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Nuclear Levels in Sr^{88} from the Disintegration of Rb^{88} and Y^{88}

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The nuclear level structure of Sr^{88} has been studied through the gamma radiation following the decays of 17.8-minute Rb^{88} and 104-day Y^{88}. Gamma rays from Rb^{88} with energies of 0.909 ± 0.004, 1.39, 1.850 ± 0.008, 2.11, 2.68, 3.01, 3.24, 3.52, 3.68, and 4.87 Mev have been resolved and fitted into a level scheme with the assistance of coincidence spectroscopy using cylindrical 3-inch×3-inch NaI(Tl) crystals. The intensity of the ground state beta ray transition from Rb^{88} was determined by comparing the total beta ray activity to the intensity of the 1.85-Mev gamma ray. It was found that 75.9 ± 5.0 percent of the decays are directly to the ground state. From the gamma-ray intensities, the comparative half-lives of all the beta groups could be determined and, thus, parity assignments were made to all the levels. The relative intensities of gamma rays leaving the same level is discussed in relation to single-particle transition probabilities.

INTRODUCTION

THE nucleus, Sr^{88}, is of particular interest since it contains fifty neutrons, a closed shell. Thus, its lower excited states would be expected to be due to the excitation of one of its protons and their character might be related to the nature of single-particle states of neighboring nuclei. Sr^{88} is the daughter of both Rb^{88} and Y^{88} and both decays have been studied in some detail in the past.

Rb^{88} has been shown to decay with a half-life of 17.8 ± 0.1 minutes.[1] Its beta ray spectrum has been studied in at least two magnetic spectrometers[2,3] and has been analyzed into at least three beta groups. The most energetic beta-ray component exhibits the well known "*a*" shape which indicates a spin change of two units and a parity change between the two states involved in the transition. Bunker *et al.*[2] reported energies of 5.13 ± 0.03, 3.39 ± 0.10, and 2.04 ± 0.015 Mev for the end points obtained from the beta-ray spectrum analysis with intensities of 66, 19, and 15 percent, respectively. Thulin,[3] using a thinner source prepared with an electromagnetic isotope separator, reported the end points as 5.30 ± 0.05, 3.6, and 2.5 Mev with intensities of 77, 13, and 9 percent and the possible existence of a fourth beta-ray component with an end point 0.7 Mev in low intensity.

Y^{88} decays to Sr^{88} with a half-life of 104 days[4] by means of electron capture and possibly positron emission of low intensity.[5]

The conversion electrons from two transitions with energies of 1.85 and 0.908 Mev have been seen in both the Rb^{88} and Y^{88} decays[5,6] and the conversion coefficients have been measured using an Y^{88} sample. The 0.908-Mev transition was characterized as mostly $E1$ and the 1.85-Mev gamma ray either $E2$ or $M1$.[6] In addition, the two gamma rays were shown to be in cascade and angular correlation experiments were carried out to determine the multipolarity of the radiation. The best fit of the data, assuming the levels in Sr^{88} are at 2.76 and 1.85 Mev, is consistent with the cascade following the scheme $3-(E1+M2)2+(E2)0+$.[7] Recently, a directional polarization correlation experiment has been performed[8] which uniquely fixes the spins of the first two excited states in Sr^{88} as $2+$ and $3-$.

The cross-over gamma ray of 2.76 Mev has been reported in the Y^{88} decay with an intensity of the order of 1 percent of the cascade,[9] using a (γ,n) reaction on deuterium. A recent measurement by Alburger and Sunyar[10] sets a limit on the intensity of the 2.76-Mev transition as less than 0.5% of the 1.85-Mev transition. Thulin,[11] using a $1\frac{1}{2}$-in.×1-in. NaI crystal, studied the gamma rays following the decay of Rb^{88} and evidence was shown for three gamma rays at 2.12, 2.76, and 4.2 Mev in addition to the two prominent gamma rays at 0.908 and 1.85 Mev.

In the present experiments, 3-in.×3-in. cylindrical NaI crystals were utilized to study the gamma radiation from Rb^{88} and Y^{88}. Both coincidence experiments and single-crystal spectroscopy were performed and a rather complex decay scheme was evolved.

EXPERIMENTAL PROCEDURES

The Rb^{88} activity was prepared from Rb_2SO_4 containing only 0.2 percent cesium and less than 0.01 percent sodium by flame photometer analysis. The samples were bombarded in the ORNL graphite reactor for 18 minutes and then rapidly transported to the counting room, where they usually were in position to be counted in less than five minutes. Y^{88} activity was produced in the ORNL 86-inch cyclotron by proton bombardment of strontium and purified by the Operations Division of this laboratory. The single-crystal

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[1] G. N. Glasoe and J. Steigman, Phys. Rev. **58**, 1 (1940).

[2] Bunker, Langer, and Moffat, Phys. Rev. **81**, 30 (1951).

[3] S. Thulin, Arkiv Fysik **4**, 363 (1952).

[4] R. T. Overman, U. S. Atomic Energy Commission declassified document MDDC-354, 1946 (unpublished).

[5] W. C. Peacock and T. W. Jones, U. S. Atomic Energy Commission Report AECD 1812, 1948 (unpublished).

[6] F. R. Metzger and H. C. Amacher, Phys. Rev. **88**, 147 (1952).

[7] R. M. Steffen, Phys. Rev. **90**, 321 (1953).

[8] G. R. Bishop and J. P. Perez Y Jorda, Phys. Rev. **98**, 89 (1955).

[9] G. R. Gammertsfelder, Phys. Rev. **66**, 288 (1944).

[10] D. E. Alburger and A. W. Sunyar, Phys. Rev. **99**, 695 (1955).

[11] S. Thulin, Arkiv Fysik **9**, 107–196 (1955).

scintillation spectrometer consisted of a cylindrical NaI(Tl) crystal 3 inches high by 3 inches in diameter whose upper edge was bevelled at an angle of 45° to the axis of the cylinder such that the top surface was a circle of two-inch diameter. Such bevelling is desirable in large crystals since one obtains higher peak detection efficiencies than with unbevelled crystals. This effect is achieved becaused the edges are relatively less efficient in the *complete* absorption of a gamma ray than the remainder of the crystal. For the measurements reported below, the sources were placed on the axis of the cylinder at a height of 9.3 cm from the top surface of the crystal. Polystyrene absorbers of 2200 mg/cm^2 were placed between source and crystal to remove the energetic beta rays. Pulse-height analysis was performed using a twenty-channel analyzer designed by Bell, Kelley, and Goss.[12] The energy scale was calibrated with the 0.908- and 1.853-Mev gamma rays in the sample. The energies of these gamma rays were checked with the 2.62-Mev gamma ray in Pb^{208} and with Zn^{65} and Cs^{137} gamma rays. The values obtained when the calibration sources and an Y^{88} sample were counted simultaneously to eliminate pulse-height changes due to a variation in counting rate were 0.909±0.004 and 1.850±0.008 Mev.

The "fast-slow" technique was used in the coincidence circuit so that energy selection could be obtained in both channels. The resolving time of the circuit[13] was $2\tau = 0.40$ μsec. The multichannel analyzer was used to analyze the pulses from the bevelled 3 inch×3 inch NaI(Tl) crystal which were in coincidence with selectively chosen gamma rays detected by an unbevelled 3-inch×3-inch NaI(Tl) crystal.

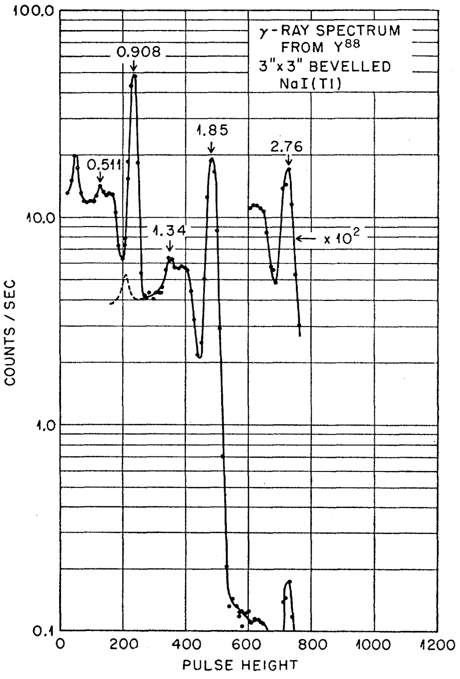

FIG. 1. Gamma-ray spectrum from Y^{88} on 3-in.×3-in. bevelled NaI(Tl) crystal.

EXPERIMENTAL RESULTS

The gamma-ray spectrum obtained from an Y^{88} source placed at 9.3 cm from the top face of the bevelled crystal is shown in Fig. 1. Similar curves were obtained using unbevelled crystals. The intensity of the coincident sum peak at 2.76 Mev, $P_{\text{c.s.}}$, may be calculated from the equation

$$P_{\text{c.s.}} = \frac{P(1.85)}{1-\epsilon_T(0.908)\Omega f}\epsilon_p(0.908)\Omega f + N_r, \qquad (1)$$

where $\epsilon_p(E_\gamma)$ and $\epsilon_T(E_\gamma)$ are the peak and total efficiencies of the crystal for a gamma ray of energy E_γ, f is the fraction of 1.85-Mev gamma rays in coincidence with the 0.908-Mev gamma rays, Ω is the solid angle, and N_r represents the random summing of two pulses of the proper pulse height. The latter term may be determined from the resolving time of the amplifier.[13] Data were taken with two crystals, one bevelled and the other not, at source distances of 3.0, 9.3, and 18.5 cm. The area of the peak at 2.76 Mev was compared with the area calculated from Eq. 1. In every case, there remained a difference which could only be explained by the the presence of a gamma ray at this energy. The

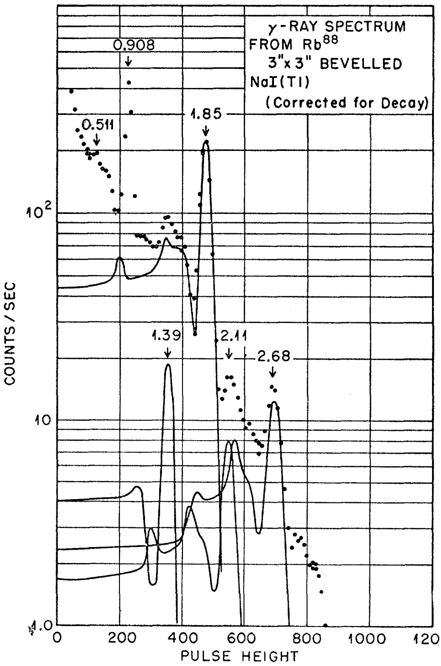

FIG. 2. Gamma-ray spectrum from Rb^{88} on 3-in.×3-in. bevelled NaI(Tl) crystal to ~2.7 Mev.

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[12] Bell, Kelley, and Goss, Oak Ridge National Laboratory Report ORNL-1278 (1951).

[13] N. H. Lazar and E. D. Klema, Phys. Rev. **98**, 70 (1955).

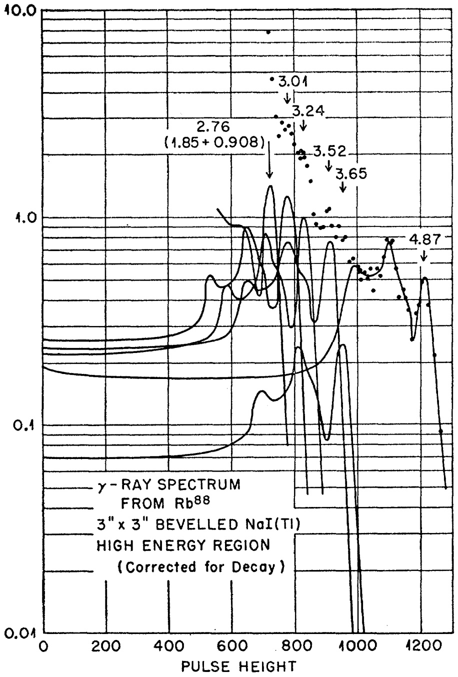

FIG. 3. Gamma-ray spectrum from Rb^{88} on 3-in.×3-in. bevelled NaI(Tl) crystal above 2.7 Mev.

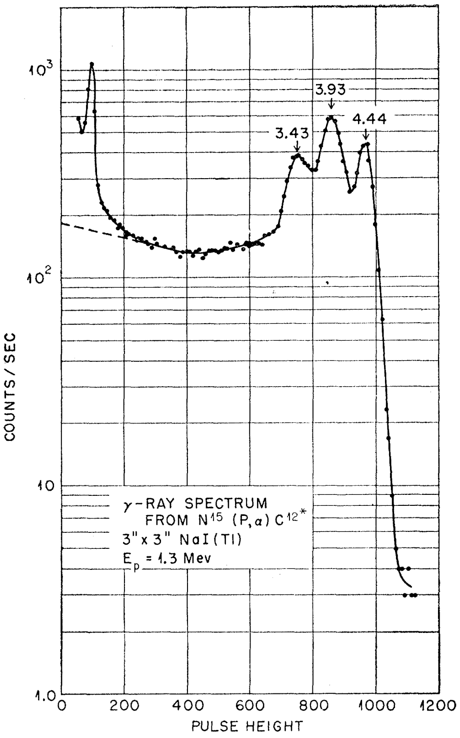

FIG. 4. Gamma-ray spectrum from the reaction N$^{15}(p,\alpha)$C^{12*} on 3-in.×3-in. NaI(Tl) crystal.

intensity of the gamma ray, relative to that of the 1.85-Mev transition, was measured as $(5\pm3)\times10^{-3}$.

The relative intensities of the 0.908- and 1.85-Mev gamma rays were also determined. Taking into account the coincident summing, the ratio $I(1.85)/I(0.908)$ was determined as 1.09±0.05, where the error quoted is primarily an estimate of the uncertainty in the ratio of the detection efficiencies for the two energies. All measurements at the various distances agreed with the indicated value within this error.

The gamma-ray spectrum from Rb^{88} obtained with the bevelled crystal spectrometer is shown in Figs. 2 and 3. The analysis was carried out using, as a guide, the spectral shapes obtained in the same crystal from Y^{88} and Na^{24} sources. The relative heights of the full energy and pair peaks in the region above 2.7 Mev were estimated with the assistance of the spectrum of the 4.44-Mev gamma ray shown in Fig. 4. The source of these gamma rays was the N$^{15}(p,\alpha\gamma)$C^{12} reaction using 1.3-Mev protons from the ORNL 5.5-Mev Van de Graaff generator.[14] Although in this case an unbevelled crystal was used, the spectral shapes at such high energies are not expected to differ greatly due to bevelling.

The relatively large distance at which the sample was placed from the crystal resulted in very few coincident sum pulses. The intensity due to summing was subtracted using the Y^{88} gamma-ray spectrum and normalizing the heights of the 0.908-Mev gamma rays, since the relative intensities of the 1.85-Mev gamma rays in the rubidium and yttrium decays are different. The peak at 120 pulse height was caused by annihilation radiation which resulted, mostly, from pairs produced in the surrounding lead shield by the high-energy gamma rays from the source. The bulge at ~280 pulse height decayed with a considerably longer half-life than the remainder of the spectrum and was attributed to the 1.076-Mev gamma ray in 19 day Rb^{86}. No other impurities were found after following the decay of some samples as long as five half-lives of Rb^{88}. The peak at 1.39 Mev would have been difficult to discern with the previously used small crystals[11] because of the presence of the middle pair peak from the 1.85-Mev gamma ray. In the spectrum obtained with our larger crystals, there can be no doubt of its existence. Peaks due to gamma rays at 2.11 and 2.68 Mev are seen in Fig. 2 and gamma rays at 3.01, 3.23, 3.52, 3.68, and 4.87 Mev are resolvable at shown in Fig. 3. The intensities of these gamma rays are given in Table I. Because of the high energy of the transitions, the conversion coefficients are probably less than 0.01 in all cases and so the relative gamma-ray intensities indicated are the transition intensities as well.

Spectra were obtained in coincidence with the gamma rays at 0.908, 1.85, 2.11, and 2.68 Mev. These are shown in Figs. 5–8. Calculations were carried out on the expected intensities of the coincidence peaks using the

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[14] The authors are pleased to acknowledge the assistance of Willard, Bair, and Cohn in performing the Van de Graaff experiment.

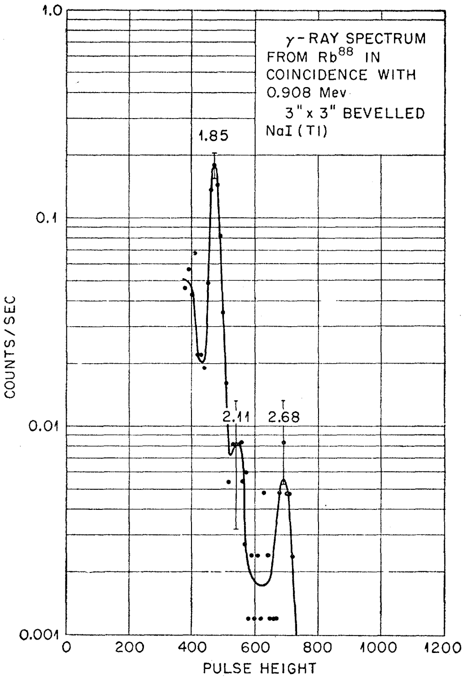

FIG. 5. Gamma-ray spectrum from Rb^{88} in coincidence with 0.908 Mev.

relative intensities obtained from the single-crystal data. Despite the poor statistics, certain facts may be deduced. Figure 8 shows a peak at 1.85 Mev obtained in coincidence with the single-channel window set to cover the region of 2.7 Mev. Because of the solid angle used (source was placed approximately midway between the crystals which were 5.8 cm apart), the coincident sum peak of the 1.85- and 0.908-Mev gamma ray appeared quite prominently in the single channel spectrum. If half the counts in the window were assumed to be in coincidence with the 1.85-Mev gamma ray, the agreement with the measured value was quite acceptable. The existence of the coincidence of the 1.85-Mev and 2.68-Mev gamma rays was confirmed by observing the 2.68-Mev peak in coincidence with the window set at 1.85-Mev. Again, the measured peak area agreed to 10 percent with the expected area. In addition, no peak appeared in Fig. 7 at 0.908 Mev. This is not surprising since the total energy available for the decay is 5.3 Mev and the coincidence of the 2.68-Mev gamma ray with both the 0.908- and 1.85-Mev gamma rays would imply a level at 5.44 Mev.

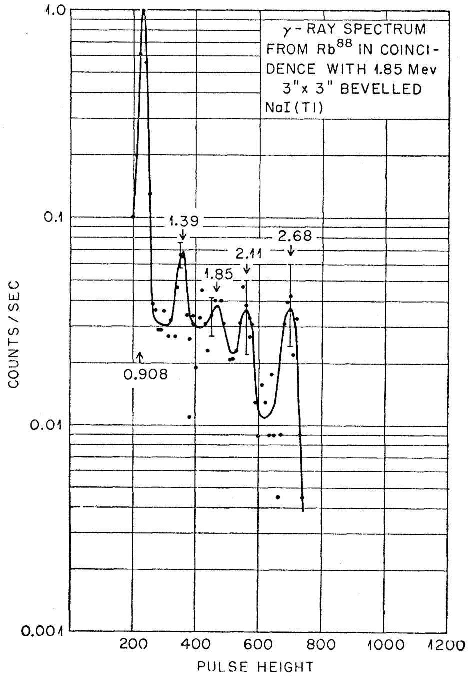

FIG. 6. Gamma-ray spectrum from Rb^{88} in coincidence with 1.85 Mev.

The spectrum in coincidence with the 2.11-Mev gamma ray shows peaks at 1.85 and 0.908 Mev whose intensities are reasonable based on the single crystal information. Further confirmation for these cascades is indicated in Figs. 5 and 6 where the single channel was set at 0.908 and 1.85 Mev. Corrections had to be made for counts in the window due to higher energy transitions, particularly for coincidences with the 0.908-Mev gamma ray, but the results were not in disagreement with the calculated values.

TABLE I. Energies and intensities of gamma rays from Rb^{88}.

Energy (Mev)	Intensity relative to 1.85-Mev gamma ray
1.850±0.008	1.000
0.908±0.004	0.631±0.050
1.39 ±0.03	0.062±0.015
2.11 ±0.03	0.045±0.007
2.68 ±0.05	0.107±0.010
3.01 ±0.05	0.014±0.005
3.24 ±0.03	0.014±0.002
3.52 ±0.05	0.011±0.002
3.68 ±0.05	0.004±0.002
4.87 ±0.05	0.014±0.003

Finally, the 1.39-Mev gamma ray appeared in coincidence with the 1.85-Mev gamma ray (Fig. 6) and its appearance in coincidence with the 0.908-Mev gamma ray (Fig. 5) could be explained by the Compton pulses of the 1.85-Mev transition in the window.

A measurement was made of the intensity of the ground-state gamma-ray transition. An aliquot of Rb^{88} was measured in a 4π β counter[15] while a larger aliquot from the same bombardment was used to determine the absolute intensity of the 1.85-Mev transition. The gamma-ray sample was placed 9.0 cm above an unbevelled 3-inch×3-inch NaI crystal and corrections were made for coincidence summing of the 1.85-Mev

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[15] The authors are indebted to A. R. Brosi for the use of the 4π β counter and his advice in making the arrangements.

gamma ray with the 0.908-, 1.39-, 2.11-, and 2.68-Mev transitions. The counting rate due to the beta rays was followed for several half-lives and the Rb^{86} intensity subtracted by a measurement of the aliquot after all the Rb^{88} had decayed out. This amounted to less than a 5% correction. The ratio of the intensity of the 1.85-Mev transition to the total number of beta rays determines the ground state intensity since the number of gamma rays bypassing the 1.85-Mev state is about one percent of the beta-ray transitions. From these measurements, the ground state transition was 75.9 ±5.0 percent of the total transitions.[16]

DISCUSSION

The decay scheme shown in Fig. 9 may be constructed from the available information. The comparative half-lives for all the β transitions from Rb^{88} were calculated from the intensities of the gamma rays leaving the levels and the assumption that 75 percent of all β transitions are to the ground state. These are listed in Table II. The log *ft* value of 7.9 for the beta-ray group to the first excited state is in good agreement with the proposed 2+ spin. However, the transition to the 2.76-Mev level is slower than expected for an allowed decay. The intensities of low-energy beta-ray groups measured by both Thulin[3] and Bunker *et al.*[2] do not agree with the measured gamma-ray intensities; however, large errors in intensities are possible in the beta-ray analyses. The comparative half-lives for the transitions to the 4.87- and 4.54-Mev states are as expected for allowed transitions, and so these states almost certainly have odd parity. The assignment 1− for the 4.87 state can probably be ruled out by the relative intensity of the 3.01- and 2.11-Mev transitions. If the spin of the 4.87-Mev state were, in fact, 1−, then the transitions to the 2.76- and 1.85-Mev levels would have to be *E*2 and *E*1 radiation, respectively. The higher intensity of the 2.11-Mev gamma ray probably rules out such a possibility.

TABLE II. Intensities and comparative half-lives of the β-ray transitions computed from the γ-ray intensities (transitions labeled by final state).

Beta-ray group	Intensity	Logarithm of comparative half-llife
β_0	0.759	7.5
$\beta_{1.85}$	0.043	7.9
$\beta_{2.76}$	0.136	6.7
$\beta_{3.24}$	0.017	7.3
$\beta_{3.52}$	0.0025	7.9
$\beta_{3.68}$	0.00083	8.1
$\beta_{4.53}$	0.025	5.2
$\beta_{4.87}$	0.017	5.0

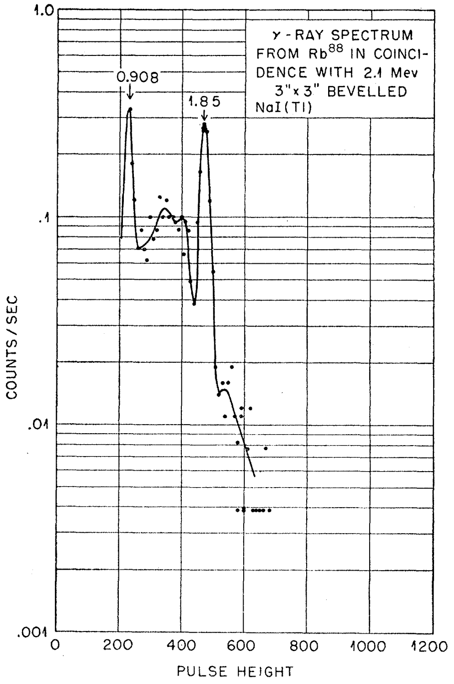

FIG. 7. Gamma-ray spectrum from Rb^{88} in coincidence with 2.1 Mev.

The states at 3.25, 3.52, and 3.68 Mev are assigned even parity from the comparative half-lives of the beta-ray transitions feeding them. The relative intensity of the 3.25- and 1.39-Mev gamma rays may be calculated

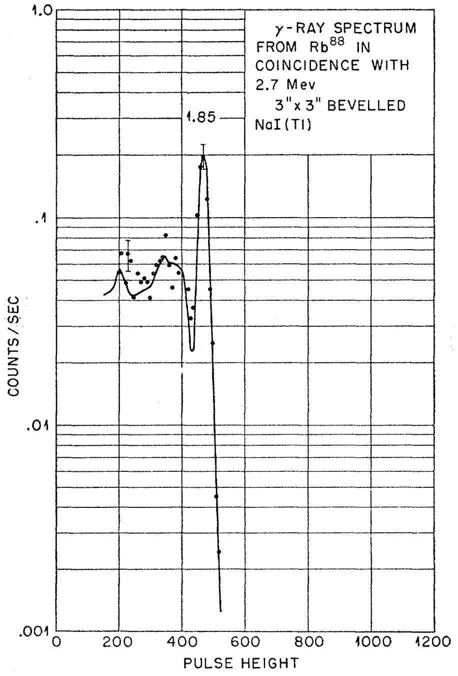

FIG. 8. Gamma-ray spectrum from Rb^{88} in coincidence with 2.7 Mev.

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[16] *Note added in proof.*—M. E. Bunker has studied the radiations from Rb^{88} and finds essentially all the transitions described above except the 3.68-Mev gamma ray.

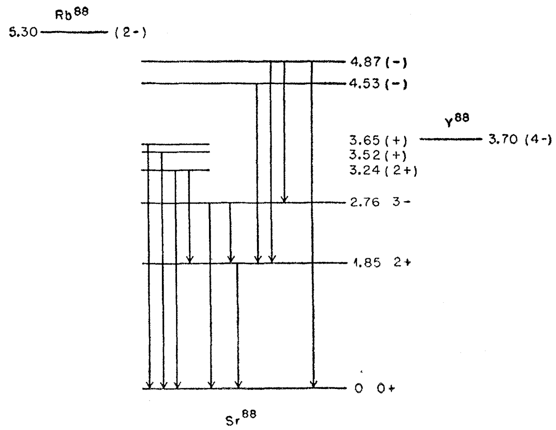

FIG. 9. Proposed energy level scheme for Sr^{88}.

from the Weisskopf formula.[17] Assuming the 3.25-Mev gamma ray is $E2$ and the 1.39-Mev radiation, $M1$, $I(3.25)/I(1.39)=0.20\times\mathcal{M}_{E2}^2/\mathcal{M}_{M1}^2$. The observed ratio is 0.23,[18] and the assignment of 2+ to this level may be made.

The ratio of the intensities of the 0.908- and 2.76-Mev gamma rays may be calculated in the same way. Here a 0.007 percent admixture of $M2$ in the predominantly $E1$ radiation of 0.908 Mev has been shown by Steffen.[8] The single particle estimate gives $I(0.908)/I(2.76)=0.2\times10^7\mathcal{M}_{E1}^2/\mathcal{M}_{E3}^2$. However, a similar calculation shows the expected $M2$ admixture in the 0.908-Mev radiation to be only 0.27×10^{-7} if $\mathcal{M}_{M2}^2/\mathcal{M}_{E1}^2=1$. The $E3$ matrix elements are not known but a fit to both the cross-over intensity and angular correlation measurement may be made if $\mathcal{M}_{M2}^2\sim10^{-2}$ and $\mathcal{M}_{E1}^2\sim3\times10^{-5}$, assuming $\mathcal{M}_{E3}^2=1$. These estimates are not out of line with $E1$ transitions in other nuclei.[18,19]

One other piece of information is available which tends to confirm at least some of the details in the proposed scheme. Kinsey and Bartholomew[20] have measured the energy of the capture gamma rays obtained from slow neutron bombardment of natural strontium. Three gamma rays with energies of 9.22, 9.06, and 8.38 Mev are presumed to occur in the nucleus Sr^{88}. The binding energy for the neutron in Sr^{88} has been shown, from the (γ,n) reaction, to be 11.2 Mev. It is suggested that the 9.22-Mev gamma ray goes to the 1.85-Mev level and the 8.38-Mev gamma ray is a transition to the 2.76-Mev state. Since the latter is the better measured value of the two, the binding energy would be 11.14 Mev. The 9.06-Mev transition is extremely weak and may be doubtful—at any rate its final state appears not be excited in the beta decays. However, other gamma radiation is seen and particularly those at 6.27 and 6.67 Mev. These gamma ray transitions would, then, end at 4.87 and 4.47 Mev, in good agreement with the two highest excited states found in the Rb^{88} decay.

As has been mentioned, Sr^{88} has 50 neutrons and it is tempting to try to identify the first few excited states with proton configurations predicted from the single particle model. The single particle states available for the 29th through 50th protons are $f_{5/2}$, $p_{3/2}$, $p_{1/2}$, and $g_{9/2}$. ${}_{40}Zr^{90}$, with two more protons, appears to fill the $p_{1/2}$ shell[21] and so a reasonable assignment for the last 10 protons in the ground state of Sr^{88} is $(f_{5/2})^6(p_{3/2})^4$. If one of the $p_{3/2}$ protons is excited into the $p_{1/2}$ orbital, the resulting coupling very likely would yield a 2+ state. If the proton is excited to $g_{9/2}$ orbital, it might couple to the resulting $p_{3/2}$ hole to yield the 3− second excited state. Thus, the pertinent configurations for the first two excited states might reasonably be $(p_{3/2})^{-1}(p_{1/2})_{2+}$ and $(p_{3/2})^{-1}(g_{9/2})_{3-}$. The neighboring nucleus ${}_{39}Y_{50}{}^{89}$ is known to bave a $g_{9/2}-p_{1/2}$ isomeric transition with an energy of 0.913 Mev, surprisingly similar in energy to the 0.908-Mev radiation seen in Sr^{88}. One might attempt to explain the low probability of the 0.908-Mev $E1$ radiation in Sr^{88} relative to the single-particle predictions by the $g_{9/2}-p_{1/2}$ proton orbital change between the initial and final states.

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[17] J. M. Blatt and V. F. Weisskopf, *Theoretical Nuclear Physics* (John Wiley and Sons, Inc., New York, 1954); A. Moszkowski, Phys. Rev. **89**, 474 (1953).

[18] A. W. Sunyar and M. Goldhaber, in *Beta and Gamma Ray Spectroscopy*, edited by K. Siegbahn (Interscience Press, New York, 1955).

[19] *Note added in proof.*—E. D. Klema has remeasured the angular distribution of the 0.908- and 1.85-Mev gamma rays with high precision and finds the correlation is consistent with a pure E1-pure E2 cascade within experimental error. These data do not greatly alter the conclusions above.

[20] B. B. Kinsey and G. A. Bartholomew, Can. J. Phys. **31**, 1051 (1953).

[21] K. Ford (private communication).