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Neutron Capture Gamma Ray Investigation of Sr^{88} Level Structure

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The level structure of Sr^{88} has been investigated at the Karlsruhe research reactor FR2 using thermal neutron capture in Sr^{87}. A pure thermal neutron beam was obtained by Bragg reflection from a lead single crystal. The target was natural strontium which gives a cross section contribution of about 87% for the reaction $Sr^{87}(n, \gamma)\,Sr^{88}$. High resolution measurements of the capture gamma ray spectrum have been performed by means of a $4\,cm^2 \times 0.5$ cm lithium-drifted germanium diode. 146 gamma lines have been observed. Cascade relationships were studied by a double and triple coincidence apparatus containing $4'' \varnothing \times 5''$ NaI(Tl) crystals and XP-1040 photomultipliers. In several cases coincident background was subtracted utilizing the double-window technique. By application of the triple sum coincidence method capture gammas from isotopes other than the investigated Sr^{88} nucleus could be eliminated. Several new levels were established. A transition scheme is proposed and discussed. The neutron binding energy of Sr^{88} is determined to be 11111 ± 4 keV.

1. Introduction

The investigation of the Sr^{88} level structure is part of a program for studying vibrational states with multiple phonon characteristics in even spherical nuclei via the (n, γ)-reaction. Thermal neutron capture in Sr^{87} leads to a capture state with spin 4^+ or 5^+, since the measured ground-state spin of the target nucleus is $9/2^+$. The binding energy of the last neutron in Sr^{88} is 11.1 MeV. Thus it is expected that high spin vibrational states in Sr^{88} are populated with reasonable intensities. The study of these levels presumes a thorough investigation of the total level structure in the corresponding energy region.

The Sr^{88} nucleus is the daugther of both Rb^{88} and Y^{88}. The former decays by β^- emission and the latter by electron capture and β^+ emission. In the earlier decay studies* consistency has been achieved as to the existence of energy levels at 1.85 and 2.76 MeV. Levels at 3.24, 3.52, 3.65, 4.53 and 4.87 were found by LAZAR et al.[1], the former two of these levels being also reported by SHASTRY et al.[2]. Gamma-gamma angular

* References to the literature on Sr^{88} up to 1955 are to be found in ref. [1].

[1] LAZAR, N. H., E. EICHLER and G. D. O'KELLEY: Phys. Rev. 101, 727 (1956).

[2] SHASTRY, S., and R. BHATTACHARYYA: Nuclear Phys. 55, 397 (1964).

correlation experiments[2,3] and conversion coefficient measurements[4] suggest that the energy levels at 1.85, 2.76 and 3.22 have spin and parity 2^+, 3^- and 2^+, respectively. Natural strontium capture gamma rays above 3 MeV have been measured by KINSEY and BARTHOLOMEW[5] using a magnetic pair spectrometer. These authors identified 12 transitions assigning gamma rays at 6.268, 8.376 and 9.22 MeV to the Sr^{88} nucleus. Inelastic scattering of deuterons from natural strontium was studied by HAMBURGER[6]. As a result energy levels at 0.85 (Sr^{87}), 1.11 (Sr^{86}), 1.835 (Sr^{88}), 2.74 (Sr^{88}), 3.22 (Sr^{88}), 3.61 (Sr^{88} ?), 4.02 and 4.27 MeV could be identified.

2. Experimental Procedure

2.1. Thermal Neutron Beam. The present experiments were performed at a horizontal core channel of the Karlsruhe research reactor FR 2. The experimental setup is shown schematically in Fig. 1 of our recent paper[7] on the level structure of Ge^{74}. In order to remove fast neutron and gamma contamination present in the initial beam thermal neutrons are diffracted from the (111) planes of a 4 cm thick lead single crystal at a Bragg angle of 12.2°. At this angle the diffracted neutrons have a wavelength of approximately 1.2 Å corresponding to an energy of 0.057 eV. The neutron flux at the target position was determined with gold foils and found to be* 0.78×10^6 cm^{-2} sec^{-1}. For the ratio of the thermal flux to the resonance flux per $\log_e$ interval measurements with indium foils yielded a value of 26000.

2.2. Target. As a target 17.3 g of spectroscopically pure $SrCO_3$ were used. Strontium consists of four stable isotopes. The capture cross section contributions and the binding energies in the product nuclei are as follows[8,9]: Sr^{84} 0.4%, 8.24 MeV; Sr^{86} 11.9%, 8.42 MeV; Sr^{87} 87.4%, 11.11 MeV (cf. sect. 4.2); Sr^{88} 0.3%, 6.5 MeV. Therefore, when using natural strontium as a target a considerable contribution of thermal neutron capture in Sr^{86} has to be taken into account. Contamination

* Due to an increase of the reactor power the flux is now about $3.5 \times 10^6 cm^{-2} sec^{-1}$.

3 STEFFEN, R. M.: Phys. Rev. **90**, 321 (1953). — BISHOP, G. R., and J. P. PEREZ Y JORDA: Phys. Rev. **98**, 89 (1955).

4 PEACOCK, W. C., and T. W. JONES: AECD 1812 (1948). — METZGER, F. R., and H. C. AMACHER: Phys. Rev. **88**, 147 (1952).

5 KINSEY, B. B., and G. A. BARTHOLOMEW: Can. J. Phys. **31**, 1051 (1953).

6 HAMBURGER, E. W.: Nuclear Phys. **39**, 139 (1962).

7 WEITKAMP, C., W. MICHAELIS, H. SCHMIDT u. U. FANGER: Z. Physik **192**, 423 (1966).

8 Chart of the Nuclides, 2nd edit.

9 LANDOLT-BÖRNSTEIN, group I, vol. I. Berlin-Göttingen-Heidelberg: Springer 1961.

of the capture gamma spectrum from chemical impurities in the sample was negligible.

The target was enclosed in a 25 mm diameter × 28 mm polyethylene container with 0.5 mm wall thickness. It was retained in the centre of a 50 mm i.d. double-walled polyethylene tube filled with 7.5 mm of packed Li^6H. The Li^6H prevents scattered neutrons from reaching the detectors, but transmitted essentially all gammas above 0.1 MeV.

2.3. Detectors and Electronics. High resolution gamma ray spectroscopy was performed using a lithium-drifted germanium detector with 4 cm^2 sensitive area and a depletion depth of 5 mm. The diode was operated at liquid nitrogen temperature and 600 V bias voltage, the temperature being automatically controlled by a temperature sensitive device. Provided the counting rates were less than about 1000 counts/sec an energy resolution of 6.7 keV FWHM was obtained for the photopeak of the Cs^{137} 662 keV gamma ray using a low noise amplifier system with 2 μsec integrating and differentiating time constants. Background consisted mainly of 2225 keV capture gamma rays from thermal neutron capture in polyethylene and the ever present 511 keV positron annihilation radiation. Above 2.23 MeV the background spectrum was essentially a continuum and could be neglected in most cases except for a small peak at 7639 keV from the $Fe^{56}(n, \gamma)\,Fe^{57}$ reaction.

Energy calibration is based on the annihilation peak and on the gamma lines from the reactions $H(n, \gamma)D$ and $C^{12}(n, \gamma)\,C^{13}$. In independent measurements the intensities of the gamma rays from the second process were enhanced by adding a graphite target to the $SrCO_3$ sample. The linearity of the system was carefully checked up to 10 MeV with a high precision mercury switch pulser. These measurements indicate that the error arising from nonlinearity is small compared to that caused by statistical uncertainties. Thus an energy calibration with the gamma lines from the above reactions was sufficient. The following values for the gamma-ray energies were adopted: 2224.9 ± 1.3 keV for the $H(n, \gamma)D$ reaction[10], 3683 ± 4 keV and 4944 ± 4 keV for the $C^{12}(n, \gamma)\,C^{13}$ reaction[11]. In the quoted uncertainties systematic errors are included.

For coincidence measurements the target was looked at by 4″∅ × 5″ NaI(Tl) crystals connected to XP-1040 photomultiplier tubes. In order to minimize counter-to-counter scattering the crystals were heavily shielded by conical lead collimators. For double coincidence measurements two detectors were used with their axes oriented to subtend a 90° angle at the target. For triple coincidence studies, three crystals were

[10] Alexander, K. F.: Private communication.

[11] Sheline, R. K., W. N. Shelton, H. T. Motz, and R. E. Carter: Phys. Rev. **136**, B 351 (1964).

placed at an angle of 120°. With the crystal face 10 cm from the beam axis the background counting rate above a bias equivalent to an energy of 100 keV was only about 200 counts/sec in the absence of a sample. Thus, the described method proves to be very efficient in suppressing the background in neutron capture gamma-ray experiments.

At a distance of 10 cm from the target axis summing in the crystals was less than 3.5%. In general, the singles counting rates did not exceed 10^4 counts/sec. With a clipping time of 0.7 μsec in the linear amplifiers pile-up was limited to less than 1%. In some cases, the distance was reduced and counting rates up to 3×10^4 counts/sec were tolerated.

The coincidence system was of the conventional fast-slow type containing a recently developed fast coincidence circuit with avalanche transistors[12]. Using an effective resolving time of 25 nsec the accidental coincidence rate was less than 1% in the double coincidence measurements. Detectors and correlated amplifiers were stabilized against gain shifts by means of a feedback system operating on an attenuator at the input of the linear amplifier[13].

In several measurements the double window technique described by WHITE[14] was applied in order to correct for the coincident background under the peak selected by the window in the gating branch of the coincidence system.

All singles spectra and the triple sum coincidence spectrum (cf. sect. 3.2) were registered with a 1024 channel pulse-height analyzer. For the double coincidence measurements a 400 channel pulse-height analyzer was used.

In the case of the three-parameter experiments recording of data was done by means of a 2×1024 channel dual ADC in connection with the Karlsruhe Multiple Input Data Acquisition System (MIDAS)[15, 16]. A block diagram of the setup is shown in Fig. 2 of ref. [7]. In the gating branch of detector 3 an integral discriminator was used. The signals accepted by detector 1 and 2 were fed into the inputs of the dual ADC which was set busy whenever the slow coincidence unit gave an output pulse and the two digital pulse-height informations were then recorded together on magnetic tape.

2.4. Data Processing. In order to minimize the influence of shifts in the analyzer system (not included in the stabilizing loop), the singles spectra were taken initially at an energy scale of 1.0 or 1.5 keV per

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[12] MICHAELIS, W., H. SCHMIDT, and C. WEITKAMP: Nuclear Instr. and Meth. **31**, 93 (1964).

[13] TAMM, U.: Nuclear Instr. and Meth. **40**, 355 (1966).

[14] WHITE, D. H.: Phys. Rev. **131**, 777 (1963).

[15] KRÜGER, G., and G. DIMMLER: KFK 242 (1964).

[16] KRÜGER, G.: Atomwirtschaft **10**, 118 (1965).

channel. Contents of three or two adjacent channels were added afterwards except for the two highest energy regions, where the channel numbers were reduced by a factor of 6 and 5, respectively. In view of the quoted energy resolution this reduction of channel numbers can be performed without loss of information. Where statistics remained poor, the spectra were smoothed by replacing the contents of each channel by the average over that channel and the two neighbouring ones.

Data processing of the three-parameter coincidence measurement was done with a special MIDAS subroutine. Details of the evaluation procedure are described in ref. [7].

3. Experimental Results*

3.1. Singles Spectra. The neutron capture gamma-ray spectra from natural strontium observed with the lithium-drifted germanium detector are shown in Figs. 1 and 2. A total of 146 gamma lines were observed most of them being previously unknown. The results are summarized in Table 1. The uncertainties quoted for the energies include both statistical and systematic errors.

Background is subtracted only in the energy region between 1000 and 2300 keV where the intense 2225 keV gamma ray from the $H(n, \gamma)D$ reaction causes prominent peaks at 2225 keV and 1203 keV (double escape), a smaller one at 1714 keV (single escape) and a high Compton continuum. The other spectra are shown without background correction (cf. sect. 2.3). The small peak at 7639 keV from the $Fe^{56}(n, \gamma)Fe^{57}$ reaction is labelled "background".

In the low energy region (up to about 1 MeV), where absorption of gamma rays by the photoelectric effect is the most important process, the detector was used as a photoelectric spectrometer. Compton distributions from intense gamma lines complicated the detection of weak radiation. Above 3 MeV energy absorption in the diode the gamma-ray energies were obtained from the dominant double escape peak which corresponds to the total kinetic energy of the electron-positron pair in the pair production process. For the medium energy part of the spectra where full-energy peak and double escape peak are of comparable intensity particular care was taken as to the interpretation of peaks. Some weak peaks, however, cannot be assigned unambiguously. Compared

* Preliminary results have been presented by the authors at the Antwerp conference[17].

[17] Schmidt, H., W. Michaelis, G. Markus, and C. Weitkamp: Proceedings of the Internat. Conference on the Study of Nuclear Structure with Neutrons, Antwerp, July 1965, p. 517. Amsterdam: North-Holland Publishing Company 1966.

Table 1. *Gamma Rays from Thermal Neutron Capture in Natural Strontium Carbonate Observed with a Ge(Li) Detector*

Line Number	Energy E_γ/keV	Error E_γ/keV	Class[a]	Line Number	Energy E_γ/keV	Error E_γ/keV	Class[a]
1	378	2	DC	47	2349	5	DC[b]
2	388	1.5	B	48	2368	5	C[b]
3	434	1.5	C	49	2396	4	A
4	464	2	DC	50	2437	5	C[b]
5	484	1.5	B	51	2578	6	C[b]
6	586	2	A	52	2682	5	A
7	685	4	DC	53	2734	6	A
8	714	4	DC	54	2905	8	DC[b]
9	850	1	A	55	3010	3	A
10	863	2	C[b]	56	3228	5	DC
11	897	1	A	57	3490	5	C[d]
12	936	3	C	58	3529	6	A
13	1029	3	DC[b]	59	3547	6	C
14	1161	3	DC[b]	60	3620	6	C
15	1220	4	C	61	3656	7	DC
16	1330	4	C[b]	62	3691	6	A[e]
17	1347	5	DC[b]	63	3737	6	C[c]
18	1388	5	A	64	3765	8	DC
19	1413	5	DC[b]	65	3827	10	DC
20	1443	4	C[b]	66	3869	8	DC
21	1473	6	C	67	3887	6	C
22	1500	6	A	68	3907	8	DC
23	1538	4	C	69	3956	8	DC
24	1559	4	C[b]	70	3973	5	C
25	1714	4	A	71	3996	8	C
26	1741	7	DC[b]	72	4025	5	C
27	1766	5	DC[b]	73	4052	8	DC
28	1799	5	DC[b]	74	4074	8	DC
29	1836	1	A	75	4100	8	DC
30	1880	4	C[b]	76	4160	8	C
31	1902	5	DC[b]	77	4128	8	DC
32	1920	5	DC[b]	78	4204	8	DC
33	1935	4	C[b]	79	4241	8	DC
34	2027	1	C[b]	80	4263	8	DC
35	2063	4	C[b]	81	4281	8	DC
36	2082	5	DC[b]	82	4295	8	DC
37	2113	4	A	83	4308	8	DC
38	2130	5	DC[b]	84	4324	8	DC
39	2148	6	DC[b]	85	4350	8	DC
40	2167	4	C	86	4375	8	DC
41	2206	5	C	87	4403	8	DC
42	2256	5	C[b]	88	4417	8	C
43	2279	5	A	89	4476	8	DC
44	2306	5	DC[b]	90	4503	6	C
45	2320	5	DC[b]	91	4533	6	C
46	2332	6	DC[d]	92	4560	6	C

Table 1 (Continued)

Line Number	Energy E_γ/keV	Error E_γ/keV	Class[a]	Line Number	Energy E_γ/keV	Error E_γ/keV	Class[a]
93	4587	6	C	120	5791	5	A
94	4610	5	C	121	5853	7	C
95	4642	7	C	122	5887	8	DC
96	4679	7	C	123	5927	8	DC
97	4712	7	C	124	6003	6	C
98	4752	8	DC	125	6040	8	DC
99	4833	8	DC	126	6101	5	A
100	4855	8	DC	127	6188	7	C
101	4888	10	DC[c]	128	6228	8	DC
102	4918	6	C	129	6264	5	A
103	4944	5	E	130	6569	10	DC
104	4988	5	C[c]	131	6612	7	DC
105	5074	6	C	132	6658	5	A
106	5106	6	C	133	6693	6	C
107	5162	5	C	134	6766	8	DC
108	5189	8	DC	135	6811	9	C
109	5245	6	C	136	6843	6	C
110	5279	6	C	137	6883	5	A
111	5304	6	C	138	6941	5	A
112	5366	6	C	139	7153	10	DC
113	5391	7	C	140	7247	10	DC
114	5424	5	C	141	7272	10	DC
115	5538	8	DC	142	7476	8	C
116	5590	10	DC	143	7527	5	A
117	5628	8	DC	144	8038	5	B
118	5687	5	C	145	8376	5	A
119	5744	10	DC[c]	146	9154	15	D(C)

a) Classes: A certain line assigned to $Sr^{87}(n, \gamma)Sr^{88}$; B certain line assigned to $Sr^{86}(n, \gamma)Sr^{87}$; C unassigned line; D line not definitely established; E $C^{12}(n, \gamma)C^{13}$ line.

b) Gamma-ray energy given in column 2 possibly corresponding to double escape peak energy.

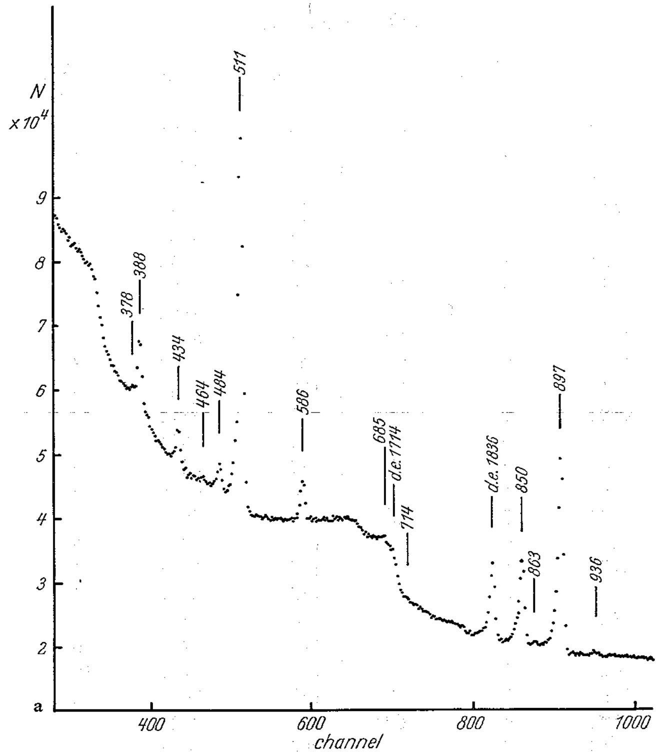
c) Broad peak, possible doublet.

d) Observed line possibly corresponding to a gamma-ray energy $E_\gamma - 2m_0c^2$.

e) Possibly containing a contribution from the $C^{12}(n, \gamma)C^{13}$ $-(3683 \pm 4)$ keV gamma ray.

to our preliminary results both statistics and resolution have been considerably improved. Therefore, several lines given in that report now appear as doublets or triplets. It is important to realize that this may also occur for the present results. If a peak which is now assumed to correspond to a single gamma ray turns out to be a closely spaced doublet or triplet, the energy quoted in Table 1 refers only to the centroid*.

* *Note added in proof.* In a recent experiment further improvement in resolution could be achieved. Among other results this measurement revealed the 6003 keV and 6658 keV gamma rays to be closely spaced doublets.



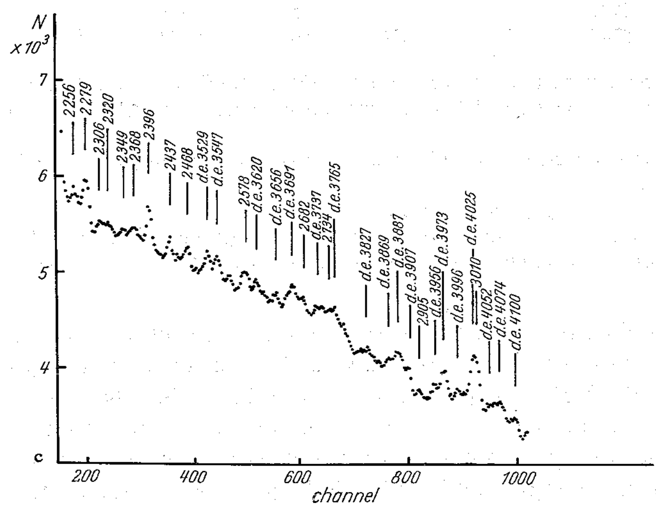
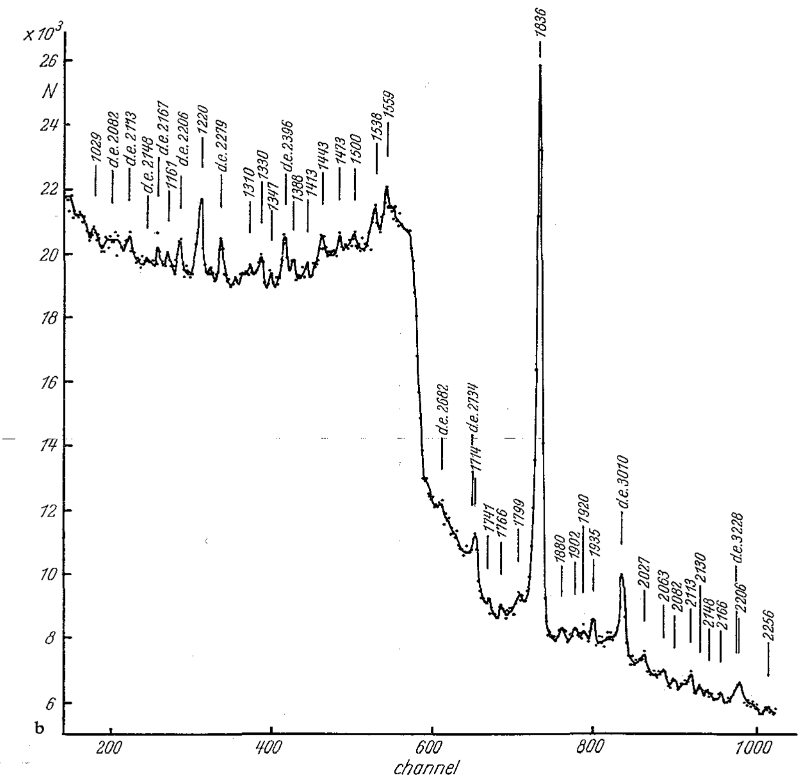
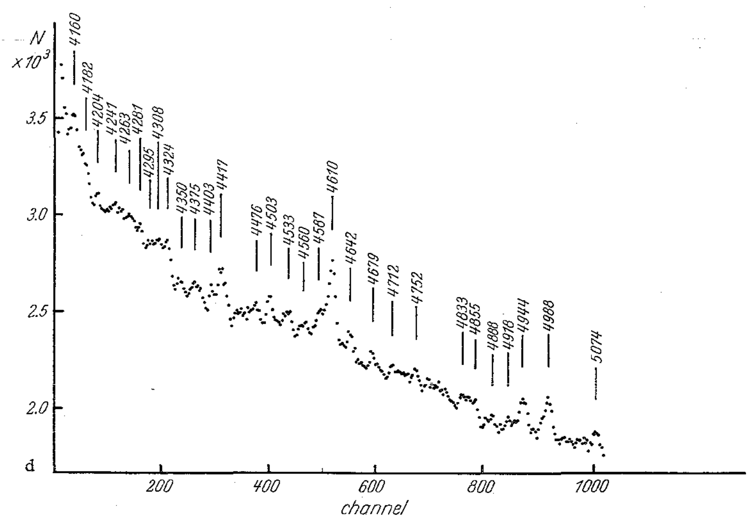


Fig. 1a—d. Singles gamma-ray spectra from thermal neutron capture in natural strontium carbonate observed with a Ge(Li) detector. a) Energy range from 300 keV to 1000 keV, without background correction, contents of two adjacent channels added. b) Energy range from 1000 keV to 2300 keV, background subtracted, contents of two adjacent channels added. c) Energy range from 2250 keV to 3100 keV, without





background correction, contents of three adjacent channels added. All peaks in a)—c) are labelled with the gamma-ray energy. Double escape peaks are labelled d.e. d) Energy range from 3100 keV to 4000 keV, without background correction, contents of three adjacent channels added. All peaks in d) are assumed to be double escape peaks and are labelled with the gamma-ray energy

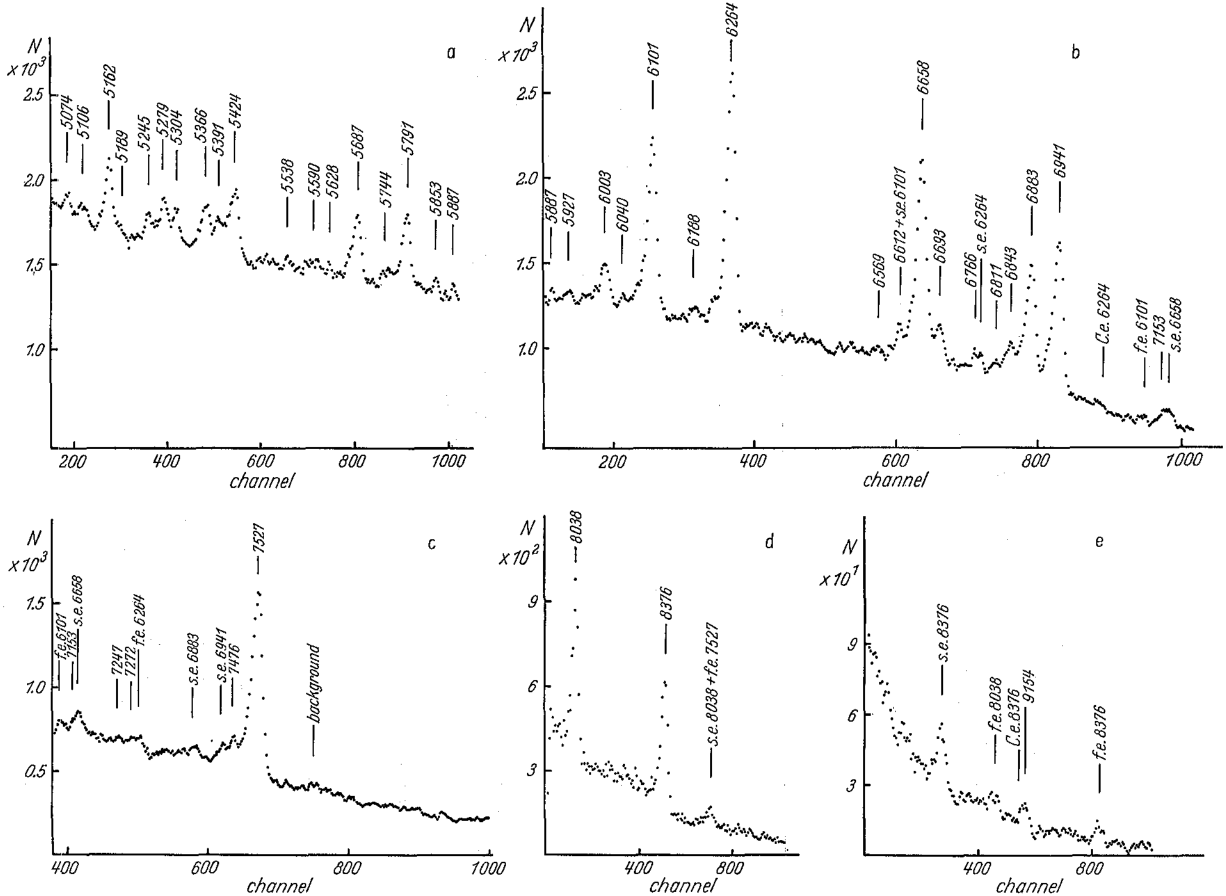


Fig. 2a—e. Singles gamma-ray spectra from thermal neutron capture in natural strontium carbonate observed with a Ge(Li) detector.
a) Energy range from 4000 keV to 4880 keV, contents of three adjacent channels added.
b) Energy range from 4850 keV to 6150 keV, contents of two adjacent channels added.
c) Energy range from 6100 keV to 7000 keV, contents of two adjacent channels added.
d) Energy range from 7000 keV to 7900 keV, contents of six adjacent channels added.
e) Energy range from 7600 keV to 8500 keV, contents of five adjacent channels added. All spectra displayed without background correction. Spectra of a), b), c) and e) are smoothed. Peaks are labelled with the gamma-ray energy. Where background is not smooth, peaks are labelled "background". For some prominent gamma rays Compton edges, single escape peaks or full energy peaks can be distinguished and are labelled C.e, s.e. or f.e., respectively

3.2. Coincidence Measurements. In view of the complexity of the gamma-ray spectrum the precise knowledge of the singles spectra from the germanium diode measurements was of considerable aid in interpreting the coincidence results since all coincidence experiments suffer from the fact that the resolution of NaI(Tl) detectors is relatively poor. This is particularly true for the high energy region where the double and single escape peaks in NaI(Tl) are of comparable intensity. When the assignment of the gamma-ray peaks found in the coincidence spectra or of the gamma rays within the window setting was not obvious, then the following criteria were used for deciding which gamma rays are responsible for the coincidence relationship: (1) the intensity of the lines in the relevant energy interval, (2) the energy difference between the NaI "group" and the nearest gamma lines observed with the germanium detector and (3) the "energy coincidence" of the resulting cascade. In some cases the spectra may be affected by pile-up which cannot easily be accounted for. However, by application of the double-window technique this background is removed.

In order to get information on the high energy transitions which have to be attributed to Sr^{88}, a triple sum coincidence experiment was performed with a window set at the binding energy for the $Sr^{87}(n, \gamma) Sr^{88}$ reaction. This energy is about 11 MeV and is well above the binding energies for the other strontium isotopes (cf. sect. 2.2). Three detectors were used for this experiment since the spin difference between capture state and ground state implies a high gamma-ray multiplicity. The sum coincidence spectrum obtained is shown in Fig. 3. It clearly demonstrates that the high energy transitions at 8376, 7527, 6941, 6883, 6658 and 6264 keV (cf. Table 1) have to be assigned to Sr^{88}. Analysis of the spectrum furthermore reveals weak lines at 7.23 and 7.91 MeV which cannot be interpreted in terms of the high resolution singles spectra. Both peaks are due to spurious events arising from pile-up and summing. These effects become important for the detection of four-step and higher-order cascades in a three-counter sum coincidence experiment. Peaks at 5.79 MeV and 6.10 MeV suggest that the gamma lines at 5791 keV and 6101 keV also arise from the Sr^{88} nucleus. However, both peaks may include a contribution from the partial detection of pair production by higher-energy transitions associated with the escape of one of the annihilation quanta. Thus the assignment cannot be definitely established*. The interpretation of the low-energy peaks in Fig. 3 directly results from the following paragraphs.

Double coincidence measurements were performed with several window settings. Some of the spectra are shown in Figs. 4 and 5. The

* *Note added in proof.* Meanwhile further experiments confirmed the assignment of these two gamma rays to the Sr^{88} nucleus.

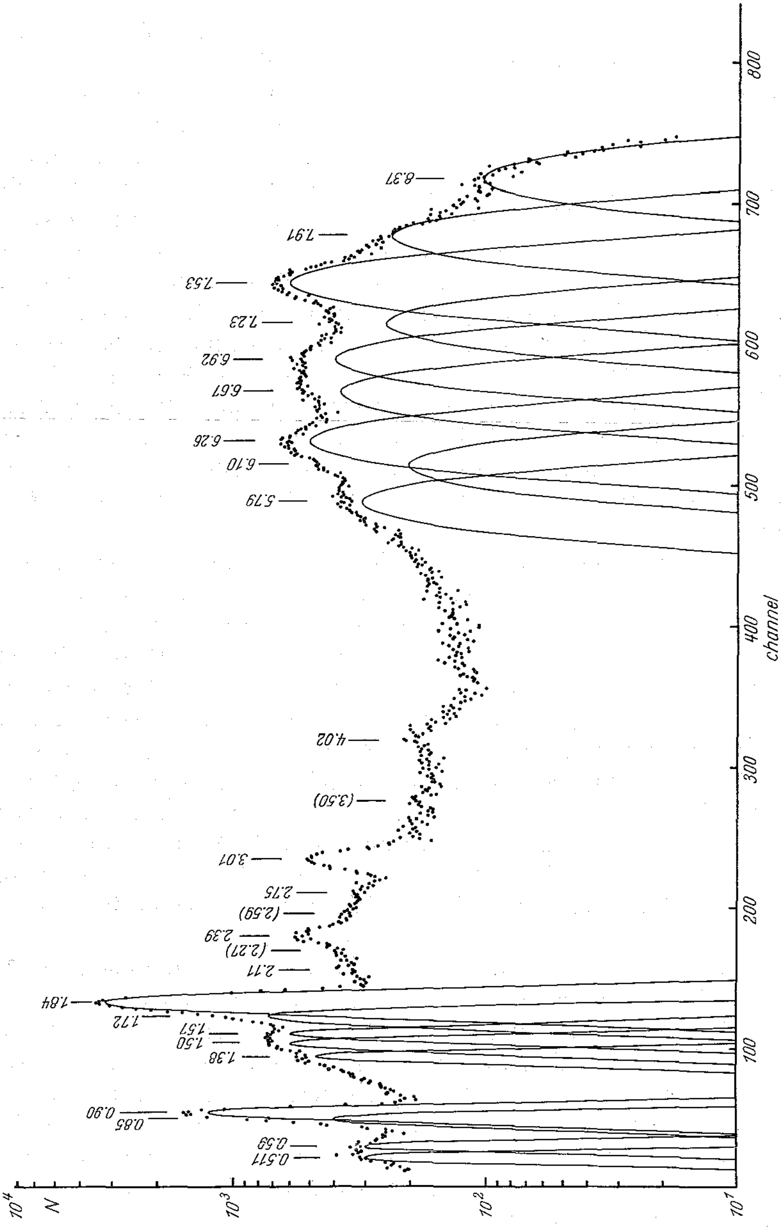


Fig. 3. Sr^{88} triple sum coincidence spectrum taken with three NaI(Tl) detectors. Sum channel set at the binding energy of the $Sr^{87}(n, \gamma)Sr^{88}$ reaction

results are summarized in Table 2. It may be noted that the cascade relationships of a major number of relatively intense gamma rays clearly present in the coincidence spectra have not yet been settled. These gamma

Table 2. *Summary of Double Coincidence Measurements**

Window setting MeV	Coincident gamma-ray energies in MeV** 0.59	0.85	0.90	1.39	1.50	1.71	1.84	2.11	2.28	2.40	2.76	3.01	6.26	6.66	6.9	7.53	8.38
0.81 – 1.00	+	+			+		+	+	+				+	+	+	+	+
1.69 – 2.00	+	(+)	+	+	+	+		+		+		+	+	(+)	+	+	+
6.08 – 6.40			+				+	+	(+)		(+)	+					
6.54 – 6.74			+		+	+	+										
6.80 – 7.05	+		+				+			+	+						
7.42 – 7.71		+	+				+				+						

* Not including even relatively intense gamma rays if their cascade relationships remain doubtful.
** Parentheses indicate less certain coincidences.

rays are not included in the table. Some of the results require comments. The presence of a gamma line at 1.71 MeV in the spectra coincident with the 1.84 MeV ground state transition (Fig. 4b) and the 6.66 MeV radiation (Fig. 5b) suggests a 6.66 MeV – 1.71 MeV – 0.90 MeV – 1.84 MeV coincidence relationship. If this conclusion is correct, then the 1.71 MeV gamma ray should also be observed in the spectrum taken with the window at 0.90 MeV. However, because of the strong 1.84 MeV transition the 1.71 MeV radiation is difficult to discern in this spectrum. Energy considerations favour the above assumption.

The existence of a coincidence between the gamma rays at 7.53 MeV, 0.90 MeV and 1.84 MeV is demonstrated in the spectra taken with double windows at the relevant energies (Figs. 4a, b and 5d). The peak at 1.33 MeV in Fig. 5d is probably due to single escape from the 1.84 MeV line. An important feature of this spectrum is the increased intensity of the gamma ray at 0.90 MeV. This result may be attributed to an unresolved 0.85 MeV transition. According to subsect. 3.1 such a transition exists. Moreover, in Fig. 4a there is a prominent peak at 0.85 MeV, the coincident background being subtracted. Thus a 7.53 MeV – 0.85 MeV – 0.90 MeV – 1.84 MeV cascade relationship can be regarded as definitely established. The gamma ray at 2.76 MeV in Fig. 5d is interpreted as being a cross-over transition parallel to the 0.90 MeV – 1.84 MeV cascade.

In the three-parameter coincidence experiment a bias equivalent to an energy of 6 MeV was set in the gating branch

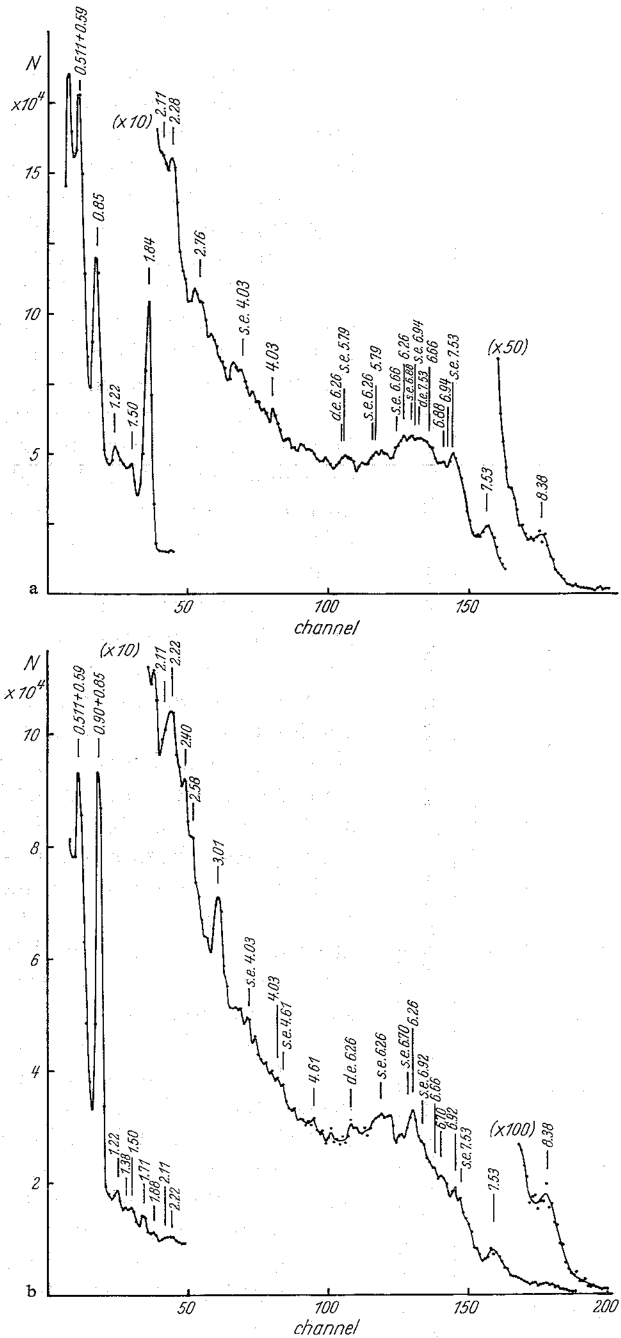


Fig. 4a and b. Sr(n, γ) gamma-gamma coincidence spectra taken with NaI(Tl) detectors. a) Spectrum coincident with the 0.9 MeV gamma ray. b) Spectrum coincident with the 1.84 MeV gamma ray. In both spectra coincident background is subtracted by application of the double-window technique

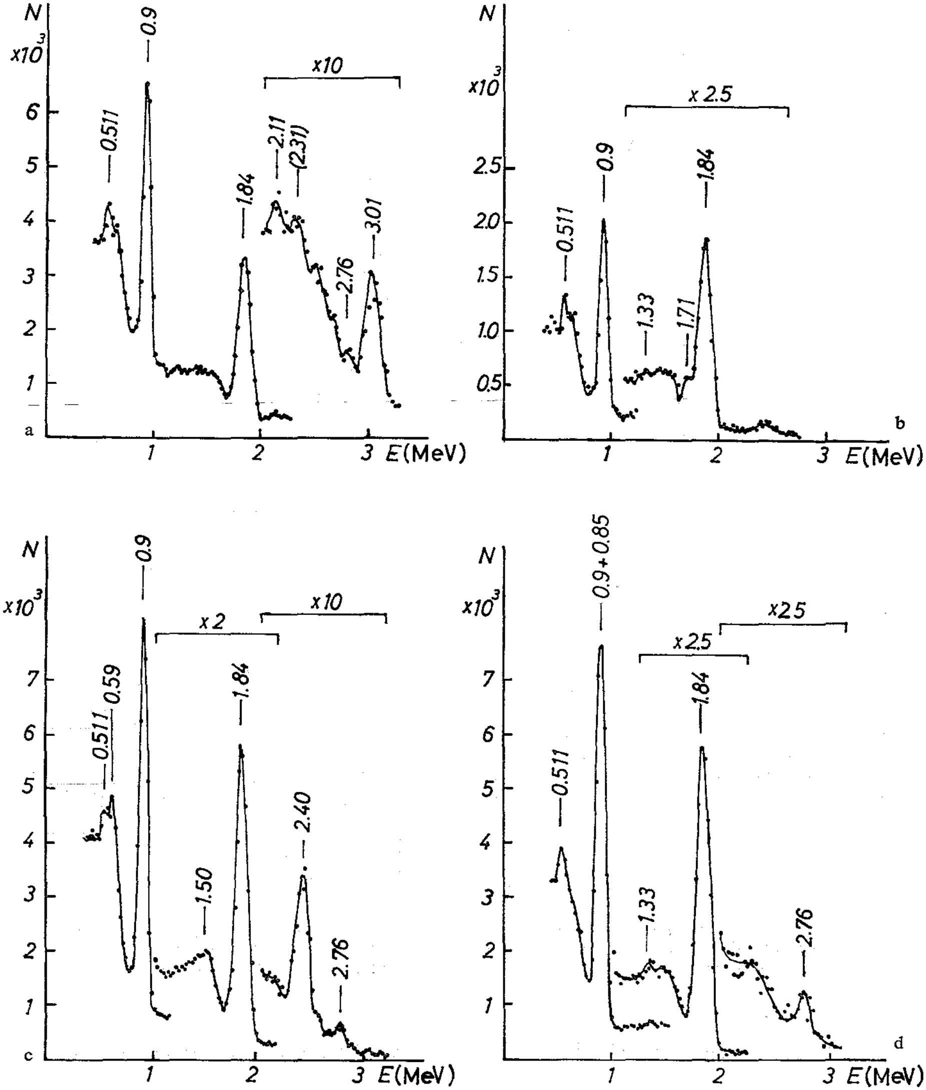


Fig. 5a–d. Sr(*n*, *γ*) gamma-gamma coincidence spectra taken with NaI(Tl) detectors. Spectrum in coincidence a) with the 6.27 MeV region, b) with the 6.67 MeV region, c) with the 6.9 MeV region, d) with the 7.53 MeV gamma ray. In spectrum c) and d) coincident background is subtracted by application of the double-window technique

of detector 3. Fig. 6 gives some spectra for illustration. The resulting coincidence relationships are listed in Table 3. Further evaluation of the triple coincidence data is in progress.

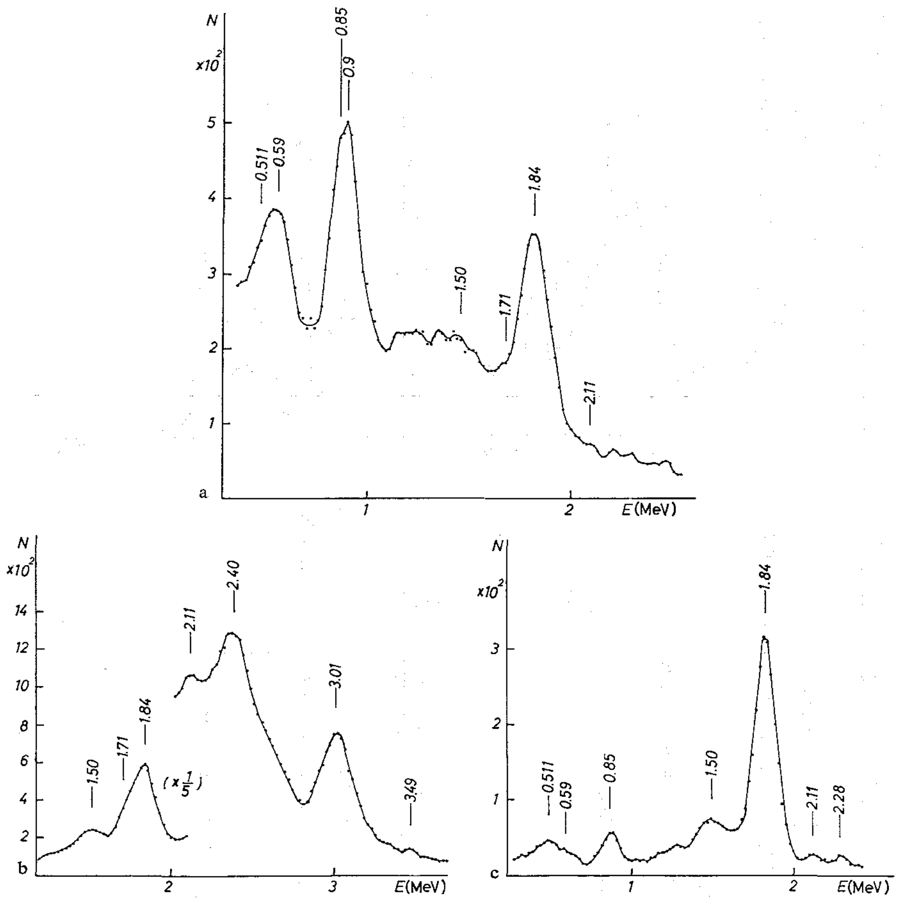


Fig. 6a—c. Sr(n, γ) triple coincidence gamma-ray spectra. Dual ADC gated by the signals from detector 3 with a bias equivalent to an energy of 6MeV set in the gating branch. MIDAS window a) at (0.89–0.99) MeV, b) at (1.76—1.91) MeV, c) at (2.76—2.9) MeV. Only relevant sections of the coincidence spectra are displayed

Table 3. *Coincidence Relationships Deduced from the Three-Parameter Spectra in Fig. 6*

MIDAS window location MeV	Coincident gamma-ray energies in MeV									
	0.59	0.85	1.50	1.71	1.84	2.11	2.28	2.40	3.01	3.49
0.90	+	+	+	+	+	+				
1.84			+	+		+		+	+	+
2.76	+	+	+			+	+			

Taking the precise energy values from the singles spectra the following cascades between capture and ground state can be definitely established from the present measurements:

$$\begin{aligned}
8376 + 897 + 1836\,\text{keV} &= 11109\,\text{keV}\\
8376 + 2734\,\text{keV} &= 11110\,\text{keV}\\
7527 + 850 + 897 + 1836\,\text{keV} &= 11110\,\text{keV}\\
7527 + 850 + 2734\,\text{keV} &= 11111\,\text{keV}\\
6941 + 586 + 850 + 897 + 1836\,\text{keV} &= 11110\,\text{keV}\\
6941 + 586 + 850 + 2734\,\text{keV} &= 11111\,\text{keV}\\
6883 + 1500 + 897 + 1836\,\text{keV} &= 11116\,\text{keV}\\
6883 + 1500 + 2734\,\text{keV} &= 11117\,\text{keV}\\
6883 + 2396 + 1836\,\text{keV} &= 11115\,\text{keV}\\
6658 + 1714 + 897 + 1836\,\text{keV} &= 11105\,\text{keV}\\
6658 + 1714 + 2734\,\text{keV} &= 11106\,\text{keV}\\
6264 + 2113 + 897 + 1836\,\text{keV} &= 11110\,\text{keV}\\
6264 + 2113 + 2734\,\text{keV} &= 11111\,\text{keV}\\
6264 + 3010 + 1836\,\text{keV} &= 11110\,\text{keV}.
\end{aligned}$$

4. Discussion

4.1. Level Scheme. The transition diagram for Sr^{88} based on the results of the present investigation is shown in Fig. 7. Coincidence relationships well established by coincidence measurements are indicated by dots. For the other transitions the correspondence between gamma line and transition is probable, but not reliably settled. Cascade relationships of gamma rays represented by dashed lines are mainly based on energy considerations and have thus to be considered as tentative. A summary of the energy levels is given in Table 4. For comparison the results of previous authors obtained from the decay of Rb^{88} and from inelastic scattering of deuterons have been included.

As to the capture gamma-ray data the most significant deviation from the previous conception consists in the assignment of the 7527 keV gamma ray to the Sr^{88} nucleus. The correctness of our interpretation is favoured by the triple sum coincidence experiment, the observed cascade relationships and by energy considerations. The sum of the relevant gamma-ray energies fits very well to the Sr^{88} binding energy. Kinsey and Bartholomew[5] assigned the gamma rays at 8038 keV and 7527 keV to the Sr^{87} nucleus interpreting them as transitions from the capture state to the first two excited levels at 388 keV and 872 keV. According to Y^{87} decay studies these levels have spin and parity $1/2^-$ and $3/2^-$, respectively. Thus they should be directly fed from the $1/2^+$ compound state. However, the energy difference of the two levels

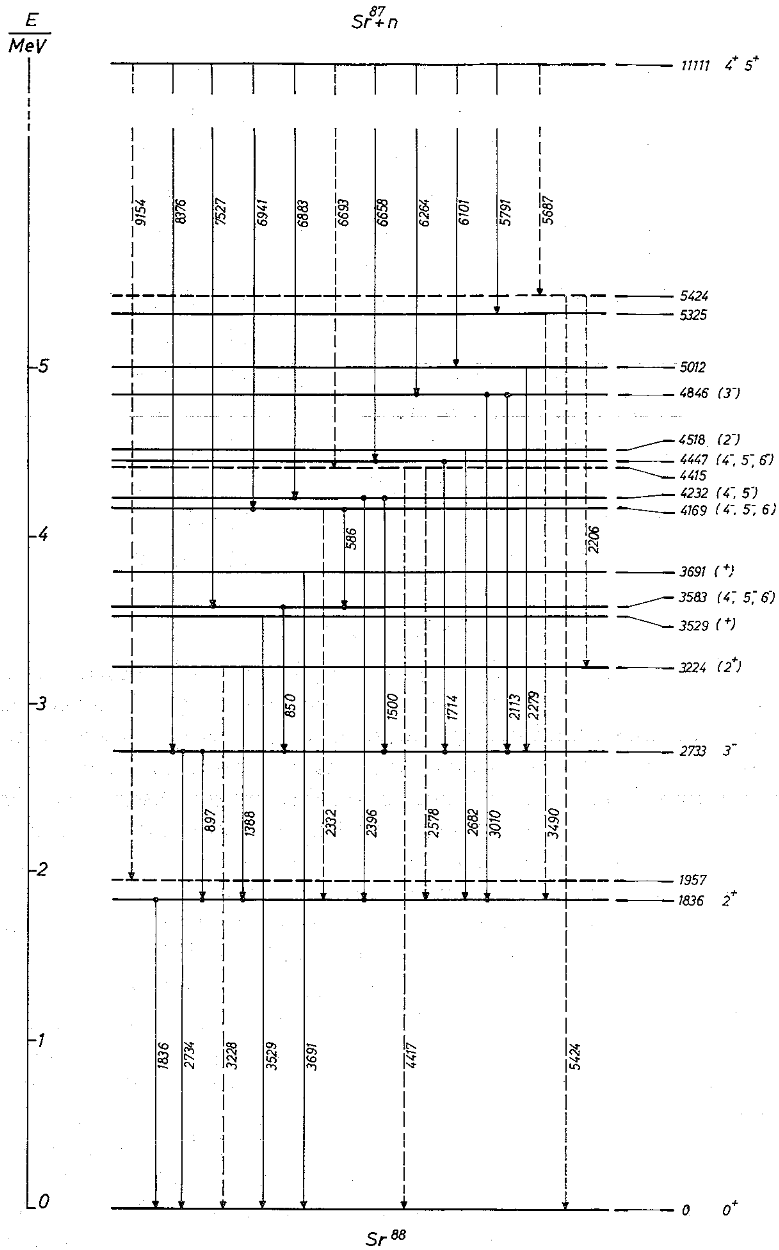


Fig. 7. Level scheme of Sr^{88}. Energies are given in keV. Dots represent coincidence relations well established by coincidence measurements. Cascade relationships of gamma rays represented by dashed lines are mainly based on energy considerations and have to be considered as tentative. Spin and parity assignments for the high-energy states are based on the assumption of $E1$ multipolarity for the most intense primary transitions from the capture state

Table 4. *Energy Levels Identified in* Sr^{88}

LAZAR et al. [a] ref. 1 [MeV]	HAMBURGER [b] ref. 6 [MeV]	SHASTRY et al. [c] ref. 2 [MeV]	This work [d] [keV]
1.85	1.835 (calib.)	1.86	1836 ± 1
			(1957 ± 15)
2.76	2.74 ± 0.015	2.76	2733 ± 2
3.24	3.20 ± 0.05	3.22	3224 ± 5
3.52		3.52	3529 ± 6
			3583 ± 2
3.65	3.61 ± 0.025		3691 ± 6
	4.02 ± 0.025		
			4169 ± 3
	4.27 ± 0.03		4232 ± 3
			(4415 ± 6)
			4447 ± 4
4.53			4518 ± 5
4.87			4846 ± 3
			5012 ± 5
			5325 ± 5
			(5424 ± 5)

a) From β^- decay of Rb^{88}.
b) From Sr(d, d').
c) From electron capture and β^+ decay of Y^{88}.
d) From Sr(n, γ). Errors estimated. Parentheses indicate less certain levels.

(484 ± 1.5 keV, cf. Table 1) considerably deviates from the energy difference of the afore-mentioned gamma rays (511 ± 10 keV) and is well outside experimental errors. Moreover, if the 7527 keV transition is assigned to Sr^{87} the 11.9% cross section contribution of Sr^{86} makes it unusually more intense than any other gamma ray in the spectrum of Sr^{87}. In addition, de-excitation of the $3/2^-$ level to the $9/2^+$ ground state being highly retarded the 484 keV gamma ray seems to be not strong enough to account for the intense 7527 keV radiation. A gamma ray which may correspond to the relevant transition in Sr^{87} could not be unambiguously identified in the singles spectra. In any case this transition is much less intense than that at 8038 keV.

KINSEY and BARTHOLOMEW found some evidence for two weak gamma rays at 9.06 MeV and 9.22 MeV. If photons in this energy range exist, they clearly arise from excitation of Sr^{88}, since their energy is higher than the neutron binding energy for the other strontium isotopes. In the relevant spectrum taken with the germanium detector (Fig. 2e) several peaks appear. Most of them, however, have to be interpreted as full-energy or single-escape peaks of lower-energy transitions. The only line which cannot be explained in this way corresponds to a gamma-ray energy of 9154 keV. No evidence is found for photons at 9.06 MeV or 9.22 MeV. As statistics remains poor with the germanium diode the existence of a weak 9154 keV radiation has to be confirmed by other methods. Fig. 8 shows the capture spectrum observed with good statistics by means of a NaI(Tl)-detector. The occurrence of photons above 9 MeV is clearly demonstrated. The same result was obtained using a 5-crystal

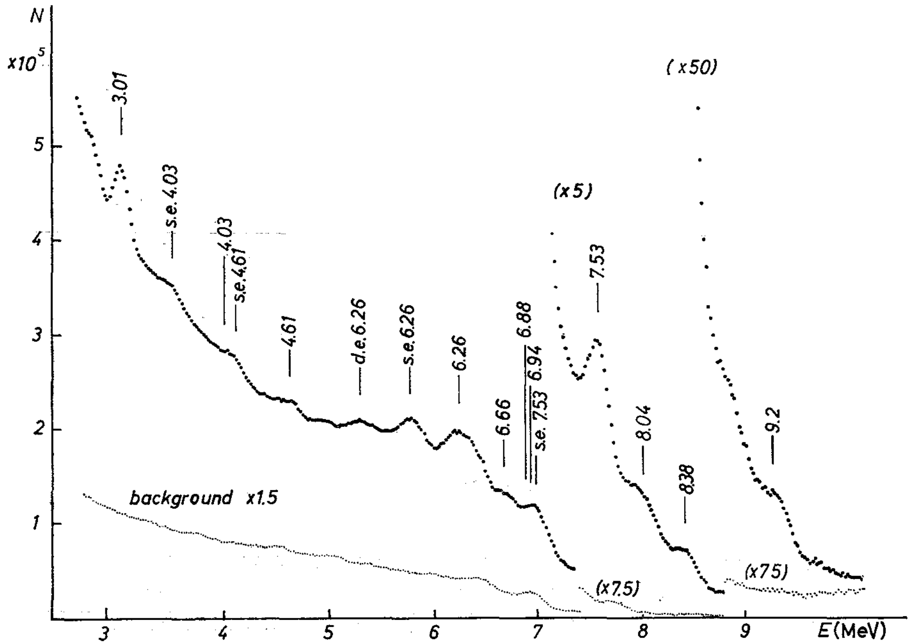


Fig. 8. High-energy portion of Sr(*n*, *γ*) singles spectrum taken with a NaI(Tl) detector

pair spectrometer. The possibility of spectrum contamination by chemical impurities was carefully checked and can be ruled out very probably. Thus the present results point to the existence of a 9154 keV transition in Sr^{88}. This would necessitate placing a level at 1957 keV. With respect to the de-excitation of such a state the hitherto existing data don't permit any statement. Thus the results are not yet conclusive. The possible occurrence of a level at about 2 MeV as following from experimental Y^{88} positron end-point energies and spectral shapes has already been discussed by SHAFROTH[18]. A search for such a state by this author was unsuccessful.

Taking into account the results of previous investigations the gamma rays at 3228, 3529 and 3691 keV may be interpreted as ground-state transitions. The feeding of the corresponding levels is still unknown.

[18] SHAFROTH, S. M.: Nuclear Phys. **28**, 649 (1961).

Obviously, the transitions at 1388, 2113, 2682 and 3010 keV in Fig. 7 have to be identified with those at 1.39, 2.11, 2.68 and 3.01 MeV observed by other authors in the decay of Rb^{88}.

Spin and parity 2^+ and 3^- for the levels at 1836 keV and 2733 keV are well established from decay studies by gamma-gamma angular correlation experiments[3], conversion coefficient measurements[4] and polarization-direction correlations[3]. A recently performed investigation of the 1.39 MeV – 1.84 MeV angular correlation[2] suggests that the level at 3224 keV has spin and parity 2^+. The even parity assignments for the states at 3529 keV and 3691 keV were adopted from ref. [1]. They are based on the comparative half-lives of the corresponding beta transitions from Rb^{88}.

Assuming that the most intense high energy transitions from the capture state have multipolarity $E1$ the levels at 3583, 4169, 4232, 4447 and 4846 keV have to be assigned odd parity and the spin values are 3, 4, 5 or 6. The assignment 3^- for the 3583, 4169, 4232 and 4447 keV states can probably be ruled out. If the spin were, in fact, 3^-, then allowed beta transitions to these levels would have been observed in the decay of 2^- Rb^{88}. The branching of the gamma rays leaving the levels is not in contrast to our conclusion. A spin value of 6^- for the state at 4232 keV seems to be unreasonable since a transition to the 1836 keV 2^+ level appears with marked intensity. The comparative half-life for the Rb^{88} beta-ray group to the state at 4846 keV is as expected for an allowed transition[1]. This is consistent with an odd parity assignment. The spin should then be 1^-, 2^- or 3^-. The strong feeding from the neutron capture state very probably rules out the values 1^- and 2^-. So this state almost certainly has spin 3^-. The $\log ft$ value for the beta group reaching the level at 4518 keV indicates that this transition is allowed, too. The failure to observe a direct feeding in the (n, γ)-reaction suggests the spin assignments 1^- or 2^-. As no ground state transition was found both in decay studies and in the present investigation, the assignment 2^- may be made to the 4518 keV level.

Systematics make probable the 1836 keV 2^+ and 2733 keV 3^- levels to be vibrational states corresponding to the one-phonon quadrupole and octupole excitation, respectively. The collective nature of these states is disclosed by the large excitation cross sections observed in inelastic scattering reactions. The branching of transitions leaving the 2733 keV state is easily understood from this interpretation. The $E1$ 897 keV gamma ray is retarded whereas the $E3$ transition to the ground state should be enhanced.

Most of the higher-energy levels are expected to be due to intrinsic particle-hole excitations. Sr^{88} has 50 neutrons, i.e. a closed neutron shell, and the states available for the 29th through 50th protons are

$f_{\frac{5}{2}}$, $p_{\frac{3}{2}}$, $p_{\frac{1}{2}}$ and $g_{\frac{9}{2}}$. It is reasonable to assume that the last 10 protons in the ground state can be assigned as $(f_{\frac{5}{2}})^6\,(p_{\frac{3}{2}})^4$. Excited levels with even parity result from particle-hole coupling of the configurations $(p_{\frac{3}{2}})^3\,(p_{\frac{1}{2}})^1$ (revealing 1^+, 2^+) and, at somewhat higher energies, $(f_{\frac{5}{2}})^5\,(p_{\frac{1}{2}})^1$ (2^+, 3^+). Possibly, at least some of the experimental even parity states in the region from 3 to 4 MeV may be attributed to these excitations. In addition to the shell model states collective two-phonon quadrupole vibrations (with spins 0^+, 2^+ and 4^+) should occur in this energy range. Above the even parity states levels with odd parity are expected from exciting one of the $p_{\frac{3}{2}}$ or $f_{\frac{5}{2}}$ protons into the $g_{\frac{9}{2}}$ orbital. The resulting coupling reveals levels with spins 3^- through 6^- and 2^- through 7^-, respectively. If the assumption of $E1$ multipolarity for the observed intense primary transitions from the capture state is valid, the corresponding odd parity states may be due to these configurations.

More definite assignments as to the nature of the levels above 3 MeV require further experimental information. Additional experiments using refined techniques and including angular correlation studies, therefore, are in progress.

4.2. Binding Energy. The values of the binding energy of Sr^{88} reported so far are[9]

$$E_B = (11140 \pm 50)\ \text{keV}$$

$$E_B = (10830 \pm 110)\ \text{keV}$$

$$E_B = (11150 \pm 200)\ \text{keV}$$

and

$$E_B = (10900 \pm 200)\ \text{keV}.$$

The present investigation suggests

$$E_B = (11111 \pm 4)\ \text{keV}.$$