Decay of 18-min Br^{80}†

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Gamma rays with energies of 0.618±0.003, 0.640±0.009, 0.67±0.02, 0.710±0.010, 1.258±0.007, and 1.333±0.010 Mev have been observed in the decay of 18-min Br^{80}, and their intensities determined. Of these, only the 0.618-Mev gamma ray has been previously reported. Two new levels are proposed at 1.26 and 1.33 Mev in Kr^{80}, and the branching (crossover/cascade) determined for these levels as 0.46±0.08 and 0.14±0.06, respectively. The 0.67-Mev gamma ray is assigned to the first 2+ state of Se^{80}, whose energy has been determined as 0.667±0.004 Mev from the $(p,p'\gamma)$ reaction. Excitation of the second level of Se^{80} at 1.44 Mev was not observed. The measured value of 0.62-Mev γ/β^+ of 2.6±0.1 has been used to evaluate log*ft* values for the transitions to various levels in Se^{80} and Kr^{80}. The allowed transitions from the 1+ ground state of Br^{80} to the ground state and first two levels of both Se^{80} and Kr^{80} are found to be successively hindered, in accord with the empirical rule of Sakai.

I. INTRODUCTION

THE 18-minute isomer of Br^{80} has been studied by various authors[1–5] and has been found to have a complex beta-ray spectrum. The first careful investigation of the beta-ray spectrum was made by Fultz and Pool[1] who reported three beta groups of energy 0.7, 1.1, and 1.97 Mev. Similar studies done more recently by Laberrigue-Frolow[2] indicate two beta groups of energies 1.1 and 1.99 Mev measured by a magnetic spectrometer. The beta group of 1.1-Mev energy reported by these authors does not agree with the first-excited state of Kr^{80} reported at 0.620 Mev by Goldhaber and McKeown.[3] In fact, from beta-gamma coincidences between the 0.62-Mev gamma ray and the rest of the beta groups, Laberrigue-Frolow concludes that the 1.1-Mev beta group could have an energy lying anywhere between 1.30 and 1.45 Mev. This possible uncertainty in the end-point energy of the low-energy beta group could cause considerable error in the relative intensities of the two accepted beta groups. It appeared therefore that the branching ratio accepted by Nuclear Data Group[4] could be subject to error.

Since the ratio of the relative intensities of the two beta groups is questionable, it was decided to try to obtain a more accurate measurement of the ratio of the intensities of 0.620- and 0.511-Mev gamma rays than was reported earlier by Scharff-Goldhaber and McKeown.[3] A sufficiently precise measurement could then be used in place of the relative intensities of the beta groups to get the branching to the various levels.

Another item of interest was the possible presence of high-energy gamma rays in the decay of Br^{80}. It has been estimated by Lidofsky *et al.*[5] that the intensity of gamma rays with an energy greater than 0.62 Mev is less than one percent of the decays. More recently the $(\alpha,\alpha'\gamma)$ studies of Se^{80} by Temmer and Heydenburg[6] indicated the presence of a 0.654-Mev gamma ray which they have assigned to the first 2+ level of Se^{80}. This evidence has been confirmed by preliminary (p,p') studies at M.I.T. by Carter[7] who reports the first three levels in Se^{80} at 0.661, 1.444, and 1.470 Mev. Further, Sakai[8] has estimated the beta branching to the second 2+ level of Kr^{80} should be 10% relative to that to the first 2+ level. In this prediction, he assumed that the second 2+ level had an energy twice that of the first 2+ level, and that the allowed transitions to both levels had the same log*ft* value. On the basis of these considerations, it was decided to investigate the gamma-ray spectrum of the 18-min Br^{80} activity.

II. EXPERIMENTAL PROCEDURE AND APPARATUS

Br^{80} sources were produced from the $Se^{80}(p,n)Br^{80}$ reaction by bombarding semithick (~50 kev) isotopically enriched Se^{80} targets[9] (94.4% Se^{80}, 2.85% Se^{78}, 10.4% Se^{76}, 0.91% Se^{82}, 0.83% Se^{77}) with 4.0-Mev protons from the Bartol-ONR van de Graaff accelerator. The targets of Se^{80} were evaporated in vacuum on to 10-mil thick gold foils. The evaporation was carried out by using a carbon rod of 0.25-in. diameter with a hole in the center 40-mil diameter and 0.125 in. deep. A small amount (1–2 mg) of the enriched isotope was placed in the hole, and evaporated on to the gold foil, which was placed 4 cm above the rod. This process was repeated a few times to obtain a suitable target. The only extrane-

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2 J. Laberrigue-Frolow, Ann. phys. **1**, 152 (1956).

3 G. Scharff-Goldhaber and M. McKeown, Phys. Rev. **92**, 356, 1094(A) (1953).

4 *Nuclear Data Sheets*, compiled by K. Way, F. Everling, G. H. Fuller, N. B. Gove, R. Levesque, J. B. Marion, C. L. McGinnis, and M. Yamada (National Academy of Sciences, National Research Council, Washington, D. C., 1959).

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9 Obtained from the Stable Isotopes Division, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

ous activity from proton bombardment found to be detectable was that from Br^{82}. The amount of Br^{82} activity was considerably less than that expected from a natural selenium target, for which the Se^{82}/Se^{80} ratio would be a factor of 19 greater. This 36-hr activity was kept low by bombarding each target for not more than one hour. Since only two Se^{80} targets were available, the singles and coincidence spectra were taken separately with an interval of two weeks. The gamma rays from the decay of Br^{80} were studied with a conventional scintillation spectrometer. Two 3-in.×3-in. NaI(Tl) crystals, each mounted on a Dumont 6363 photomultiplier, were supplied by the Harshaw Chemical Company. These selected phosphor-photomultiplier assemblies had a resolution of 7.6% for the 0.662-Mev gamma ray of Cs^{137}. The crystals were shielded by 0.5-in. thick lead cylinders. Pulse-height spectra were registered on a 400-channel RIDL transistorized analyzer.

The singles spectra were analyzed in a manner described by Heath.[10] The response functions for both crystals for monoenergetic gamma rays were obtained from observed pulse-height distributions of gamma rays of Ce^{141}, Cr^{51}, Cs^{137}, Na^{22}, Y^{88}, and Pr^{144}. These pulse-height spectra were obtained in geometrical conditions approximating those in which Br^{80} spectra were taken. When a response function was required with an energy differing from those available, the function was obtained by graphical interpolation. The total efficiency of the crystals was checked by using a standard Co^{60} source. The value for total efficiency obtained experimentally agreed within 3% to the theoretically calculated value of Heath.[10] Also a check was made on the peak-to-total ratio using the 0.662-Mev gamma of Cs^{137} and the 1.837-Mev gamma ray of Y^{88}. The value for this ratio for both sources agreed within 4% with the values obtained by Heath for similar crystals. It was therefore decided to use Heath's reported values for the above two quantities.

Gamma-gamma coincidences were measured by using a pair of 3-in.×3-in. NaI detectors at 90° and 180° to each other. These crystals were shielded from each other by a anti-Compton shield of the type described by Bell.[11] A "fast-slow" coincidence circuit with a fast resolution of 18 nanosec was employed. The coincidence spectrometer consisted of a single-channel pulse-height analyzer operated in coincidence with a 400-channel analyzer. The linear amplifiers used with the coincidence circuit were Hewlett-Packard 460 A fast amplifiers. The coincidence efficiency of the circuit was checked by using annihilation gamma rays from a Na^{22} source, and was found to be 99%.

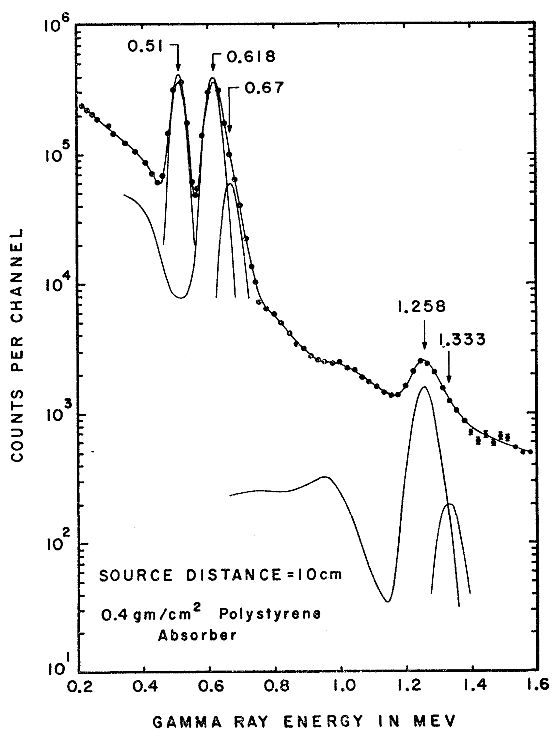

FIG. 1. Gamma-ray spectrum of Br^{80} with source 10 cm from the face of a 3-in.×3-in. NaI crystal.

III. SINGLES GAMMA-RAY SPECTRA

The gamma-ray spectrum obtained from the 18-min isomer of Br^{80} taken at 10 cm from the face of 3-in. ×3-in. NaI crystal is shown in Fig. 1. The source was sandwiched between two pieces of Lucite to absorb positrons. The spectrum shown in Fig. 1 has been corrected for the contribution of the 36-hr activity of Br^{82}. This correction was applied by taking the spectrum of the source 46 hr after the time of bombardment, under similar geometrical conditions. This spectrum showed only Br^{82} gamma rays and was subtracted from the raw Br^{80} spectrum after proper correction for decay. This correction reduced the area of the 1.333-Mev photopeak of Br^{80} by roughly 30%. The intensities of the remaining gamma rays from Br^{80} were essentially unaffected by the subtraction of Br^{82} activity.

Gamma rays with energies of 0.618 ± 0.003, 0.67 ±0.02, 1.258 ± 0.007, and 1.333 ± 0.010 Mev were observed. The 1.333-Mev gamma ray has the smallest intensity, and therefore its existence is less sure. The peak at 0.67-Mev is broadened due to the presence of two low-intensity gamma rays with energies of 0.64 and 0.71 Mev, which were separated in the coincidence spectra. The energy measurements are based on calibrations using annihilation radiation, and the latest value for the Na^{22} gamma ray of 1.2736 ± 0.0016 Mev.[12] The decay of each of the gamma rays was carefully followed and was found to have a half-life of approximately 18

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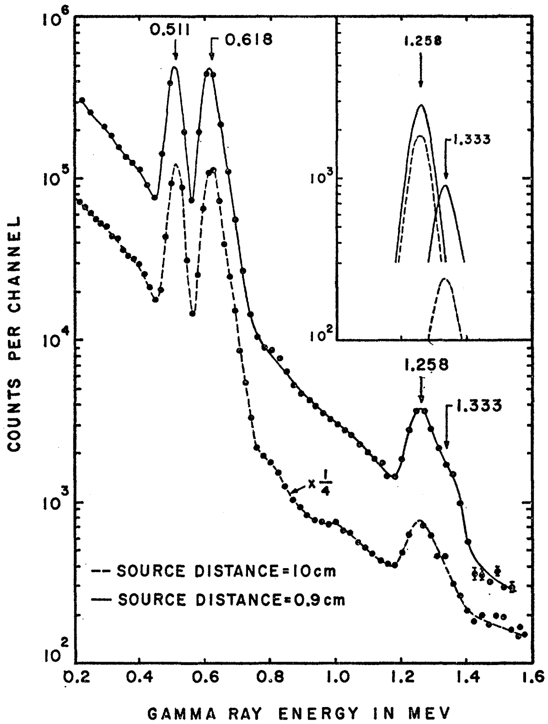

FIG. 2. Gamma-ray spectrum of Br^{80}. (a) Source at 0.9 cm from the 3-in.×3-in. NaI crystal; (b) source at 10 cm from the 3-in. ×3-in. NaI crystal. The insert shows the analyzed spectrum above 1.18 Mev for both distances. The intensity of the 0.511-Mev annihilation radiation is normalized for these spectra.

min. This indicated that all the gamma rays observed were due to the 18-min isomer of Br^{80}. The 4.4-hr activity of Br^{80} did not affect the relative intensity of the various gamma rays since this activity is known to decay to the ground state of Br^{80}.[4]

A sum spectrum for Br^{80} was taken with the source at a distance of 0.9 cm from the crystal, which is shown in Fig. 2 together with a singles spectrum taken with the source at a distance of 10 cm from the crystal. The intensity of the 0.511-Mev gamma ray has been normalized for these spectra. It is evident from the insert of Fig. 2 that the relative yield of each of the 1.26- and 1.33-Mev gamma rays is increased at 0.9 cm due to the effect of summing. This increase in gamma-ray intensity can be accounted for by introducing two new levels at 1.26 and 1.33 Mev, and two new cascade gamma rays of energy 0.64 and 0.71 Mev corresponding to these levels. From the combined analysis of singles and sum spectra, the relative intensities of all the gamma rays have been obtained. These relative intensities together with the energies of the various gamma rays are given in Table I.

TABLE I. Summary of Br^{80} gamma-ray data.

Gamma-ray energy (Mev)	Intensities relative to 0.620-Mev gamma ray: From singles and sum data	Best value from coincidence data
0.618±0.003	100[a]	
0.640±0.009	⌈2.8±0.5	2.9±0.3[a]
0.667±0.004	16.0±2.4[a]	
0.710±0.010	1.9±0.5	2.1±0.3[a]
1.258±0.007	1.3±0.2[a]	
1.333±0.010	0.3±0.1[a]	

[a] These values are used in the evaluation of transitions to the various levels.

The relative yield of the 0.62-Mev gamma ray and annihilation radiation has been measured as 1.29±0.05. This gives the value of the 0.62-Mev γ/β^+ ratio as 2.58±0.10.

IV. GAMMA-GAMMA COINCIDENCE SPECTRA

Figure 3 shows the coincidence spectrum obtained with a differential discriminator set at the 0.62-Mev peak. The two 3-in.×3-in. NaI crystals were located at 90° to each other, and at a distance of 6 cm from the source. The errors indicated for each point are the calculated probable errors based on counting statistics. This spectrum has been corrected for Br^{82} coincidences, which were run separately 6 hr after the Br^{80} run using the same geometry. This subtraction had a negligible effect on the Br^{80} coincidence spectrum.

The full energy peaks in the coincidence spectrum were determined in a manner similar to that described for the single-crystal spectra. This spectrum shows peaks at 0.630±0.009 and 0.710±0.010 Mev. The peak at 0.67 Mev prominent in the singles spectra does not appear in coincidence with 0.62-Mev peak. In addition, a weak peak at about 0.4 Mev is indicated in Fig. 3 which is unexplained.

When the window of the single-channel analyzer is

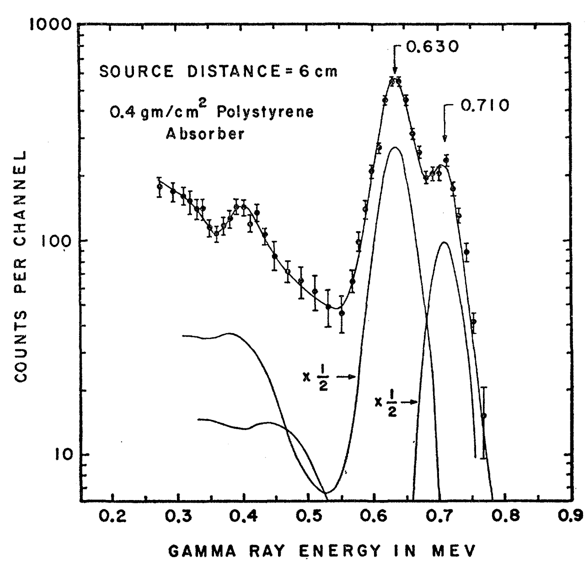

FIG. 3. Br^{80} gamma-ray spectrum in coincidence with 0.62-Mev gamma ray. The two 3-in.×3-in. NaI crystals were set at 90° to each other and at 6 cm from the source.

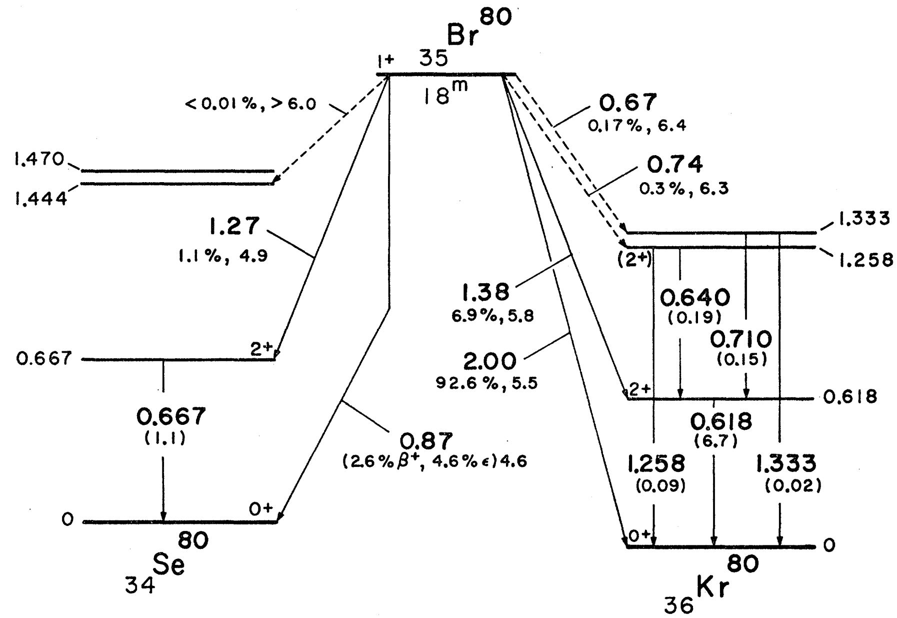

FIG. 4. Decay scheme proposed for Br^{80}. All energies are in Mev and numbers in parentheses beneath the gamma-ray energies are the percentage decays.

set at the 0.62-Mev peak, it receives some contribution from the 0.64-Mev gamma ray. Thus the 0.630-Mev gamma ray in the coincidence spectra is made up of two gamma rays, 0.64 Mev (56%) and 0.62 Mev (44%). This superposition of two gamma rays causes the lowering in energy of the coincidence peak from 0.640 to 0.630 Mev. A correction is applied for this effect in evaluating the intensities of 0.64- and 0.71-Mev gamma rays. In Table I are shown their intensities relative to the intensity of the 0.62-Mev gamma ray as obtained from this coincidence measurement. The intensities listed have not been corrected for possible angular corrections between various pairs of gamma rays, since this information is not presently known.

The coincidence spectrum was run with the differential discriminator set at the 0.511-Mev annihilation peak. The two 3-in.×3-in. NaI crystals were set at 180° to each other and at 5 cm from the source. Coincidences were observed only with the annihilation gamma ray.

V. STUDY OF $Se^{80}(p,p'\gamma)$ REACTION

The above measurements can give conclusive results for the assignment of all but one gamma ray of energy ~0.67 Mev. This gamma ray was not observed in any of the coincidence spectra. In order to make a definite assignment of this gamma ray, and to find its energy more precisely, a $(p,p'\gamma)$ study of Se^{80} was carried out. A target of Se^{80} evaporated on 5-mil gold backing was placed in a target chamber of a similar design as discussed earlier by Van Patter *et al.*[13] A bombarding energy was chosen just below the $Se^{80}(p,n)Br^{80}$ threshold, in order to obtain a maximum $(p,p'\gamma)$ yield without contribution from the (p,n) reaction. The target was bombarded by 2.60-Mev protons and the gamma-ray spectra obtained using a 3-in.×3-in. NaI crystal. This spectrum showed a prominent gamma ray of energy 0.667 ± 0.004 Mev, corresponding to the first level of Se^{80}. The energy of this gamma ray was determined by comparison to a Na^{22} source.[12] No indication of a 1.444-Mev gamma ray corresponding to a transition from the 1.444-Mev level in Se^{80} was seen.

VI. DISCUSSION OF DECAY SCHEME

The proposed decay scheme for Br^{80} is shown in Fig. 4. The branching ratio to the various levels has been obtained by using the following measurements.

(1) The ratio of 0.62-Mev $\gamma/\beta^+=2.58\pm0.10$ measured in the present experiment.

(2) The ratio of $\beta^+/\beta^-=0.028\pm0.002$ measured by Laberrigue-Frolow.[2] We regard this measurement as the most reliable of the various available measurements.[4]

(3) The ratio of $(\beta^+ + \epsilon)/\beta^-=0.090\pm0.002$ which has been measured by Reynolds[14] using a mass spectrometer.

(4) The relative intensities of the various gamma rays as measured in the present experiment.

The gamma ray at 0.618 Mev originates from the previously known first 2+ level in Kr^{80}. From coincidence and sum spectra studies the 0.64- and 1.258-Mev gamma rays are assigned to the level at 1.258 Mev. This level is given a tentative assignment of 2+ due to the following reasons:

(1) The position of this level agrees (~0.1 Mev) with the expected position for the previously missing second 2+ level predicted from a study of the systematic

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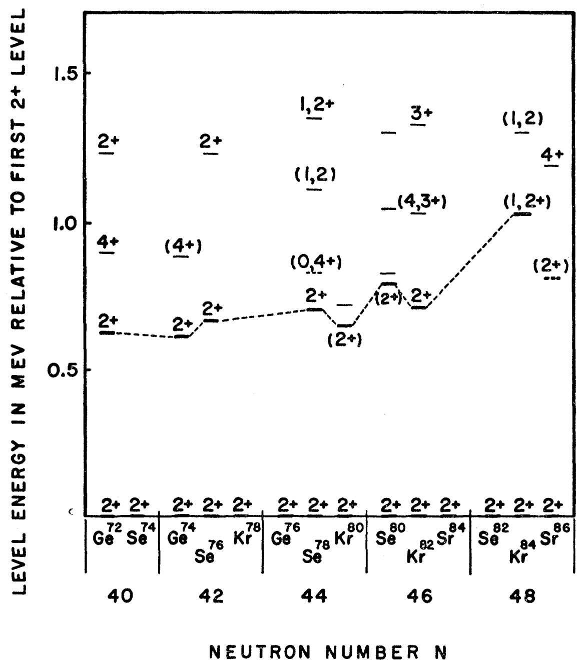

FIG. 5. Systematics of the energy levels of stable even-even nuclei with neutron number 40–48.

properties[15] of the energy levels of the neighboring even-even nuclei as shown in Fig. 5.

(2) The spin of the ground state of Br^{80} is known to be 1+.[4] Sakai has tabulated the log*ft* values for the allowed transitions from an odd-odd parent nucleus (1+) to the low-lying states of the daughter nucleus.[8] The log*ft* value of the transition to the 1.258-Mev level is measured as 6.3, which lies within the range of values observed from other nuclei for an allowed transition to the second 2+ state.[8]

Another level at 1.333 Mev is proposed on the basis of the 1.333-Mev gamma ray observed in the singles spectra and the 0.71-Mev gamma ray observed in coincidence with the 0.62-Mev gamma ray. Since there is a crossover transition observed from this level, this indicates a low spin assignment for this level. The log*ft* value for this level is 6.4, which suggests that this is an allowed transition.

The branching ratio (crossover/cascade) of the 1.258-Mev level has been measured as 0.47 ± 0.08. If we assume that the transition is pure $E2$, the ratio of the reduced $E2$ transition probabilities $B(E2;2'\rightarrow 2)/B(E2;2'\rightarrow 0)$ is 64 ± 12. This value is similar to that found for the second 2+ level of Kr^{82}, but somewhat exceeds values found for similar states in other neighboring nuclei below the $N=52$ shell.[16] The branching of the 1.33-Mev level has been measured as 0.14 ± 0.06.

The gamma ray of energy 0.67 Mev is assigned to the first 2+ level in Se^{80}. The log*ft* value of the transition to this level is 4.9 which represents an allowed transition, and agrees with the 2+ spin assignment for this level. Since no coincidences were observed between annihilation and 0.67-Mev gamma rays, it indicates that the transition to this level from the 1+ ground state of Br^{80} is mainly due to electron capture. The K capture to positron emission ratio for this level is expected to be ~0.1% from theoretical estimates by Zweifel.[17]

No definite ground-state gamma-ray transition from the second 2+ level at 1.444 Mev in Se^{80} has been observed. This possible gamma ray lies close to the 1.445-Mev gamma ray of Br^{82}, and the 1.46-Mev gamma of K^{40} which are present in the uncorrected singles spectrum as contaminants. Thus it was possible to put only an upper limit to the intensity of γ ray as ~0.1% of the intensity of the 0.62-Mev gamma ray, which gives the log*ft* value for the transition to this level as >6.0. The ratio of electron capture to positron emission for the transition to the ground state of Se^{80} has been evaluated at 1.8 ± 0.3 which lies close to the theoretically expected value of 2.2.[17]

VII. FINAL COMMENTS

The radioactive nuclide Br^{80} (1+) is unusual in the respect that, for both β^+ and β^- branches, allowed transitions to the ground state and first two 2+ states can be studied. There are two other 1+ parent nuclei, Ag^{108} and I^{128}, where both β^+ and β^- branches to at least the first 2+ state have been studied.[18,19] However, it is unlikely that excitation of the second 2+ state in Cd^{108} can be observed, and it is energetically impossible for the second 2+ state of Te^{128} to be excited from the decay of I^{128}.

Examination of the log*ft* values given in Fig. 5 for the various beta transitions of Br^{80} reveal certain interesting features.

(a) The allowed transitions to the ground and first 2+ state of Se^{80} are about an order of magnitude faster than the β^- transitions to the same states in Kr^{80}. Since these transitions all originate with the same parent state, the results appear to indicate a difference in the wave functions of the ground states (and first 2+ states) of the final nuclei, Se^{80} and Kr^{80}.

(b) The log*ft* value for the transition to the second excited state is higher than that to the first 2+ state (or to the ground state). This difference in log*ft* values, $\Delta_{21}\log ft$, is more pronounced for Se^{80} (>1.1) than for Kr^{80} (0.5). If the second-excited state is 2+ for both nuclei, then the transitions to all three states are allowed.

It appears that the observed beta transitions in the decay of 18-min Br^{80} provide two examples of the empirical rule suggested by Sakai[18,19]: that the allowed beta transitions from an odd-odd parent nucleus (1+,

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[19] M. Sakai, Nuclear Phys. (to be published).

2+ or 3+) to the 0+ ground state, to the first 2+ level, and to the second 2+ level are usually successively hindered.

At the present time, there is considerable more information available for 1+ parents than for 2+ or 3+ parents. Also in this case the three transitions are all allowed. For such 1+ parents, the two largest positive values found to date for the difference $\Delta_{21}\log ft$ are the present value of >1.1 for the $Br^{80}\rightarrow Se^{80}$ decay and that of >0.8 obtained for the $Br^{78}\rightarrow Se^{78}$ decay in a recent investigation at this laboratory.[20] It would be interesting to examine the question of whether or not this effect could be generally larger for β^+ decays than for β^- decays. Pertinent to this point would be an investigation of the hitherto unobserved decay of Rb^{80} (1+) to the second level of Kr^{80}, which could provide a value of $\Delta_{21}\log ft$ to be compared to the present result for the $Br^{80}\rightarrow Se^{80}$ decay. Allowed transitions have been observed in the decay of Rb^{80} to the ground state and first 2+ level of Kr^{80}, each with a log-ft value of 4.6.[21]

ACKNOWLEDGMENTS

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Excitation Function of the Reaction $Ti^{47}(n,p)Sc^{47}$ at Neutron Energies between 2.0 and 3.6 Mev

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The relative cross section for $Ti^{47}(n,p)Sc^{47}$ has been measured by an activation method for neutron energies of 2.0 to 3.6 Mev. The absolute cross section at 3.55-Mev neutron energy is found to be 62.7±9.7 mb by comparing the absolute 160-kev gamma activity of Sc^{47} with the absolute beta activity of Si^{31} from the $P^{31}(n,p)Si^{31}$ reaction, which has a known cross section of 96.2±9.0 mb. The cross section rises from 40.1 mb at 1.99 Mev to 69.9 mb at 3.40 Mev. A comparison is made of the observed cross sections for $P^{31}(n,p)Si^{31}$, $S^{32}(n,p)P^{32}$, $Ti^{47}(n,p)Sc^{47}$, and $Ni^{58}(n,p)Co^{58}$ with a theoretical estimate based on the statistical theory of nuclear reactions with the assumption that only the ground states and possibly the first excited states of the residual nuclei contribute to the cross section.

INTRODUCTION

In this paper we report on measurements of the cross section for the reaction $Ti^{47}(n,p)Sc^{47}$. This work is part of an investigation of (n,p) cross sections of medium-weight isotopes.[1–3] These cross sections are of interest in connection with nuclear reaction theory, neutron detection and nuclear reactor physics. No data seem to be available on the $Ti^{47}(n,p)Sc^{47}$ reaction in the neutron energy range of 2.0 to 3.6 Mev.

The reaction has a positive Q value of 182.6±2.0 kev[4] and the product Sc^{47} decays with a half-life of 82.3 hr.[5] The ground state of Sc^{47} decays to the 160-kev excited state of Ti^{47} with a branching ratio of 0.63±0.03[5]; other transitions are to the ground state of Ti^{47}. We have measured the relative yield of the reaction $Ti^{47}(n,p)Sc^{47}$ through the 160-kev gamma ray of Ti^{47}. The absolute cross sections are obtained by comparing the Sc^{47} activity with the Si^{31} activity formed in the $P^{31}(n,p)Si^{31}$ reaction which has a cross section of 96.2±9.0 mb at 3.56-Mev neutron energy.[6]

EXPERIMENTAL PROCEDURE

The experimental equipment and procedure were the same as described by Rapaport and van Loef.[1] The excitation function was obtained by placing titanium samples at various angles around the d-D neutron source at a distance of 6 cm and irradiating them simultaneously. Irradiations were performed at deuteron energies of 600 kev (24 hr) and 400 kev (27 hr). In this way the neutron energy range from 2.0 to 3.6 Mev was covered in steps of about 200 kev. The neutron

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