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Beta Spectrum of ^{87}Kr

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(Received 21 August 1972)

A measurement of the β spectrum of ^{87}Kr was undertaken to resolve some discrepancies in recently reported values of the branching of the β decay to the ground state of ^{87}Rb. Sources of mass-separated ^{87}Kr, provided by the TRISTAN on-line isotope separator, were investigated with a high-resolution $\pi\sqrt{2}$ magnetic spectrometer. Using constraints based on previous γ-ray decay schemes, the measurement yielded a Q value of 3.888 ± 0.007 MeV and a ground-state β intensity of $(30.5 \pm 2.2)\%$. In addition, the intensity ratio for an unresolved γ-ray doublet at 2555 keV was independently determined on the basis of β-branch intensities to the levels at 2555 and 2960 keV.

I. INTRODUCTION

There have been five recent measurements[1-5] of the level structure of ^{87}Rb populated from the decay of ^{87}Kr. The most recent work by Shihab-Eldin *et al.*[1] (referred to subsequently as SPBR), contains a brief summary of the earlier γ-ray studies. The level scheme reported by SPBR is shown in Fig. 1; 28 transitions have been placed in this level scheme, which proposes the existence of three new levels not reported previously. A major discrepancy in these recent γ-ray studies involves the relative intensities of the two components of a γ-ray doublet, consisting of a 2554.5-keV transition from the 2555-keV level and a 2557.7-keV transition from the 2960-keV level. The intensity ratio of the 2554.5- to the 2557.7-keV transition was reported as 2.01 in SPBR, 1.0 in the work of Bocquet *et al.*[2] (BBCPSM), 0 by Onega and Carpenter[3] (OC), 1.88 by Lycklama, Archer, and Kennett[4] (LAK), and ∞ by Holm[5] (H). The doublet was unresolved in all five of these measurements; the intensity ratio was determined either by fitting the observed doublet to two components or by the intensity of the doublet in coincidence with the 402.7-keV transition. The ^{87}Kr β-spectrum measurement reported here is sufficiently sensitive to the relative β feeding to the two levels depopulated by the doublet to allow a choice to be made among the different reported intensity ratios of the two γ rays.

Four of the five γ-ray studies also reported measurements of the β spectrum of ^{87}Kr.[2-5] With the intensity of the ground-state β decay designated as β_0, BBCPSM reported $\beta_0 = 32\%$ with $Q = 3.95 \pm 0.05$ MeV, OC found $\beta_0 = 13.6\%$ with $Q = 3.85 \pm 0.04$

MeV, LAK reported $\beta_0 = 19.6\%$ with $Q = 3.90 \pm 0.01$ MeV, and H found $\beta_0 = 15\%$ with $Q = 3.90$ MeV. The direct measurement of the ^{87}Kr β spectrum with a uniform-field magnetic spectrometer by BBCPSM resulted in $\beta_0 = 26\%$. This measurement also gave a first excited state to ground-state intensity ratio, β_1/β_0, of 1.18, which, together with the relative β intensities determined from the γ-ray studies, yielded the reported value of $\beta_0 = 32\%$. The difference in the two results for β_0 may be indicative of spectral distortions in the spectrum measurement. The other three measurements of the ^{87}Kr β spectrum, by OC, LAK, and H, were done with scintillation spectrometers, where the accuracy of the results is limited by the inherent distortions in scintillation spectra. A β intensity ratio β_1/β_0 of 2.5 was obtained by OC and LAK and 3.7 by H; these ratios then yielded the reported ground-state β intensities mentioned above. The primary purpose of the work reported here is to resolve these large discrepancies in the ground-state β intensity. This should be possible since the distorting factors which affected the previous measurements should be absent.

II. EXPERIMENTAL PROCEDURE

A. Source Preparation

The sources of ^{87}Kr used in this study were provided by the TRISTAN on-line isotope-separator facility at the Ames Laboratory research reactor. The facility for providing mass-separated gaseous fission products has been described preliminarily elsewhere.[6,7] It is sufficient here to mention only that the collection of ^{87}Kr is completely free of isotopic contamination. In particular, the adjacent mass contamination caused by the hydride of the lower adjacent Kr isotope (which is typically less than 1 part in 10^4) has no effect on the ^{87}Kr measurement since ^{86}Kr is not radioactive. Before any measurements were made, a delay of several minutes was allowed to insure that activities of ^{86}Br and ^{87}Br, both of which have half-lives of less than one minute, had decayed away.

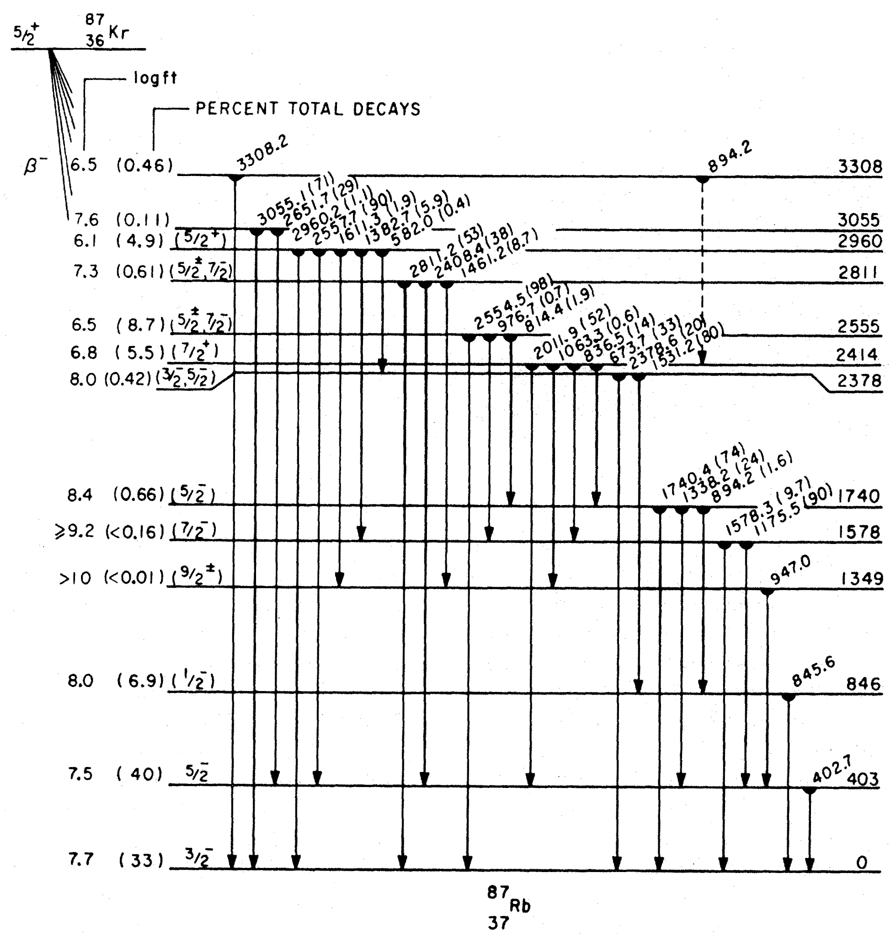

FIG. 1 Decay scheme of ^{87}Kr based on the γ-ray study of SPBR (Ref. 1).

The ^{87}Kr sources were made on-line by imbedding 60-keV ions in aluminized Mylar targets within the magnetic spectrometer. The target consisted of a 1.25-cm-wide strip of tape which had 0.0075 mm of aluminum bonded to 0.025 mm of Mylar. A groove was cut lengthwise down the center of the tape; the groove had a depth of about 0.010 mm and a width of about 0.5 mm. The two aluminum sides of this "split" tape were thus electrically insulated from each other and were used to stabilize the position of the ion beam on the target. The ion-beam stabilizer utilizes a differential amplifier which responds to the difference of the portions of the ion-beam current incident on each half of the split tape, thus indicating an off-center position of the ion beam. The ion beam is directed into the spectrometer by a switching magnet, and the stabilizer output is used to adjust the magnetic field of the switching magnet to maintain a centered position of the ion beam on the tape and thus ensure that the width of the β source is not increased due to any change of the ion beam position on the tape.

According to the results of Davies, Domeij, and Uhler,[8] 50% of the Kr ions at an energy of 60 keV are stopped in aluminum within 14 μg/cm^2, and less than 5% of the ions penetrate deeper than 40 μg/cm^2. Thus the source thickness of the ^{87}Kr sources was small enough to ensure that distortions in the β spectrum due to source thickness are quite negligible. The thickness of the tape, however, which is 2.1 mg/cm^2, is such that spectral distortions due to backscattering are not negligible. The backscattering effect is substantial only at small β-ray energies, and the results of the analysis of the ^{87}Kr spectrum indicate that this effect contributes less than 0.2% to the intensity of the ground-state β decay.

B. β-Ray Measurements

The ^{87}Kr β-ray spectrum was measured with the high-resolution $\pi\sqrt{2}$ magnetic spectrometer of the TRISTAN facility. The spectrometer is a 30-cm radius of curvature, $\pi\sqrt{2}$ iron spectrometer which is similar to the instrument built by Bartlett, Ristenin, and Bird.[9] For the ^{87}Kr measurements, the spectrometer was operated at a resolution of 0.5% and a transmission of 1%. The detector consists of a constant-gas-flow side-window proportional counter with end-correction electrodes. The proportional-counter window in use is 0.5-mg/cm^2 aluminized Mylar. The magnetic field of the spectrometer is determined by an iron-free water-cooled solenoid. The magnetic field of the solenoid is directly proportional to the current through the solenoid with a deviation from exact proportionality of less than 10^{-5} at the maximum current of 2 A. The magnetic field of the spectrometer is adjusted by a field-stabilization system such that the magnetic fields of the spectrometer and solenoid cancel at the center of the solenoid. A detailed description of the TRISTAN spectrometer is available.[10]

10 sources of ^{87}Kr were made for the β-spectrum measurements. Each source was obtained by collecting ^{87}Kr ions for approximately one half-life (78 m). Data were taken with each source for a period which ranged from two to three half-lives, depending on the source strength. The momentum range covered in each measurement varied from one fourth to one half of the maximum β momentum. At least two sources were used to record data for each momentum value; the momentum range near the maximum β momentum was covered by four sources. In order to correct for the different strengths of the sources, one source was used to obtain a "normalization" spectrum; it covered six momentum regions, or bands, that were equally spaced over the entire momentum region. The spectrum from each of the other nine sources contained at least one of the momentum bands which were then used to correct for source strength variations. A consolidated spectrum was computed by taking the weighted average of the 10 normalized spectra. The uncertainties in the data points of the consolidated spectrum were calculated in terms of the statistical uncertainties of the individual spectra, background, and normalization constants. The uncertainties in the consolidated spectrum were about 1.8% over the lowest third, about 1.2% over the middle third, and about 0.5% over the highest third of the spectrum.

III. RESULTS

The β spectrum of ^{87}Kr, consolidated from 10 sources, is shown in Fig. 2. The fit shown in Fig. 2 contains the seven most intense β groups in the ^{87}Kr decay. This fit was obtained by a weighted least-squares fitting procedure, with the inverse square of the uncertainties used as the weights. There were eight free parameters in this fit, the seven β-group intensities and the Q value. The end-point energy of each β group was taken to be the Q value minus the energy of the ^{87}Rb level fed by the group, and the energy levels were held fixed in the fit. The results of this fit are shown in Table I in the column labeled "no intensity constraints." The fit gave a Q value of 3.881 MeV and a variance of fit, V (defined as the square root of the least-squares sum divided by the degrees of freedom) of 0.927. The ground-state β intensity β_0 was 30.8% and the β-intensity ratio β_1/β_0 was 1.45.

In the "no intensity constraints" fit of Table I not all of the information available about the level structure of ^{87}Rb was used. In addition to constraining the β end-point energy differences to the appropriate ^{87}Rb energy-level differences, it is also possible to constrain the relative intensities of the β branches to the excited states of ^{87}Rb. Such intensity constraints utilize the β feedings to the excited states as determined from γ-ray studies of the decay of ^{87}Kr. Fits to our β spectrum were made using these intensity constraints in addition to the energy constraints. In such fits there are only three parameters, the Q value, β_0, and β_1; the β intensities to the other excited states are held fixed relative to β_1. The application of the maximum number of constraints in this fashion can greatly improve the accuracy of the determination of the Q value and the ground-state β intensity β_0, since the resulting fit is forced into agreement with the daughter-level-structure information and allows the "lever arm" of the fit to be increased without requiring additional parameters. In contrast, with the old "Fermi stripping technique" the lever arm for the ground-state fit is much shorter and the resulting value of β_0 is much less reliably determined.

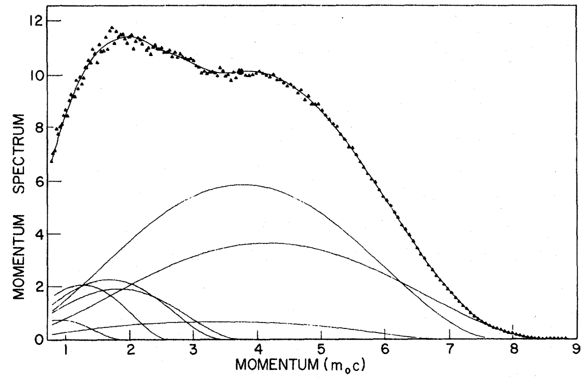

FIG. 2. β spectrum of ^{87}Kr consolidated from 10 sources; the fit curve shown represents the no-intensity-constraints fit of Table I.

When information from more than one γ-ray study is available, the maximum-constraint fitting technique can be applied using the constraints resulting from each study, and comparison of the resulting fits to the β spectrum can be used to resolve discrepancies in the studies. Table I also gives the results of maximum-constraint fits made using the decay schemes of each of the five recent γ-ray studies.[1-5] The β-group intensities to the levels reported in each study are shown in Table I;

TABLE I. Results of least-squares fits to ^{87}Kr β spectrum.

Daughter energy level (keV)	β group intensities						
	No intensity constraints	Intensity constraints from γ-ray studies					
		Ref. 1	Ref. 2	Ref. 3	Ref. 4	Ref. 5	Ave. 1 & 4
0	30.80 [a]	31.50	33.39	49.91	26.25	23.47	30.52
		(33) [b]	(32)	(13.6)	(19.6)	(15)	
403	44.71	42.02	39.38	24.74	46.61	50.36	42.90
		(40)	(38)	(34)	(49.7)	(55)	
846	5.14	7.11	8.07	7.71	7.73	7.45	7.22
1578	...	0.02	...	0.06	...	...	...
1740	...	0.67	0.99	2.02	0.56	0.46	0.60
2378	...	0.40	...	...	...	...	...
2414	6.72	5.25	4.64	4.98	5.10	5.37	5.07
2555	7.21	8.11	7.23	...	8.39	12.41	8.09
2811	...	0.53	...	...	0.25	...	0.42
2960	4.52	4.04	6.31	10.23	4.64	...	4.27
3055	...	0.09	...	...	...	...	...
3308	0.90	0.28	...	0.36	0.46	0.42	0.91
Q value (MeV)	3.881 [c]	3.882	3.872	3.781	3.915	3.930	3.888
Variance of fit	0.927	1.212	1.290	4.126	1.225	3.495	1.027

[a] Statistical uncertianties in the ground-state intensities are typically 0.2%.
[b] Values obtained by previous author(s) given in parentheses.
[c] Statistical uncertainties in the Q value are typically 0.5 keV.

for reference, the values of β_0 and β_1 reported in these studies are given in parentheses.

The quantity V, the variance of the fit, can be used to rate the "goodness" of the fit for each of the maximum-constraint fits. Two cases stand out from the others; the very large values of V obtained with the intensity constraints from OC and H are due to the treatment of the γ-ray doublet at 2556 keV. In OC, all of the "doublet" intensity is assigned to the 2960-keV level; the best fit to our data using this information was obtained by reducing the β intensity to the 2960-keV level from the 25% reported by OC to the 10.2% given in Table I, also causing the value of β_0 to increase from 13.6 to 49.9%. According to H, all of the "doublet" intensity is assigned to the 2555-keV level, and the best fit with the resulting intensity constraints was obtained by reducing the intensity to the excited states and consequently raising the value of β_0. In both of these cases the large values of V were due to poor fits to the data, caused by the incorrect assumptions regarding the relative β intensities to the two levels at 2555 and 2960 keV.

The fit obtained with the intensity constraints from BBCPSM was only slightly poorer than the fits obtained with the constraints from SPBR and LAK. In BBCPSM, the two components of the γ-ray doublet at 2556 keV were assumed to have equal intensities, whereas in SPBR and LAK, the 2555-keV component was assigned about twice the intensity of the 2557-keV component. Our data agree best with this latter assumption; it is not possible to distinguish between the γ-ray intensity ratio of 2.01 from SPBR and the ratio of 1.88 from LAK from the analyses of our β-spectrum measurement. The measurement does, however, clearly favor these two relative-intensity assignments over the assignments of the other studies.

The two maximum-constraint fits that agree best with our spectrum measurement were obtained with the over-all relative intensities of SPBR and LAK. Although these two fits have nearly identical variances and consequently are of nearly identical quality, the differences in β_0 and the Q value are not insignificant. These differences are due to the differences in the relative β intensities reported in these two studies. In order to "smooth" over these differences, an average was formed of the ratios of the intensities of the excited states relative to the first excited state. The last column of Table I gives the results of the maximum-constraint fit obtained with these average relative intensities. The resulting Q value of 3.888 MeV and β_0 of 30.5% can be regarded as the best determination of these quantities. With these values of β_0 and the Q value, the $\log ft$ values of the β groups are changed by less than 0.1 from the values given in Fig. 1, which were calculated by SPBR assuming a Q value of 3.89 MeV and a β_0 of 33%.

The average of the Q values obtained by the various fits in Table I is 3.888 MeV. This average was obtained from five of the seven fits, disregarding the two fits with the large variances. The rms deviation in the average is 0.007 MeV. The average of β_0, obtained in a similar manner, is 30.5%, with an rms deviation of 2.2%. These rms deviations are both much larger than the corresponding standard deviations determined by the least-squares fitting process or due to the uncertainty in the half-life of ^{87}Kr. Since the deviations in the Q value and β_0 due to the choice of relative-intensity constraints are much larger than the uncertainties associated with the fitting process or half-life corrections, the rms deviations give the most meaningful uncertainties in the Q value and β_0.

In the average relative-intensity fit of the last column of Table I, there were four free parameters. In addition to the three free parameters of the usual maximum-constraint fit, the intensity of the lowest-energy β group was allowed to vary since our measured spectrum showed a small but significant increase in the intensity at the lower end of the spectrum. If it is assumed that the increased intensity of this group is due to the backscattering effect of the target tape, and if it is further assumed that the intensity should be the 0.3% reported by SPBR rather than 0.9%, then the value of β_0 should be corrected by multiplying β_0 by 1.006. This correction, which is an overestimation, is insignificant since it changes β_0 by an amount which is less than one tenth of the uncertainty in β_0. As a further consideration of possible spectral distortions, it is particularly significant to note that the average value of β_0 is in very good agreement with the value of β_0 obtained in the fit with no intensity constraints. This good agreement can be compared with the lack of agreement in the work of BBCPSM, which was the only work to report values of β_0 obtained both with and without intensity constraints. As mentioned previously, the direct measurement of BBCPSM gave $\beta_0 = 26\%$, whereas the constrained value was $\beta_0 = 32\%$. In contrast, the good agreement obtained for both unconstrained and constrained analyses in the present work indicates that our measured spectrum is essentially free of the distorting effects which were apparently present in their measurement.

The ^{87}Rb level at 846 keV has been assigned a spin and parity of $\frac{1}{2}^-$.[1-5] This assignment is consistent with the shell-model prediction of a low-lying $p_{1/2}$ state in ^{87}Rb. It is also consistent with the $\log ft$ of the β group and the absence of a γ-ray transition to the first excited state at 403 keV. In an attempt to establish this spin-parity assignment more firmly, the ^{87}Kr β spectrum was fitted with two different shape factors for the β group feeding the 846-keV level. The group was fitted with a first-forbidden-unique shape factor, as is appropriate for the $\frac{1}{2}^-$ assignment, in all of the fits given in Table I. In particular, the fit with no intensity constraints had a least-squares sum of 155 with the unique shape factor. With a statistical shape factor for this group the least-squares sum was 194. This 25% increase in the least-squares sum is rather substantial for a β group with only 5% of the total intensity. However, the Fermi plot obtained after subtracting the higher-energy groups from the spectrum had enough statistical fluctuations to prevent a distinction between the unique and statistical spectrum shapes. Thus the identification of the 846-keV level as $\frac{1}{2}^-$ by direct observation of the first-forbidden-unique shape of the β group could not be made with our data. The $\frac{1}{2}^-$ assignment could not therefore be firmly established by our measurement; however, the better fit obtained with the unique shape does give some support to the assignment.

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PHYSICAL REVIEW C VOLUME 7, NUMBER 1 JANUARY 1973

Quasifree $(p, p\alpha)$ Scattering on ^{6}Li, ^{24}Mg, ^{28}Si, ^{40}Ca, ^{140}Ce, and ^{232}Th at 156 MeV

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Knockout of α particles by 156-MeV protons from ^{6}Li, ^{24}Mg, ^{28}Si, ^{40}Ca, ^{140}Ce, and ^{232}Th has been used to investigate the A dependence of α clustering in nuclei. Protons and α particles were detected in coincidence under conditions of quasifree scattering. Corresponding reaction cross sections were measured. Cross sections for ^{24}Mg and ^{40}Ca were found to be about 2 orders of magnitude lower than for ^{6}Li. The cross section for ^{28}Si was found to be about 3 times lower than that for ^{24}Mg and ^{40}Ca. Upper limits of the integrated cross sections for ^{140}Ce and ^{232}U are still compatible with a $A^{2/3}$ dependence of the α knockout process.

I. INTRODUCTION

The quasifree $(p, p\alpha)$ reaction provides a convenient approach for investigating the parentage of α clusters in target nuclei. Recent interest in this information is due to its relevance to the new α-particle models[1] and also to the question of existence of quartets in nuclear structure.[2]

The problem of four-nucleon structures in nuclei is also being approached by means of reactions such as $(d, {}^6\text{Li})$, $({}^3\text{He}, {}^7\text{Be})$, $({}^{12}\text{C}, {}^{16}\text{O})$, etc.[3] However, the relative complexity of the projectiles and the outgoing particles, and of the reaction mechanism, complicates the interpretation of such data. By comparison, the quasifree $(p, p\alpha)$ knockout can be considered a "clean" process, directly interpretable in terms of the parentage of α-particle structures in target nuclei within the framework of impulse approximation.[4]

Unfortunately, the $(p, p\alpha)$ cross sections are generally low and consequently the experiments are not easy to perform. No coincidence data were available, to our knowledge, on the quasifree $(p, p\alpha)$ knockout process for targets having