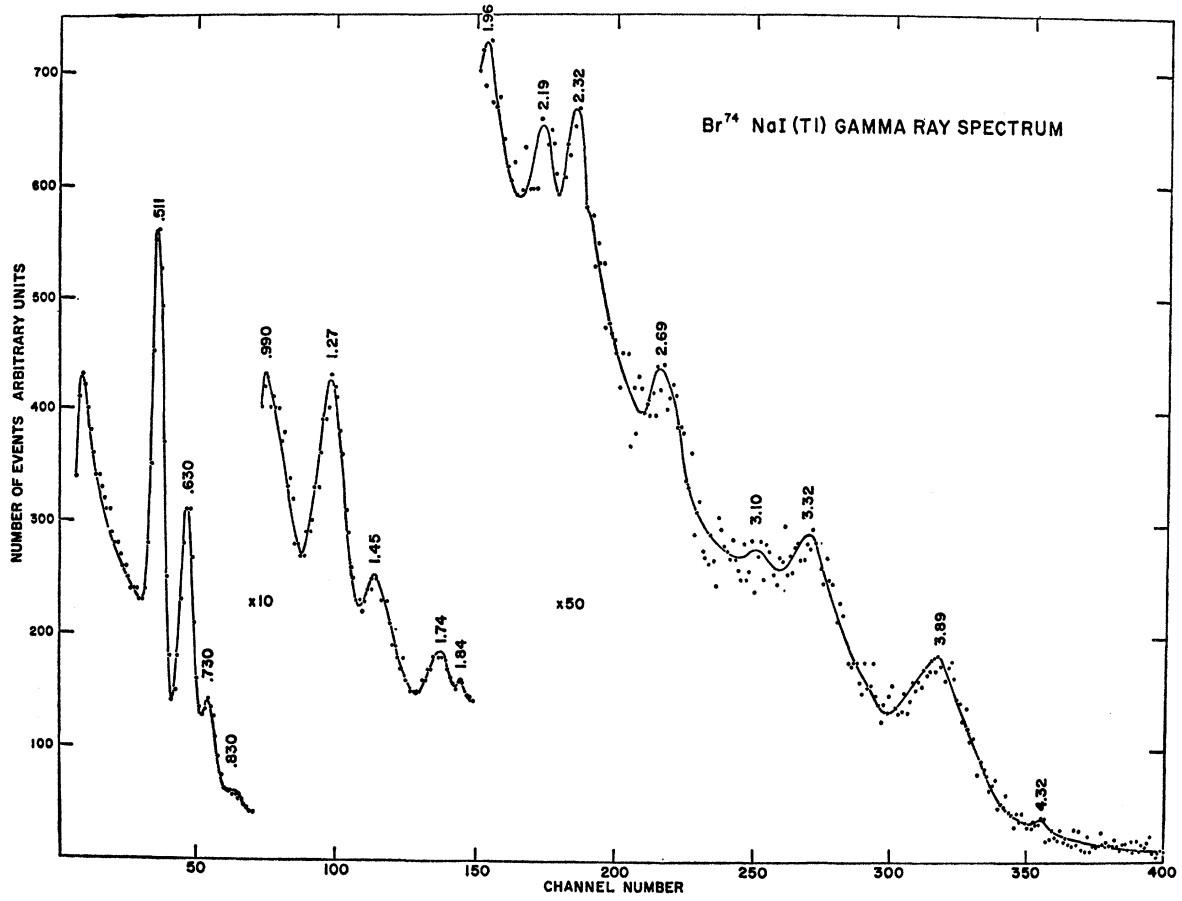


FIG. 2. Br^{74} γ-ray spectrum accumulated with a 5×4-in. NaI(Tl) crystal. The source-to-crystal distance was kept at 20 cm and the source was enclosed with 2 in. of Plexiglass to avoid summing effects.

always kept to be greater than 50. For the high-energy γ-ray determination a 28-cm^3 coaxial Ge(Li) detector and a Nuclear Data 1024-channel analyzer were used. The calibration was performed with the following listed sources: Ba^{133}, Cs^{137}, Na^{22}, Co^{60}, Na^{24}, and Th^{228} (2.614 MeV). With a 5×4-in. NaI(Tl) crystal in connection with a 400-channel analyzer, the Ge(Li) γ-ray measurements were confirmed.

III. EXPERIMENTAL RESULTS

A. Half-Life and Single γ-Ray Measurements

For the half-life measurements of the various γ rays, the small Ge(Li) detector was used. For the higher-energy γ-ray detection the 28-cm^3 Ge(Li) detector with the Nuclear Data 1024-channel analyzer was employed. The spectrum taken with two sources and accumulated for 3 h is shown in Fig. 1. The γ-ray energies and their relative intensities are given in Tables I and II. Since the γ-ray spectrum was observed without the use of a biased amplifier, we give the energies for these γ rays with a rather large error. The half-life was established with the following γ rays: 220, 355, 511, 610, 633, 722, 835, 985, 1190, 1220, and 1260 keV and found to be 38±1 min. We also found that there is always a small contamination of Br^{75} in our samples. We have therefore investigated the decay of Br^{75} and could establish the γ rays belonging to this isotope. The half-life value found in our studies agrees well with the value of 36±1 min reported by Belyaev *et al.*[3] Furthermore, a 5×4-in. NaI(Tl) crystal was used to measure the high-energy γ rays. The source-to-crystal distance was kept large, and sufficient absorbers were used to keep the summing of the various γ rays low. This spectrum is given in Fig. 2 and agrees well with that obtained by Belyaev. Figure 1 shows the γ spectrum with the 28-cm^3 Ge(Li) detector, and Fig. 3 shows some of the half-life measurements.

The identification of the various γ-rays was established by internal intensity calculations, i.e.,

4.5 MeV: DE/R=1.5, 3.8 MeV: DE/R=1,

3.0 MeV: DE/R=0.5, 2.5 MeV: DE/R=0.2.

TABLE I. γ rays of Br^{74} with intensities above 1%. R=real true γ peak, SE=single escape peak, and DE=double escape peak.

Energy (keV)	Relative intensities %	Identification
220±2	3.9	R
610±2	6.6	R
633±2	100	R
722±2	39.3	R
740±2	1.1	R
835±2	6.8	R
985±2	6.0	R
1190±5	7.6	R
1220±5	10	R
1260±5	11.1	R
1355±5	2.9	R
1445, 1455 ±5	10.1	R
1705±5	8.5	R
1830±5	3.2	R
1870, 1880 ±5	2.3	R+DE 2.87
1910±5	1.8	R
2030±10	2.3	R+DE 3.04
2300±10	4.3	R+DE 3.31
2335±10	4.6	R+DE 3.34
2700±10	5.1	R+DE 3.73
		+SE 3.22
3310±10	1.7	R+SE 3.80
3340±10	1.2	R+SE 3.85
3430±10	1.8	R+DE 4.45
3450±10	2.0	R+SE 3.95
3800±15	1.0	R+DE 4.45
3850±15	1.5	R
3955±15	7.4	R
4030±15	1.5	R

B. Coincidence Measurements

As one can see from Tables I and II, the low relative intensities of the various γ rays, the short-half life of the isotope, and the low efficiency for high-energy γ-rays in the Ge(Li) detector make only a few γ-γ coincidence measurements possible. The coincidence of the 633-keV line was measured in two ways. At first the Ge(Li) detector was used as a gate and the γ spectrum was accumulated with a 3×3-in. NaI(Tl) crystal (Fig.

TABLE II. γ rays of Br^{74} with intensities less than 1%. R=real true γ peak, SE=single escape peak, and DE=double escape peak.

Energy (keV)	Identification
160±2	R
355±2	R
1070±5	R
1140±5	R
1280±5	R
1320±5	R
1400±5	R
1480±5	DE 2.49
1540±5	R
1640±5	R+DE 2.65
1680±5	DE 2.70
1760±5	R
1965±5	R
1980±5	R
2120±10	R+DE 3.14
2150±10	DE 3.17
2170±10	R
2200±10	DE 3.22
2230±10	R
2380±10	DE 3.38
2400±10	DE 3.43
2450±10	DE 3.45+R
2490±10	R+DE 3.51
2520±10	DE 3.52
2540±10	R
2570±10	R
2610±10	R+SE 3.12
2650±10	R+SE 3.43/3.45
2680±10	R+SE 3.17
2780±10	DE 3.80
2810±10	R+SE 3.31
2830±10	DE 3.85+SE 3.34
2870±10	R+SE 3.38
2930±10	DE 3.95+SE 3.43/3.45
3010±10	DE 4.03+SE 3.52
3040±10	R+DE 4.06
3120±10	R
3140±10	R
3170±10	R
3220±10	R+SE 3.73
3380±10	R
3510±10	R
3520±10	R+SE 4.03
3730±10	R
4060±15	R
4450±20	R

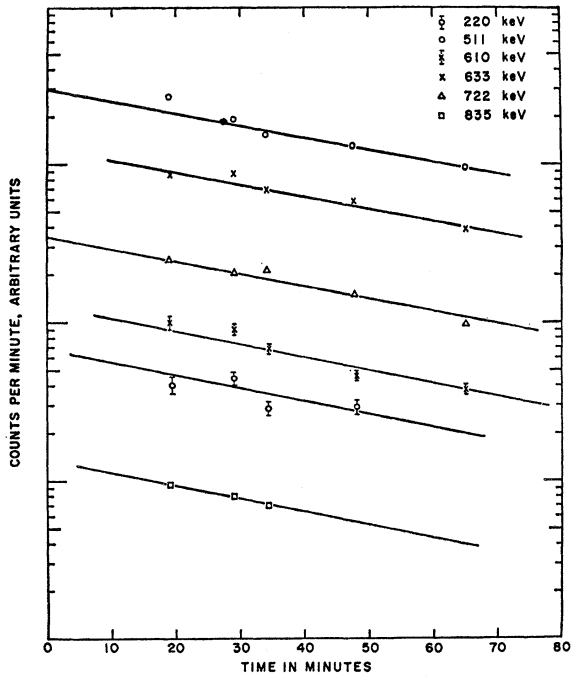


FIG. 3. Half-life measurements of some of the γ lines of Br^{74}.

4). The other time we gated with a 3×3-in. NaI(Tl) crystal and counted with the Ge(Li) detector (Fig. 5). The 633-keV γ ray is in coincidence with 511, 610, 722, 835, and 985 keV. The coincidence measurement of the 722-keV γ line gated with a NaI(Tl) crystal, and counted with a Ge(Li) detector, showed coincidences with 511, 610, 633, 835, and 985 keV (Fig. 5). The coincidence with the 985-keV γ line was established in another experiment of which the figures are not given in this paper. In Fig. 6, the β^+ endpoint energy measured with a plastic detector is given in coincidence with the 633-keV γ line. The value obtained is 4.5±0.1 MeV. The total β spectrum measured in singles as well as in coincidence with 511 keV gave a β^+ endpoint energy of 5.2± 0.1 MeV. This makes the mass difference of Br^{74} to Se^{74} 6.2 MeV. The estimated value given in Ref. 8 is 6.8 MeV and in Ref. 9 it is 5.7 MeV. We repeated our β endpoint energy measurement several times; however, no positrons higher than 5.2 MeV were detected.

IV. DISCUSSION

Part of the above results as well as some information from previous references were used to establish a tentative decay scheme of Br^{74}. The decay scheme is shown

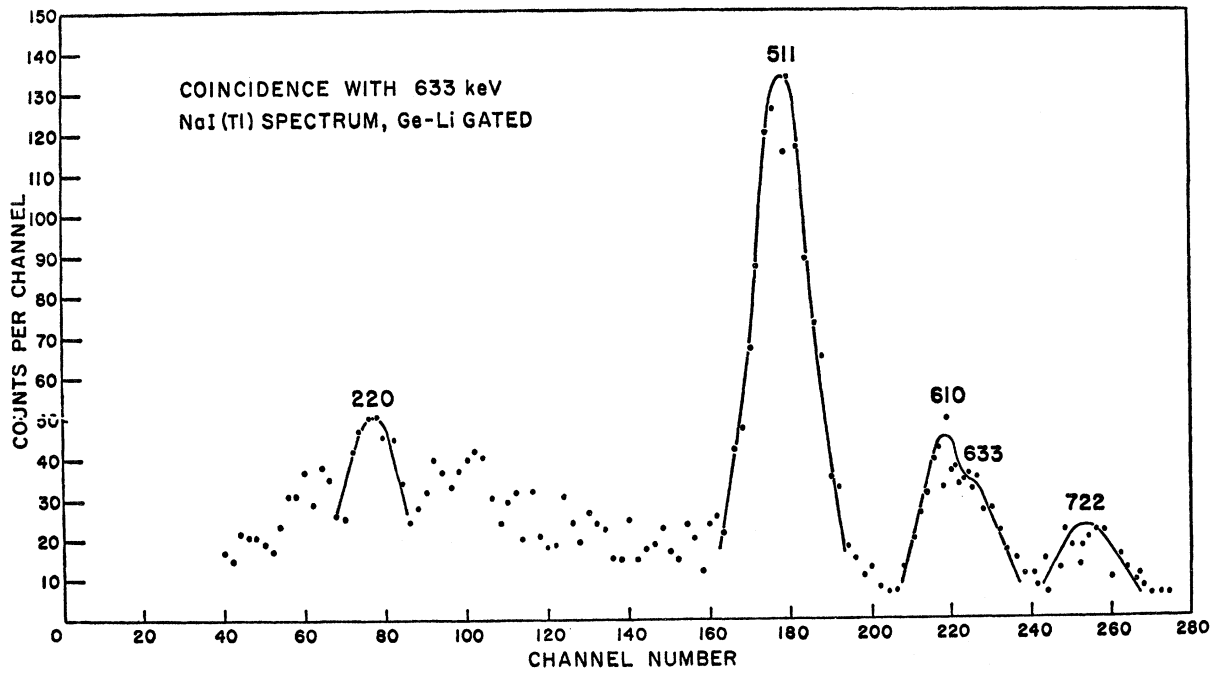


FIG. 4. Coincidence measurement with the 633-keV γ line gated with a 6-cm^3 Ge(Li) detector and counted with a 3×3-in. NaI(Tl) crystal.

[8] C. M. Lederer, J. M. Hollander, and I. Perlman, *Table of Isotopes* (Wiley-Interscience, Inc., New York, 1967).
[9] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Academic Press Inc., New York, 1966), B1-6-60 and B1-6-64.

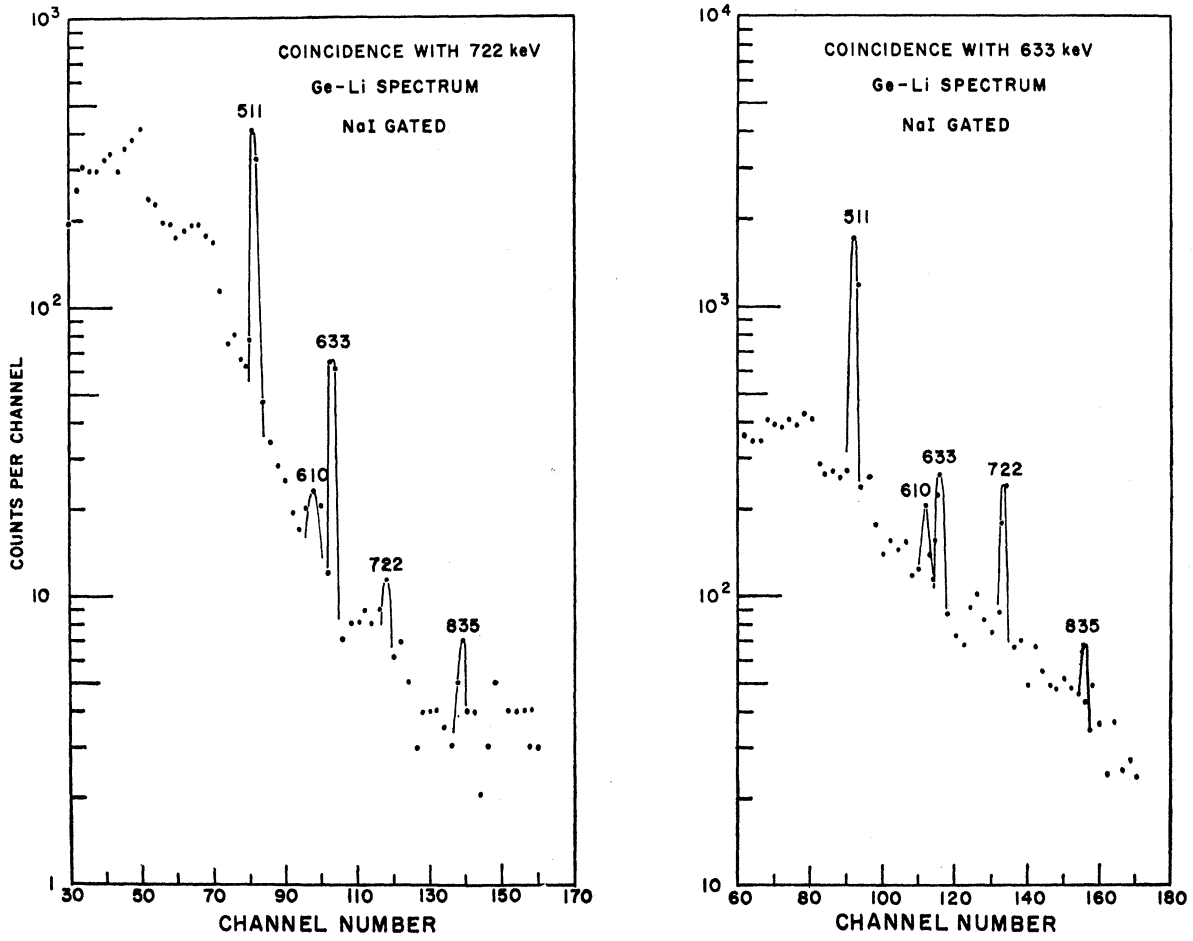


FIG. 5. γ-ray spectra in coincidence with the 633- and 722-keV photopeaks. In each experiment, the γ-ray spectrum is recorded with a 6-cm^3 Ge(Li) detector and the gate is selected with a 3×3-in. NaI(Tl) crystal.

in Fig. 7. The levels of 633, 1355, and 1965 are confirmed by the various γ-γ coincidence measurements in the paper and partly by Coulomb excitation of Se^{74}.[5,6] The observed γ lines at 3.80, 3.85, 3.95, 4.03, 4.06, and 4.45 MeV have been identified with a 5-in.×4-in. NaI(Tl) crystal as well as with the 28-cm^3 Ge(Li) detector. No higher energetic γ lines were found; therefore, these peaks are true γ peaks and not single- or double-escape peaks of higher energetic γ lines. This indicates that these are the high-energy states in Se^{74}.

However, as the γ spectrum of Br^{74} shows, it is rather difficult to establish the levels between 3 and 3.8

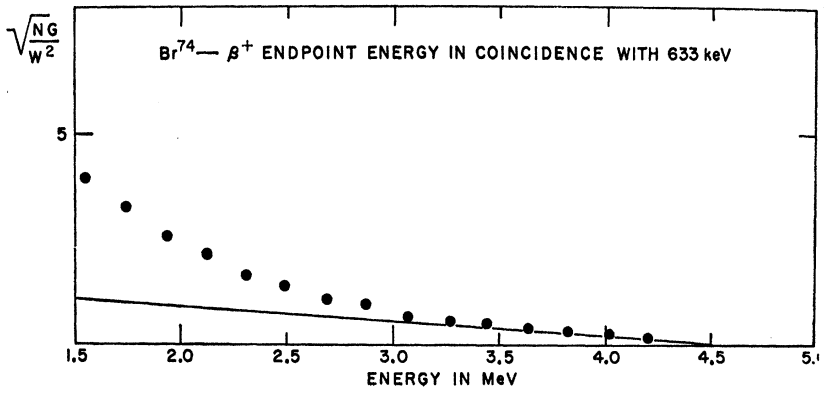


FIG. 6. Fermi-Kurie plot of the β spectrum in coincidence with the 633-keV γ line. The source thickness was about 3.5 mg/cm^2.

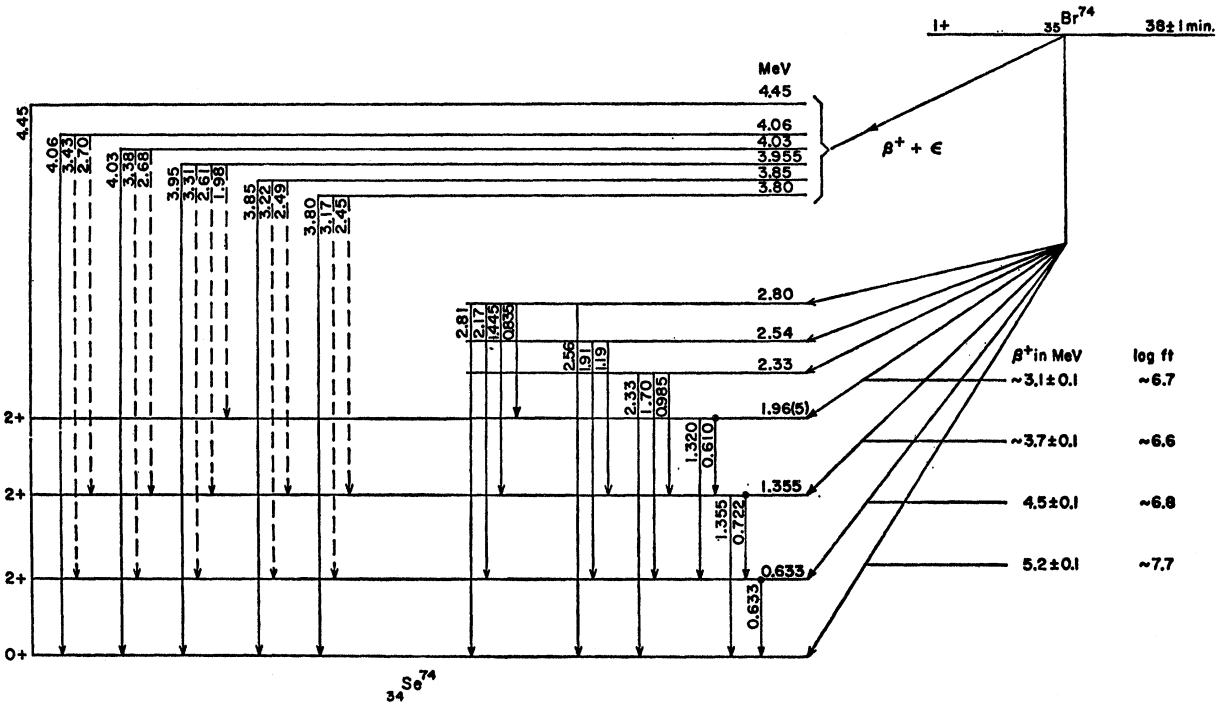


FIG. 7. Tentative decay scheme of Br^{74}.

MeV, since the intensities of these γ rays are very low. Furthermore, the low efficiency of the Ge(Li) detectors for this energy region makes any γ-γ coincidence measurement impossible. Other difficulties are the close-lying γ lines and the overlapping of real-, single-, and double-escape peaks (see Table I and II). The use of a NaI(Tl) crystal as a gate has the disadvantage of not being able to separate the various close-lying γ lines and completely avoiding any summing of the many γ rays. Besides these difficulties, the relatively short half-life of Br^{74} and the low relative intensity of Br^{74} in our sources was the most serious problem and limitation in this investigation of the Br^{74} decay.

The mass difference, as mentioned previously, was measured to be about 6.2 MeV, showing a large discrepancy from the estimated value of 5.7 MeV given in Ref. 9 as well as from the value of 6.8 MeV reported in Ref. 8. We repeated our measurements several times, and the result of the β endpoint energy was always the same. The error in our measurement is about ± 100 keV.

The ground state of Br^{74} is 1^+ or 0^+, as reported in Ref. 9. The Se^{74} ground-state spin of 0^+ is well known, and, by Coulomb excitation, a spin of 2^+ was assigned to the 635- and 1360-keV levels by various authors.[5,6] The 1965-keV level has probably a spin of 2^+, since the crossover of 1.32 to the first excited 2^+ level as well as the 0^+ ground state was observed. For a more detailed examination of this decay scheme, higher efficiency Ge(Li) detectors and a Ge(Li) Compton suppression spectrometer should be used.

ACKNOWLEDGMENTS

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