Decay of Rb^{89}

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Sources of Rb^{89} were prepared from the decay of fission product Kr^{89} and studied by scintillation methods. The half-life was found to be 14.9±0.3 minutes.

Gamma rays of energy 0.663±0.006, 1.05±0.02, 1.26±0.01, 1.55±0.03, 2.20±0.02, 2.59±0.03, 2.75 ±0.05, and 3.52±0.07 Mev and relative intensity 0.217±0.026, 1.00, 0.717±0.090, 0.048±0.010, 0.190 ±0.025, 0.169±0.031, 0.037±0.007, and 0.029±0.005 were measured. Gamma-gamma coincidence spectroscopy and summing of gamma rays in a $4\frac{3}{4}$-inch diameter NaI(Tl) crystal, used in anticoincidence with a surrounding solution phosphor tank, establish a decay scheme with levels in Sr^{89} at 1.05, 2.31, 2.59, 2.75, 3.25, and 3.52 Mev.

The ground-state beta-ray transition was measured as 3.92±0.05 Mev, and is present in about 7% of the beta-ray transitions.

INTRODUCTION

EARLY studies by Seelman-Eggebert of the radioactive fission products with inert gas precursors disclosed a beta-ray activity in rubidium with a half-life of 15.5 minutes.[1] That this activity was not 18-minute Rb^{88} was established by its growth from a krypton isotope of half-life[1] about 3 minutes while the parent of Rb^{88} was known to be 2.8-hour Kr^{88}. Further investigation by Hahn and Strassman[2] and by Glasoe and Steigman[3] demonstrated that the 15-minute rubidium isotope was the parent of a long-lived strontium isotope having a half-life of about 54 days. Glasoe and Steigman[3] assigned the rubidium activity to mass 89, reported the Rb^{89} half-life as 15.4±0.2 minutes, and measured the beta-ray energy as 3.8 Mev by aluminum absorption techniques. Recalculating the beta-ray absorption results of Glasoe and Steigman, and Bleuler and Zunti[4] proposed an energy of 4.5 Mev for the beta-ray energy of Rb^{89}. The beta-ray energy of 3.92 Mev reported below is in good agreement with the early value of 3.8 Mev from aluminum absorption measurements.

Because of the lack of detailed information regarding the decay of Rb^{89}, the present study was undertaken, using scintillation methods for the study of both beta- and gamma-ray spectra.

EXPERIMENTAL METHODS AND RESULTS

Irradiations and Source Purification

The favorable distribution of krypton and rubidium half-lives among the fission products makes it possible to prepare rather pure sources of Rb^{89} by judiciously "milking" the 3-minute Kr^{89} parent. Experimentally the decay products of xenon as well as krypton must be considered, since both are found in high yield in uranium fission. To prepare Rb^{89} sources uncontaminated by cesium activities, it is necessary, therefore, to separate the inert fission product gases before the rubidium milking, to chemically separate the rubidium activity from any other alkali metal activity, or to separate the krypton and xenon fission fragments during the neutron irradiation of uranium. For the work reported here, the last two of these techniques were employed as described below.

Irradiations to collect krypton fission gas by separating fission fragments were performed in the pneumatic transfer tube "rabbit" sketched in Fig. 1. The fission source consisted of enriched uranium, about 0.3 mg/cm² thick and 1.6 cm in diameter, over which

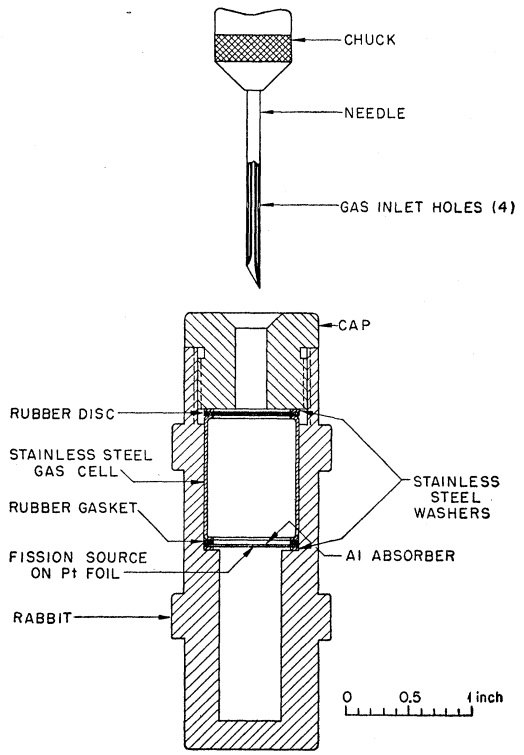

FIG. 1. Apparatus for separation of fission fragments during irradiation and rapid removal of krypton gas.

[1] W. Seelman-Eggebert, Naturwiss. **28**, 451 (1940).
[2] O. Hahn and F. Strassman, Naturwiss. **28**, 455 (1940).
[3] G. N. Glasoe and J. Steigman, Phys. Rev. **58**, 1 (1940).
[4] E. Bleuler and W. Zunti, Helv. Phys. Acta, **19**, 375 (1946).

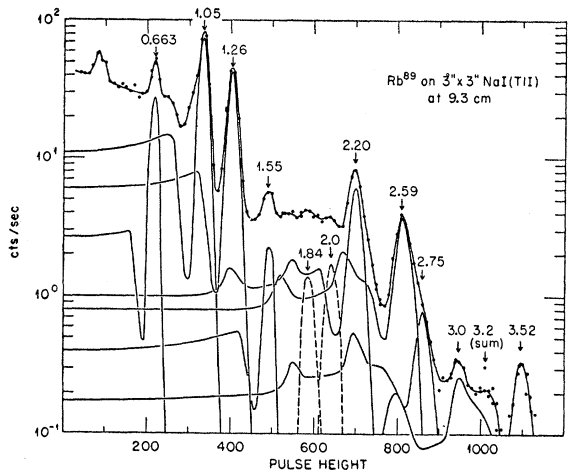

FIG. 2. Gamma-ray spectrum from a source of Rb^{89}, 9.3 cm above a NaI(Tl) crystal 3 inches in diameter and 3 inches high.

a 3.12-mg/cm² aluminum foil was placed to absorb the heavy xenon fission fragments. When the apparatus was assembled in the micarta rabbit, the stainless steel gas cell was sealed at the top by the rubber disk, and at the bottom by the rubber gasket and aluminum absorber foil.

In experiments where larger amounts of Rb^{89} activity were desired, the gas cell in the rabbit was longer and closed at the bottom. Enriched uranium was deposited on a large platinum foil to which the aluminum absorber was cemented; the foil "sandwich" was then rolled into a cylinder and inserted in the gas cell, where it formed a liner.

Samples were irradiated for 3 minutes, the approximate half-life of Kr^{89}. After irradiation, the sample was ejected from the reactor core and dropped into a shielded holder for another 3 minutes, permitting the higher-mass krypton isotopes of shorter half-life to decay out. At this time a needle (see Fig. 1), made of two concentric stainless steel tubes sealed at the tip, was forced downward until the rubber disk covering the gas cell was punctured and the needle chuck engaged the cap of the rabbit. Simultaneously, air was drawn down the inner tube of the needle and, after sweeping the gas cell, passed into the jacket of the needle through the gas inlet holes. Air and radioactive gas traveled up the needle jacket, through a trap of glass wool refrigerated with dry ice-acetone mixture, and finally into an evacuated collection cell. For another 3-minute period the krypton gas was allowed to decay, the Rb recoil atoms being collected on a negatively charged strip of thin aluminum foil.

Although the beta-decay curves of Rb^{89} samples prepared in this way indicated a high degree of purity, the gamma-ray spectra always showed several percent of the 1.44-Mev gamma ray of 30-minute Cs^{138}, due to straggling of the xenon recoils through the aluminum absorber.

The fission recoil absorber technique reduced the yield of Rb^{89} considerably, since the absorber foil was made relatively thick to reduce the Xe recoil straggling contribution. Both the yield and purity of the Rb^{89} samples were improved by substituting a chemical separation of the alkali metal daughters of the inert gas fission products for the physical separation of the recoils. In these experiments large, enriched uranium foils were irradiated as described above, except that there was no aluminum absorber foil. After milking the alkali metal daughters as described, the aluminum collecting foil was boiled in a few ml of distilled water to remove the activity. The active solution was poured onto an ion exchange column of Amberlite IR-100 resin, 100–170 mesh, 0.4 cm in diameter and 26 cm long. When the water had flowed through the column, the rubidium and cesium were eluted with 1*N* HCl. By this technique a good rubidium-cesium separation was accomplished. While the recoil absorber technique was employed as an exploratory method, the conclusions to be discussed later were all checked using the chemically separated samples.

Source Purity and Half-Life

A few mg of Rb carrier were added to the eluent from the ion exchange purification of Rb^{89}, and precipitated as the phosphotungstate. This sample was mounted and its decay followed on a 2π beta proportional counter. The decay curve thus obtained was exponential over about 8 half-lives, after which the contribution from the growth of 54-day Sr^{89} became appreciable. A least squares analysis of the decay data was made, using the counts taken early enough so that the contribution of Sr^{89} was unimportant. The half-life thus obtained was 14.9 ± 0.3 minutes.

In the gamma-ray spectroscopy measurements to be described, several gamma-ray spectra were run on each chemically purified sample over periods of from 3 to as long as 9 half-lives, during which time all gamma-ray peaks were found to decay with the same half-life.

It is concluded that the source purity was adequate for the measurements described below, and that the radiations measured below, indeed, are due to the decay of Rb^{89}.

Gamma-Ray Spectroscopy

The scintillation spectrometers used in this investigation consisted of cylindrical NaI(Tl) crystals, 3 inches in diameter and 3 inches long, attached to Dumont 6363 photomultiplier tubes in the manner described by Lazar and Klema.[5] For the single-crystal measurements reported below, the sources were centered 9.3 cm above the top surface of the crystal. About 2 g/cm² of polystyrene was placed between the source and crystal to remove the beta rays. The lead spec-

[5] N. H. Lazar and E. D. Klema, Phys. Rev. **98**, 710 (1955).

trometer shield had 4-inch thick walls, and inside dimensions of 14×14×22 inches. All inside lead surfaces were covered first with 0.015 inch of cadmium and then 0.005 inch of copper. Experience in this Laboratory has shown that such a shield achieves the low scattering required for the analysis of complex gamma-ray spectra. A twenty-channel analyzer designed by Bell, Kelley, and Goss[6] was employed for pulse-height analysis.

The single-crystal pulse-height spectrum of Rb^{89} was analyzed as shown in Fig. 2. Analysis of gamma-ray spectra in the manner demonstrated is possible since the shape of the pulse height distributions obtained from various energy gamma rays impinging on large NaI(Tl) crystals of the dimensions used in the present work, under similar scattering conditions, is known from past experience at this Laboratory. The full-energy peak of a gamma ray at 3.52 Mev is seen, together with its middle pair peak at 3.0 Mev. In Fig. 2 the expected Compton distribution and pair peaks for the 3.52-Mev gamma ray have been drawn in, using careful measurements of the spectrum from the 2.76-Mev gamma ray of Na^{24} and the 4.44-Mev gamma ray from the $N^{15}(p,\alpha\gamma)C^{12}$ reaction for comparison. A counting rate in excess of the expected Compton distribution from the 3.52-Mev gamma ray is seen in the region of 3.2 Mev. A calculation of the summing of the 1.05- and 2.20-Mev gamma rays[7] showed that the excess counting rate at 3.2 Mev is of the expected intensity for the summing process. In the many gamma-ray spectra of Rb^{89} which were measured, the full-energy peak for the 2.59-Mev gamma ray always showed an asymmetry on its high-energy side, which was attributed to a low-intensity gamma ray at 2.75 Mev. The intensity of the 2.75-Mev gamma ray was determined by using the shape of the full-energy peak of the 2.62-Mev gamma ray from ThC″ for comparison with the 2.59-Mev peak.

The valley between the 1.55- and 2.20-Mev gamma rays cannot be accounted for by the several pair peaks and Compton distribution from the 2.20-Mev and higher energy gamma rays and so two gamma rays of energy 1.84 and 2.0 Mev are postulated to account for the experimentally observed spectrum. For clarity only the full-energy peaks from these gamma rays are dotted in the figure, although their Compton and pair spectra were included in the analysis. These latter transitions are in less than 5% of the intensity of the 1.05-Mev gamma ray. The intensity of the 1.84-Mev peak is reasonable if it is assumed to be the 1.85-Mev gamma ray from Rb^{88}, but it was impossible to study the origin of the 2.0-Mev gamma ray with any precision because of its low intensity and position in a complex gamma-ray spectrum.

Analysis of the 1.26-, 1.05-, and 0.66-Mev gamma rays used the spectral shapes from sources of Y^{88} (0.908 and 1.85 Mev), Zn^{65} (1.11 Mev), and Cs^{137} (0.662 Mev) for comparison. The remaining, broad peak at about 80 pulse height is attributed to gamma-ray scattering from the source environment, and no special attempts have been made to establish the presence of nuclear gamma rays in this region.

TABLE I. Energies and intensities of the Rb^{89} gamma rays.

Gamma-ray energy, Mev	Intensity relative to 1.05-Mev gamma-ray	Intrinsic peak efficiency used (h =9.3 cm)
0.663±0.006	0.217±0.026	0.327
1.05 ±0.02	1.00	0.216
1.26 ±0.01	0.717±0.090	0.183
1.55 ±0.03	0.048±0.010	0.153
2.20 ±0.02	0.190±0.025	0.113
2.59 ±0.03	0.169±0.031	0.098
2.75 ±0.05	0.037±0.007	0.092
3.52 ±0.07	0.029±0.005	0.056

For calibration of the energy scale of a scintillation spectrometer using type 6363 photomultiplier tubes, it is advisable to measure both energy standards and unknown gamma-ray source together to avoid gain shifts with counting rate.[8] Four gamma-ray lines in the Rb^{89} spectrum were measured in this way and, using these lines as internal standards, the other Rb^{89} gamma-ray energies were obtained. From these measurements, the lowest energy gamma ray was measured as 0.663 ±0.006 Mev, using Sr^{85} (0.513 Mev) and Y^{88} (0.908 Mev) standards. The gamma rays at 1.05±0.02 and 1.26±0.01 Mev were measured against Y^{88} (0.908 and 1.85 Mev), and the 2.20±0.02 Mev gamma ray was referred to Y^{88} (1.85 Mev) and ThC″ (2.62 Mev) sources.

Relative gamma-ray intensities were calculated from the full-energy peak areas corrected for loss of intensity due to summing, and from values of intrinsic peak efficiencies determined according to the method described by Lazar and Klema.[5] Table I lists the measured gamma-ray energies, their relative intensities, and the intrinsic efficiencies used.

A NaI(Tl) spectrometer,[9] designed to reduce the contribution to the spectrum from gamma rays which have undergone Compton scattering in the crystal, was used to investigate the radiations from Rb^{89}. The spectrometer consists of a $4\frac{3}{4}$-inch NaI(Tl) crystal and photomultiplier tube, surrounded by a large liquid scintillator tank with five 5-inch photomultiplier tubes viewing its scintillations. Only those pulses from the NaI(Tl) spectrometer are recorded which are not in coincidence with pulses from the liquid scintillator. Thus, Compton pulses in the crystal whose associated scattered radiation has a high probability of being detected in the tank simultaneously, would not appear

[6] Bell, Kelley, and Goss, Oak Ridge National Laboratory Report ORNL-1278, 1951 (unpublished).
[7] Lazar, Eichler, and O'Kelley, Phys. Rev. **101**, 723 (1956).
[8] Bell, Davis, and Bernstein, Rev. Sci. Instr. **26**, 726 (1955).
[9] P. R. Bell, Science **120**, 625 (1954); Bell, Kelley, Lazar, Harris, Davis, Neiler, Hall, and Sampley, Oak Ridge National Laboratory Report ORNL-1798, 1954 (unpublished), p. 23.

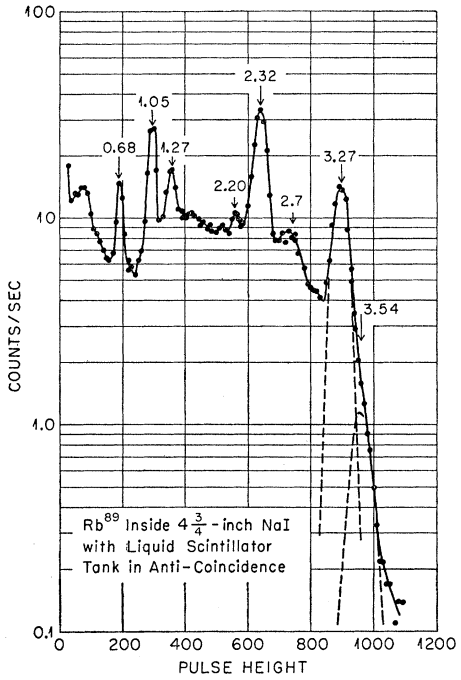

FIG. 3. Gamma-ray spectrum from a Rb^{89} source inside a $4\frac{3}{4}$-inch NaI(Tl) crystal, with a surrounding liquid scintillator tank in anticoincidence.

in the spectrum. Coincident radiation from a source placed at the center of the crystal, if completely absorbed in the NaI(Tl), would appear as a peak at the sum of the gamma-ray pulse heights, and no other pulses should be seen. In practice, since the scintillator tank has less than 100 percent efficiency for such high-energy gamma-rays, some of those pulses which are incompletely absorbed in the NaI(Tl) crystal also escape the tank, and a low Compton background is still found.

A source of Rb^{89} activity was surrounded by brass thick enough to absorb the beta-rays, and was placed inside the $4\frac{3}{4}$ inches diameter NaI(Tl) crystal. Figure 3 shows the spectrum obtained. Sum lines at 2.32 ± 0.04 Mev (1.05+1.26 Mev) and 3.27 ± 0.05 Mev (1.05+2.20 Mev and 2.59+0.66 Mev) are clearly indicated. The energy values from the large crystal data should not be taken as the most accurate ones, since the $4\frac{3}{4}$-inch crystal lacks the resolution of the crystals used in the experiments described previously. In addition to the unsummed remainder of the gamma-ray peaks at 0.66, 1.05, 1.26, and 2.20 Mev, two small peaks at 2.7 and 3.54 Mev are seen; these are best interpreted as the 2.75- and 3.52-Mev gamma-ray peaks, which apparently do not sum with any other intense gamma rays. The 2.75-Mev peak is more prominent inside the large crystal since the 2.59-Mev peak has been greatly reduced by summing with the 0.66-Mev transition. (See decay scheme below.)

Gamma-gamma coincidence measurements were made using a "fast-slow" coincidence circuit, so that energy selection could be used in both channels. The resolving time of the circuit was $2\tau=0.40$ μsec. The multichannel analyzer displayed the pulse-height distribution from a 3-inch×3-inch NaI(Tl) crystal in coincidence with selectively chosen gamma-rays from another 3-inch ×3-inch NaI(Tl) crystal. Only the 1.05-Mev transition appeared in coincidence with the 1.26-Mev gamma ray and, with the gate set on 2.59 Mev, only the 0.663-Mev peak was seen in coincidence. These results establish the levels at 2.31 and 3.25 Mev, in agreement with the summing data from the $4\frac{3}{4}$-inch NaI(Tl) crystal.

Beta-Ray Spectroscopy

Beta-ray spectra were measured on a well-type, anthracene scintillation spectrometer[10] used in conjunction with the 20-channel analyzer. Small amounts of rubidium phosphotungstate precipitated from the ion exchange eluent were slurried onto laminated Formvar-polystyrene films about 25 $\mu g/cm^2$ thick, and dried. The total source thickness was less than about 1 mg/cm^2. Energy calibration was accomplished using the 0.625-Mev Ba^{137m} and 0.976-Mev Bi^{207} conversion lines.

Fermi analysis of a typical beta-ray spectrum is shown in Fig. 4. The figure shows the data resolved into components of energy 3.92 ± 0.05 and 2.81 ± 0.15 Mev. From the Fermi analysis, the following intensity ratios were obtained: $I(2.8)/I(3.9)=0.57$, and $I(3.9)/I(\text{total }\beta)=0.11$.

An independent measurement of the beta-ray branching of Rb^{89} to the ground state of Sr^{89} was undertaken. In this experiment a small sample of Rb^{89} was mounted on a Formvar-polystyrene film about 25 $\mu g/cm^2$ thick and counted in a 4π counter[11] to measure the beta disintegration rate. The sample was then rapidly trans-

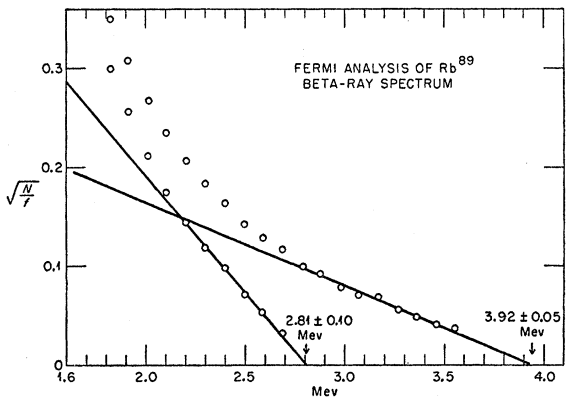

FIG. 4. Fermi analysis of the Rb^{89} beta-ray spectrum.

[10] P. R. Bell in *Beta- and Gamma-Ray Spectroscopy*, edited by K. Siegbahn (Interscience Publishers, Inc., New York, 1955), Chap. V.

[11] The authors are indebted to A. R. Brosi for the use of his 4π counting equipment.

ported to the scintillation spectrometer, where it was positioned 9.3 cm above the 3-inch×3-inch NaI(Tl) crystal, with 2 g/cm² of polystyrene absorber between source and crystal. The area of the 1.05-Mev peak, corrected for Compton and pair distributions from the higher energy gamma rays and for summing with the 1.26- and 2.20-Mev gamma rays, was divided by the product of geometry and peak efficiency to obtain the absolute number of 1.05-Mev gamma rays in the sample. From these data, the relative gamma-ray intensities, and the decay scheme proposed below, it is estimated that 7±5% of the beta decays are ground-state transitions, in agreement with the beta-ray spectroscopy results.

DISCUSSION

The decay scheme shown in Fig. 5 summarizes the available information on the decay of Rb^{89}, and Table II includes numerical values for the intensities and comparative half-lives of the beta-ray transitions. Beta-ray intensities were calculated from relative gamma-ray intensities and the decay scheme, assuming that seven percent of the beta-ray transitions decay to the ground state; however, the logarithm of the comparative half-life is not sensitive to rather large errors in the ground state beta-ray intensity. It should be mentioned that the beta-ray intensities are in some error due to the lack of information on additional cascading gamma rays which must be present and unknown, but probably small, internal conversion of the high-energy gamma rays. The cascading gamma rays would be of such an energy that they could not be resolved from the strong lines of the Rb^{89} spectrum. Detection of these gamma rays would be helpful in assigning spins and parities to the levels of Sr^{89}, and in further establishing the decay scheme.

Data on the $Sr^{88}(d,p)Sr^{89}$ reaction may be compared with the level scheme proposed here. McFarland and Shull[12] found excited states in Sr^{89} at 1.07±0.10, 2.07 ±0.10, and 2.54±0.20 Mev, while Holt and Marsham[13] measured these levels at 1.07±0.08, 2.09±0.08, 2.66 ±0.08 Mev, and others above the 3.9-Mev excitation available from Rb^{89} decay. Two of the levels correspond within experimental error to the 1.05- and 2.59-Mev levels reported here; the 2.1-Mev level in the nuclear reaction work does not appear to be present in the Rb^{89} beta decay. It is tempting to attribute the weak gamma ray seen on the 3-inch×3-inch NaI(Tl) spectrometer at 2.0 Mev to the deexcitation of this level, but the origin of this gamma ray is not sufficiently established to warrant such an assignment.

TABLE II. Intensities and comparative half-lives of Rb^{89} beta-ray transitions. (Subscripts denote final states.)

Beta-ray group	Intensity	Logarithm of comparative half-life
β_0	0.07[a]	7.8
	0.11[b]	
$\beta_{1.05}$	0.05[a]	7.4
	0.06[b]	
$\beta_{2.31}$	0.53[a]	5.2
$\beta_{2.59}$	0.02[a]	6.4
$\beta_{2.75}$	0.03[a]	6.0
$\beta_{3.25}$	0.28[a]	4.0
$\beta_{3.52}$	0.02[a]	4.5

[a] From β/γ ratio and relative gamma-ray intensities.
[b] From Fermi analysis of beta-ray spectrum.

[12] C. E. McFarland and F. B. Shull, Phys. Rev. **89**, 489 (1953).
[13] J. R. Holt and T. N. Marsham, Proc. Phys. Soc. (London) **A66**, 565 (1953).

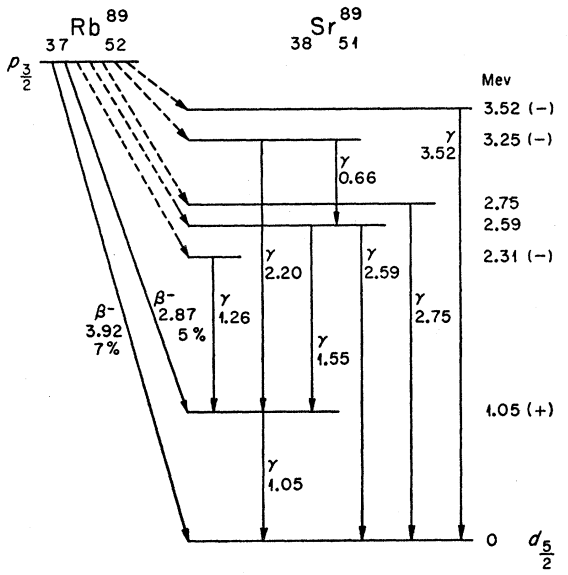

FIG. 5. Decay scheme proposed for Rb^{89}.

As expected from the shell model, the ground state of Sr^{89} can be assigned a $d_{5/2}$ configuration on the basis of the unique shape of its beta-ray spectrum.[14] The logft for the 3.92-Mev beta-ray group in Rb^{89} indicates a first forbidden transition, which supports the shell model assignment of $p_{3/2}$ to the Rb^{89} ground state.

The remaining levels do not lend themselves to interpretation by the single-particle model. Positive parity is assigned to the fist excited state on the basis of the $p_{3/2}$ configuration of Rb^{89}, and the logft for the beta-ray transition. The excited states at 2.31, 3.25, and 3.52 Mev all are assigned negative parity from the low logft values for the associated beta-ray groups. The remaining levels at 2.59 and 2.75 Mev cannot be assigned parities from comparative half-life data alone, since a logft of about 6 might indicate an allowed, first forbidden, or l-forbidden transition, and further data are needed to establish even the parities of these levels.

ACKNOWLEDGMENTS

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[14] L. M. Langer and H. C. Price, Jr., Phys. Rev. **76**, 641 (1949).