correctness of Kotajima's[2] work and conclusions which were based on the $Sm^{144}(\gamma,n)Sm^{143}$ reaction and on shell model considerations. No reason appears immediately evident for the difference between these results and those of James[1] whose work was based on the reaction of 20.6-MeV protons with samarium oxide enriched in Sm^{144}.

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Levels in Y^{89} Excited by the $Y^{89}(n,n'\gamma)$ Reaction*

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Gamma-ray spectra from the $Y^{89}(n,n'\gamma)$ reaction have been studied using a ring geometry for fifteen $Li^7(p,n)$ neutron energies ranging from 0.78 to 3.36 MeV. Ground-state gamma-ray transitions arising from levels in Y^{89} at 0.908±0.003, 1.506±0.005, 1.745±0.006, 2.84±0.02, and 3.05±0.03 MeV, as well as cascade gamma rays of 0.71±0.01, 1.31±0.01, and 1.62±0.01 MeV arising from levels in Y^{89} at 2.22±0.01 and 2.53±0.01 MeV, have been observed. Spin and parity assignments of $3/2^-$ and $5/2^-$ have been made for the 1.51- and 1.75-MeV levels, primarily as a result of comparisons of ratios of experimental cross sections for these two levels with theory. Tentative assignments are made for higher levels. Theoretical level excitation cross-section calculations for various values of spin and parity are done with a computer using the Hauser-Feshbach method and optical-model transmission coefficients obtained from various theories. The 1.75-MeV gamma-ray angular distribution was calculated using Satchler's theory and the corresponding level excitation cross section was corrected accordingly.

A new level scheme is presented for Y^{89} which takes into account all known data up to the present time. It is suggested that some of the levels excited in the present work may be due in part at least to coupling of a $p_{1/2}$ proton to the 2^+, 3^-, and (2^+) excited levels of a Sr^{88} core.

I. INTRODUCTION

As the theory of nuclear level structure becomes increasingly refined, more precise and extensive knowledge concerning individual nuclei becomes necessary. Level structures of nuclei in the 50-neutron region have been the subject of several recent theoretical investigations.[1–3] In one of these,[1] the positions of three levels in Y^{89} having various spins and parities were calculated and the $g_{9/2}-p_{1/2}$ splitting was predicted very accurately. Studies of beta-decay energy systematics[4] have led to the suggestion of a new $9/2^+$ level in Y^{89}. Recently, de-Shalit[5] has suggested that in certain cases levels of odd nuclei may be formed by coupling the odd nucleon to excited states of the even core. The Y^{89} nucleus with one $p_{1/2}$ proton outside the 38-proton shell and a strongly closed 50-neutron shell might be such a nucleus. Some examples of isomerism involving very high spin levels such as the $21/2^+$ level[6,7] in Mo^{93} find simple explanations on the basis of the core excitation model.

Most of the knowledge up to 1960 concerning the level structure of Y^{89} has been compiled by the Nuclear Data Group.[6,8] Only three levels in Y^{89} are known to be fed by radioactive decay.[6–9] An investigation of the $Y^{89}(p,p')$ reaction, which was done by Cohen and Rubin[10] as part of a survey of about 35 nuclei, revealed the presence of five proton groups which were thought to correspond to five or more additional levels in Y^{89}. A similar study of the $Y^{89}(d,d')$ reaction by Cohen and Price[11] revealed deuteron groups corresponding to the five proton groups and two more deuteron groups which roughly corresponded to levels in Y^{89} which had already been established.[6,8] However, the excitation energies in Y^{89} corresponding to the proton and deuteron groups differed from energies of levels in Y^{89} reported from radioactivity studies and $(n,n'\gamma)$ studies by up to 100 keV.

With the exception of the early work of Swann and Metzger[12] concerning the excitation curve for produc-

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tion of Y^{89m}, and two time-of-flight investigations[13,14] of the $Y^{89}(n,n')$ reaction, where only neutron groups to the 0.91- and 1.51-MeV levels were observed, no neutron work has been published which relates to the Y^{89} level structure. The results of two previous investigations of the $Y^{89}(n,n'\gamma)$ reaction are unpublished. Bostrom *et al.*[15] measured differential production cross sections at $\bar{\theta}=67°$ for gamma rays of energies 0.915 ± 0.007, 1.50 ± 0.02, 1.74 ± 0.01, 2.01 ± 0.03, 2.86 ± 0.04, and 3.09 ± 0.02 MeV for four incident neutron energies ranging from 3.46 to 4.59 MeV. Rothman *et al.*[16] observed the yield of the 0.91-MeV gamma ray at $\bar{\theta}=90°$ from threshold to 1.97 MeV in steps of 50 keV, as well as the thresholds for production of gamma rays of 1.53 and 1.78 MeV, which correspond to ground-state transitions. The measurement of the excitation curve for the production of the 0.91-MeV isomeric transition by Swann and Metzger[12] had shown a sharp break at $E_n=1.2$ MeV which was attributed to the presence of a level at about this energy which decays at least partially to the 0.91-MeV metastable state. Rothman *et al.* searched for such a low-energy gamma-ray transition in the region of 0.30 MeV. Because the usual method of background subtraction using a graphite scatterer proved to be difficult, they measured the effect of interposing a $\frac{1}{4}$-in. Mallory metal absorber between the Y^{89} scatterer and the NaI detector. Using the same method for a Nb^{93} scatterer revealed a known 0.335-MeV cascade gamma ray.[17] However, in the case of Y^{89}, no low-energy gamma ray in the region of $E_\gamma=0.2$ to 0.4 was observed at $E_n=1.97$ MeV with an intensity greater than 0.10 of the yield of 0.915-MeV radiation, since the low-energy gamma-ray spectrum was essentially unchanged when the incident neutron energy was increased from 1.07 to 1.97 MeV. This result limits the possible branching of the 1.78-MeV level to the 1.53-MeV level to <0.07 of the ground-state transition. The structure reported by Swann and Metzger in the excitation curve for 0.91-MeV radiation remains unexplained.

The $(n,n'\gamma)$ reaction, which has been used in this laboratory to study the structures of a number of nuclei in the medium weight region[17–19] and by Van Patter *et al.*[20] (henceforth referred to as VNSMR), is an excellent tool for this purpose. In addition to revealing new levels, $(n,n'\gamma)$ reaction studies give information on the spins and parities of excited levels; through gamma-ray branching ratio measurements; by comparison of experimental level excitation cross sections with calculated cross sections using reaction theory; and by gamma-ray angular distribution measurements. Conversely, if the spins and parities of the excited levels are known, the reaction data can be used to test the theory. Y^{89} is well suited to study by the $(n,n'\gamma)$ reaction, since it is monoisotopic and can be readily obtained in kilogram quantities. It has the additional advantage that for the most part its levels seem to be widely spaced so that the $(n,n'\gamma)$ gamma rays can be resolved. Furthermore, it has a low-spin ground state $(1/2^-)$ and a high-spin first excited state $(9/2^+)$, so that high-spin levels tend to decay to the first excited state and low-spin levels to the ground state.

For these reasons, and also because the previously mentioned $(n,n'\gamma)$ work left a gap between $E_n=1.8$ and 3.46 MeV, the present investigation covering the range of neutron energies from 0.78 to 3.36 MeV was undertaken. A preliminary report of this work has been given.[21]

II. EXPERIMENTAL PROCEDURE

A disk of $>99\%$ pure yttrium metal of density 5.52 g/cm^3 was machined into the shape of a ring. The mass of the ring was 607 g and its dimensions were 11 cm o.d.$\times$6 cm i.d.$\times$2 cm thick. A pure iron ring of the same dimensions, whose mass was 1048 g and whose density was 7.80 g/cm^3, was also used in the experiment. These rings became sources of gamma radiation when bombarded with fast neutrons mostly because of the $(n,n'\gamma)$ reaction. By comparing the yield of $Y^{89}(n,n')$ gamma radiation at any incident neutron energy, with the known yield of the 0.845-MeV $Fe^{56}(n,n')$ gamma ray at $E_n=2.56$ MeV,[22,23] it was possible to obtain cross sections for production of the $Y^{89}(n,n')$ gamma rays.

Gamma rays were detected by means of a 35-mm diameter by 40 mm long NaI(Tl) crystal optically coupled to a Dumont 6292 photomultiplier tube. Pulses from it were fed to the amplifier of an RIDL 400 channel analyzer, and then analyzed with respect to amplitude. The scintillation counter was shielded from the direct neutron beam by means of a shadow cone consisting of lead and iron as shown in Fig. 1. This proved to be slightly better than a pure lead shadow cone of the same dimensions.

The neutrons which bombarded the yttrium ring were produced by proton bombardment of lithium. The Bartol-ONR Van de Graaff Generator supplied a

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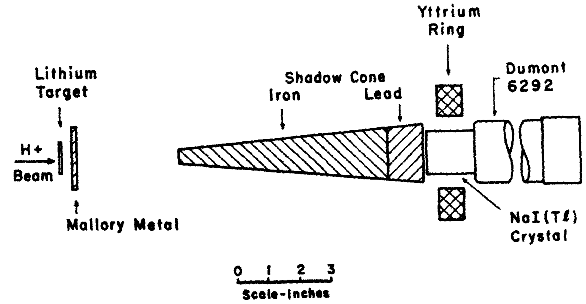

FIG. 1. Experimental arrangement. The lithium target is evaporated *in situ* on to a tantalum-lined copper sheet which is cooled by liquid nitrogen. The Mallory Metal reduces the target x and gamma radiation scattered into the NaI(Tl) crystal.

beam of protons of 1 to 2 μA whose energy varied from 2.52 to 5.06 MeV, providing neutrons at a mean incident angle of 7.7° on the scattering ring with energies of from 0.78 to 3.36 MeV. The lithium targets were 70 keV thick to 1.88-MeV protons. The major source of neutron energy spread at the ring was the lithium target thickness which ranged from 58 keV at the lowest neutron energy to 33 keV at the highest neutron energy. The neutron flux at the ring was monitored by a conventional long counter placed at 90° to the incident proton beam with its front face 1 m from the lithium target.

The data-taking procedure for the gamma-ray production cross-section measurements (which were done in steps of approximately 0.20 MeV) was as follows. The gamma-ray spectrum was accumulated for 10^6 or more neutron monitor counts with the yttrium ring in place. The neutron flux was adjusted so as to keep the analyzer dead time at about 20% and as nearly constant as possible. After sufficient statistics had been obtained in the gamma-ray spectrum, the run was stopped, and the duration of the run (clock time), as well as the analyzer live time, were recorded. A hollow Lucite ring containing 128 g of powdered graphite was then substituted for the yttrium ring. The amount of graphite was chosen to give the best background subtraction at $E_n=2.18$ MeV. The analyzer was set in the subtract mode, and this ring was bombarded with neutrons for a live time which was as nearly equal to the live time of the previous run as possible so as to obtain the best subtraction of the 25-min $I^{128}(\beta^-)$ activity. The approximate number of neutron monitor counts desired was determined by multiplying the original number of neutron monitor counts by the ratio of the percent live time in the original run to the percent live time in the background run. This procedure did not always yield a satisfactory background subtraction and the exact neutron flux required for the background run was determined by observing the spectrum on the analyzer during the process of subtraction, and judging when the subtraction appeared to be correct. In the runs at neutron energies above $E_n=1.97$ MeV, the most frequently used criterion was that no peak should be left at 0.63 MeV since this is known to be due to the $I^{127}(n,n'\gamma)$ reaction. At $E_n=1.97$ MeV and lower, this criterion could not be used because oversubtractions would occur for the higher energy Y^{89} gamma rays. Therefore, the most frequently used criterion for stopping the background run was that the 0.908-MeV gamma-ray valley at 0.82 MeV should not be so deep as to make it impossible to fit the residual spectrum with the known shape curve for the 0.908-MeV gamma ray. Deviations between the actual and the calculated number of neutron monitor counts required for the background subtraction introduced by these criteria for stopping the background runs were less than 2.5% for $E_n>1.4$ MeV.

In some cases it was necessary to compensate for different amounts of 25-min iodine activity in the run with the yttrium ring present and the background subtraction run. This was done by adding to the residual spectrum the iodine activity spectrum for a few minutes. The estimated errors in the gamma-ray

TABLE I. Gamma-ray energies and levels of origin in MeV and gamma-ray production differential cross sections for Y^{89} in millibarns/steradian at $\bar{\theta}=98°$.

$\bar{E}_n$ (MeV) \ E_{level} / E_γ				2.22±0.01		2.53±0.01		
	0.908±0.003	1.506±0.005	1.745±0.006[a]	0.71±0.01	1.31±0.01	1.62±0.01	2.84±0.02	3.05±0.03
0.98	2.4±0.4							
1.18	6.0±0.7							
1.37	11 ±1							
1.46	13 ±1							
1.57	13 ±1	10±1						
1.77	15 ±2	41±6	2.6±0.2					
1.97	14 ±2	44±7	22 ±2					
2.18	15 ±2	43±7	33 ±3					
2.38	19 ±2	42±4	35 ±3	2±1	4±2			
2.57	23 ±3	47±5	38 ±3	4±2	8±2			
2.77	26 ±3	44±5	37 ±3	3±2	10±3	5±2		
2.97	30 ±3	41±4	37 ±3	3±2	8±2	10±2	1.3±0.6	
3.16	31 ±3	36±4	34 ±3	3±2	9±2	6±2	10 ±3	2±1
3.36	33 ±3	40±4	30 ±3	4±2	8±2	8±2	8 ±1	20±2

[a] These cross sections must be multiplied by 0.93 to obtain production differential cross sections at 98° due to the nonisotropic angular distribution of the 1.75-MeV gamma ray.

photopeak area determinations introduced by these procedures range typically from 2% for strongly excited gamma rays to 8% for the 0.908-MeV gamma ray and 16% for the weak 1.31-MeV gamma ray.

III. RESULTS

(1) Gamma-Ray Spectra

Eight $Y^{89}(n,n')$ gamma rays observed in the present work are listed and classified with respect to level of origin in Table I. Five of these have been observed in previous $(n,n'\gamma)$ investigations.[15,16] Three of the weaker gamma rays have not been previously reported, although they originate from levels in Y^{89} which roughly correspond to proton and deuteron groups observed in the $Y^{89}(p,p')$ and $Y^{89}(d,d')$ reaction studies of Cohen and Rubin[10] and Cohen and Price.[11]

No attempt was made to search for gamma rays of energy less than 0.5 MeV, since the work of Rothman *et al.*[16] showed that no observable low-energy gamma radiation was present up to $E_n=1.97$ MeV (Introduction) and since the ring geometry of this investigation was not favorable for studying such radiation.

No evidence was found for a 0.59-MeV gamma ray such as should have been present if the $9/2^+$ state at 1.50 ± 0.03 MeV postulated by Everling[4] were present. (See Sec. IV, 3.)

No evidence was found for a (2.01 ± 0.03)-MeV gamma ray with a threshold at that energy such as would arise if the 2.01-MeV gamma ray observed by Bostrom *et al.*[15] at $E_n \geqslant 3.46$ MeV were a ground-state transition. Typically the intensity of such a gamma ray is less than 0.014 the intensity of the 1.75-MeV gamma ray for $E_n=2.38$ MeV. Thus there is no evidence for the level in Y^{89} at 2.01 ± 0.03 MeV which has appeared in several recent level schemes.[6–8]

Some evidence was found for the existence of a 1.70-MeV gamma ray for $E_n \geqslant 2.6$ MeV (see below). A gamma ray observed in this investigation whose average energy was 0.50 ± 0.01 for $E_n \leqslant 2.97$ MeV remains unexplained (see below).

A typical gamma-ray spectrum resulting from $Y^{89}(n,n'\gamma)$ is shown in Fig. 2. The original spectrum consisting of $Y^{89}(n,n'\gamma)$ and background and the background spectrum are also shown. At this neutron bombarding energy ($E_n=3.36$ MeV), and in the 98° geometry, the number of background counts per channel is of the same order of magnitude as the number of $Y^{89}(n,n'\gamma)$ counts. Many peaks are observed in the background spectrum. Those at 0.63 and 0.74 MeV are due to the $I^{127}(n,n'\gamma)$ reaction in the crystal. The peaks at 0.84, 1.01, 1.74, 2.16, 2.21, and 3.0 MeV are due to the $Al^{27}(n,n'\gamma)$ reaction arising from the aluminum light shield containing the NaI(Tl) crystal, which was insufficiently shielded from the neutron source. The other peaks are not identified as to source. The presence of all of these peaks contributed to un-

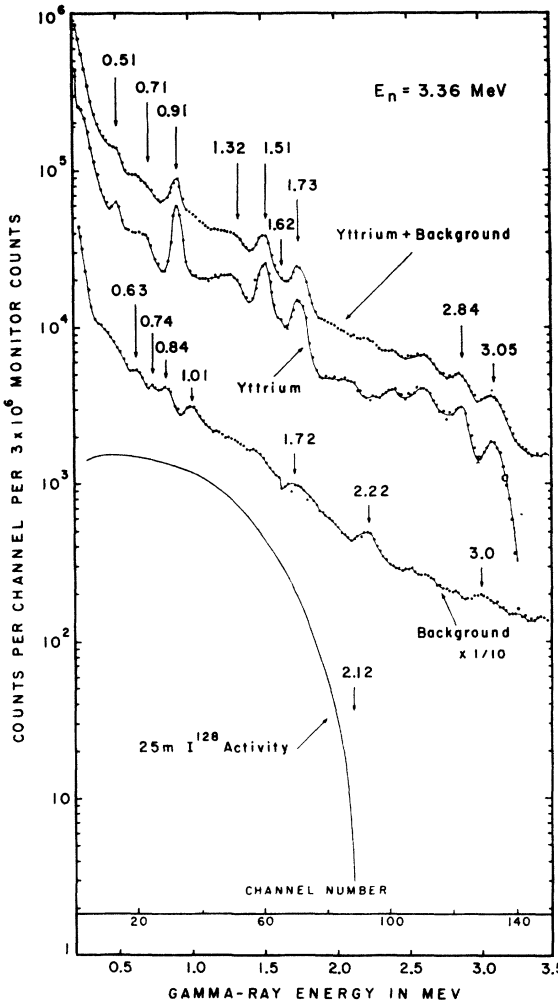

FIG. 2. Gamma-ray spectra for $E_n=3.36$ MeV. Upper curve: Spectrum obtained with the yttrium ring in place for 3×10^6 neutron monitor counts without background subtraction. The spectrum labeled background was obtained by replacing the yttrium ring with a hollow Lucite ring containing 128 g of powdered graphite and bombarding it with an equivalent number of neutrons. The amount of graphite was chosen so as to produce a spectrum which approximates as nearly as possible the true background when the yttrium ring is present. The spectrum labeled yttrium was obtained by subtracting the background spectrum from the yttrium spectrum. Lowest curve: spectrum of induced radioactivity in the 35-mm diam×40 mm long NaI(Tl) crystal due to neutron bombardment. The ordinate scale is arbitrary for this curve.

certainty in the analysis, but fortunately they are quite effectively removed in the background subtraction process. A further source of difficulty, as mentioned previously, is the 25-min activity which builds up in the crystal due to $I^{127}(n,\gamma)I^{128}(\beta^-)$ Xe^{128}. The beta spectrum after the neutron beam is turned off is shown at the bottom of Fig. 2.

The gamma-ray spectra after background subtraction were analyzed to find the energies and intensities of the remaining gamma rays. The method of analysis has been described in VNSMR. The analysis for the most

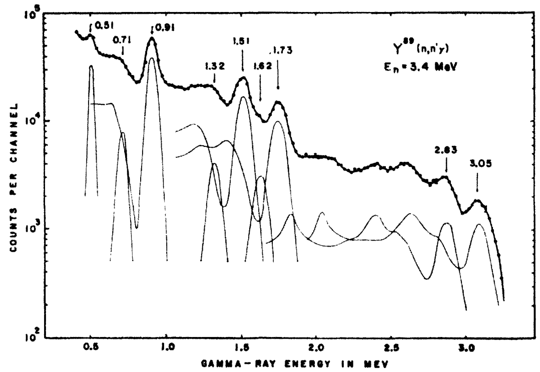

FIG. 3. Gamma-ray spectrum after background subtraction for $E_n = 3.36$ MeV. The decomposition of the spectrum is shown.

complicated spectrum obtained in this experiment is shown in Fig. 3.

The following procedure was used to determine the energies of the gamma rays listed in Table I. First the energies of the three gamma-ray transitions in Y^{89} arising from the decay of 79-h Zr^{89} and 4.3-min Zr^{89m} were determined. These gamma rays were observed with a 3-in.×3-in. NaI(Tl) crystal scintillation counter under essentially background free and closely reproducible counting rate conditions. Since positrons are emitted in the decay of Zr^{89} and Zr^{89m}, a peak due to annihilation radiation is always present in their respective gamma-ray spectra. The Zr^{89} spectra showed peaks due to the well-known gamma ray whose energy has been taken as 915±7 keV,[6–8] and to the newly discovered gamma ray whose energy has been reported as 1.75±0.02 MeV.[9] The energy of the former gamma ray was found to be 908±3 keV by superimposing a Co^{60} spectrum on the Zr^{89} spectrum and using the annihilation (0.51094 MeV)[24] and the highest energy Co^{60} gamma ray (1.3325 MeV)[24] as calibration points. The energy of the latter gamma ray was then found to be 1703±9 keV on the basis of internal calibrations of Zr^{89} gamma-ray spectra. The energy of the Y^{89} gamma ray arising from the decay of 4.3-min Zr^{89m} was determined to be 1506±5 keV by superimposing spectra from various combinations of Zr^{89m} and Co^{60}, Y^{88} ($E_\gamma = 1837$ keV)[25] and Na^{22}(1.2736 MeV).[24]

Finally, each $(n,n'\gamma)$ spectrum which had been recorded with the apparatus of Fig. 1 was self-calibrated using three points: the channel corresponding to zero energy (which was determined before the $(n,n'\gamma)$ run with standard sources and which was found to be quite independent of counting rate), and the channels corresponding to the 908- and 1506-keV gamma-ray peaks. This calibration method is more accurate than the one which was used to obtain the gamma-ray energies listed in a preliminary report of this work,[21] where the $(n,n'\gamma)$ spectra were self-calibrated using the zero-energy point as above and assuming that the energy of the isomeric transition was 915 keV.[6–8]

The energies of all of the $Y^{89}(n,n')$ gamma rays known to be excited at each neutron bombarding energy (Fig. 4) were determined using the three previously mentioned calibration points. Gamma-ray energies listed in Table I were obtained by averaging over all reliable data for each gamma ray. The errors in the gamma-ray energies listed in Table I were determined by including effects due to possible small nonlinearities (<0.5% of full scale) and errors in the energies of the calibration gamma rays. However, in most cases the final errors are primarily determined by uncertainties in the peak positions of the various gamma rays in a given spectrum.

An exception to the procedure of averaging over all data to determine a gamma-ray energy occurred in the case of the 1.745-MeV gamma ray. There, only data up to $E_n = 2.58$ MeV were used, since there is a state in Y^{89} at 2.61 MeV which decays by a 1.70-MeV gamma ray. In fact, above $E_n = 2.58$ MeV the average energy corresponding to the observed peak is 1.734 rather than 1.745 MeV, while the reproducibility in these values was better than ±2 keV. This is interpreted as indicating that the state at 2.61 MeV is being excited at the higher neutron bombarding energies.

The assignment of observed gamma rays to levels in Y^{89} was based on their production thresholds and on their energies. In the case of the gamma rays going directly to the ground state, i.e., 0.908, 1.51, 1.75, 2.84, and 3.05 MeV, the assignments were obvious. However, in the case of the weak cascade gamma rays at 0.71, 1.32, and 1.62 MeV, the assignments require further discussion. The origin of the 1.62-MeV gamma ray is quite certain since it has the correct threshold and energy to originate from the 2.53-MeV state. Similarly, the 1.32-MeV gamma ray has the correct production threshold and energy to originate from the 2.22-MeV state at lower neutron bombarding energies. However, at the highest bombarding energy, when the 2.84- and 3.05-MeV states are excited, there might be 1.32-MeV cascade radiation from these states to the 1.51- and 1.75-MeV states, which would contribute to the 1.32-MeV peak.

The 0.71-MeV gamma ray is due to a transition from the 2.22-MeV state to the 1.51-MeV state. Its yield has been corrected for a possible underestimate of the effect of the two-escape peak from the 1.75-MeV gamma ray. This correction amounted to 4% of the area of the 1.75-MeV photopeak.

The peak in the gamma-ray spectra at 0.50 MeV seems to appear suddently at $E_n = 1.37$ MeV, but its origin is not understood. In some spectra its width suggests that it is made up of more than one gamma ray. It might possibly be due to a state in Y^{89} at 1.41 MeV, but this seems unlikely because it is relatively too

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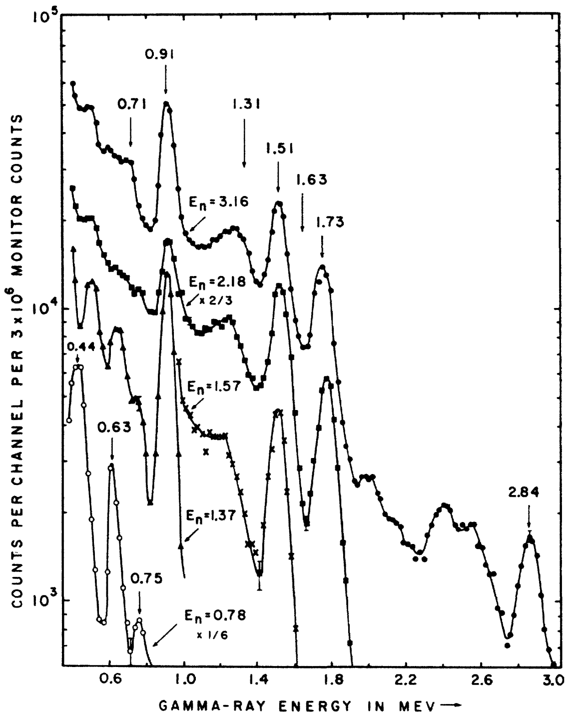

FIG. 4. Gamma-ray spectra from Y^{89} after background subtraction at various neutron bombarding energies (lab). All spectra are for 3×10^6 neutron monitor counts. Two curves have been displaced for clarity of presentation. The gamma rays whose energies are given at the top of the figure are due to the $Y^{89}(n,n'\gamma)$ reaction ($E_n=3.16$ MeV) with the possible exception of the 0.51-MeV gamma ray (see text). The gamma rays of 0.63 and 0.74 MeV shown in the lowest spectrum ($E_n=0.78$ MeV) are due to the $I^{127}(n,n'\gamma)$ reaction in the NaI(Tl) scintillation crystal, since the bombarding energy is too low to excite states in Y^{89}.

intense near threshold. Some of its intensity is probably due to annihilation radiation. At $E_n\gtrsim1.52$ MeV, some of its intensity is due to the two-escape peak of the 1.51-MeV gamma ray. At higher neutron bombarding energies, it may be due partly to an 0.48-MeV transition between states at 2.22 and 1.75 MeV. Its average production cross section is only about 0.01 b, if it is a $Y^{89}(n,n')$ gamma ray.

(2) Experimental Cross Sections

The method of extracting gamma-ray production cross sections at various neutron bombarding energies by comparison with the 0.845-MeV gamma-ray production cross section for Fe^{56} at $E_n=2.56$ MeV was almost exactly the same as the one described in VNSMR, and, therefore, will not be repeated here except where there are differences. The iron comparison ring was machined to the same dimensions as the yttrium ring. When runs were done at $E_n=2.56$ MeV with the iron ring, it was placed in the position which was occupied by the yttrium ring. Thus, Eq. (1) of VNSMR reduces to

$$\left(\frac{d\sigma}{d\omega}\right)_{\bar{\theta}}=GN_pc/\epsilon_pK_0, \qquad (1)$$

where G is a numerical constant for this investigation which depends on the value of the Fe^{56} 0.845-MeV gamma-ray production cross section at $E_n=2.56$ MeV (averaged over the finite geometry shown in Fig. 1), the mass ratio of the two rings, the photopeak efficiency and area for the 0.845-MeV gamma ray, the transmission of the iron ring for 0.845-MeV gamma radiation, the neutron correction factor, the ratio of the atomic weights of yttrium and iron, and the abundance of the Fe^{56} isotope; N_p is the number of counts in the photopeak per 10^6 neutron monitor counts for the relevant gamma ray; ϵ_p is the photopeak efficiency; c is the correction factor to the neutron flux incident on the ring; $K_0=\int_{r_1}^{r_2}\exp[-\mu^*(r-r_1)]dr/r$, and is proportional to the gamma-ray transmission factor for a two-dimensional ring; r refers to the ring radius; and μ^* is the gamma-ray absorption coefficient of the ring corrected for small-angle Compton scattering which does not reduce the gamma-ray energy enough necessarily to remove it from the photopeak. Using Eq. (1), the gamma-ray production cross sections listed in Table I were obtained.

In order to obtain the level excitation cross sections given in Table II, the gamma-ray production cross sections were corrected for cascades from higher levels and simply multiplied by 4π in every case but one. This procedure was justified for the 0.91-MeV gamma ray which arises from a state with a 16-sec half-life. It was also shown to be reasonable for the 1.51-MeV gamma ray since a preliminary analysis of experimental angular distribution data, obtained at $E_n=2.18$ and 2.57 MeV, indicated approximate isotropy for the 1.51-MeV gamma ray. However, the data indicated that a substantial correction to the cross section would be necessary for the 1.75-MeV gamma ray. Lacking precise knowledge of the angular distribution of this gamma ray at each bombarding energy, it was decided to calculate the expected angular distribution for several energies, using Satchler's theory[26] and the transmission coefficients of Beyster *et al.*[27] The 1.75-MeV gamma ray was assumed to be due to a $\frac{5}{2}^-(E2)\frac{1}{2}^-$ transition for these calculations. These calculations showed that the gamma ray yield is a minimum at 90° with respect to the incident neutron beam (as is characteristic for $E2$ radiation) and gave reasonable agreement with the preliminary analysis. As a result of averaging the angular distribution over the finite geometry, it was found that the 1.75-MeV level excitation cross sections should be

[26] G. R. Satchler, Phys. Rev. **104**, 1198 (1956); **111**, 1947(E) (1958).

[27] J. R. Beyster, R. G. Schrandt, M. Walt, and E. Salmi, Los Alamos Scientific Laboratory Report LA-2099, 1957 (unpublished).

TABLE II. Inelastic neutron cross sections in barns for levels of Y^{89}.

$\bar{E}_n$ (MeV)	0.908	1.51	1.75[a]	Y^{89} level (MeV) 2.22	2.53	2.84	3.05	Total inelastic cross section
0.98	0.030±0.01							0.03±0.01
1.18	0.08±0.01							0.08±0.01
1.37	0.14±0.02							0.14±0.02
1.46	0.16±0.02							0.16±0.02
1.57	0.17±0.02	0.12±0.02						0.29±0.03
1.77	0.18±0.02	0.52±0.07	0.04±0.01					0.74±0.08
1.97	0.17±0.03	0.55±0.08	0.33±0.04					1.1 ±0.1
2.18	0.19±0.03	0.53±0.08	0.49±0.05					1.2 ±0.1
2.38	0.18±0.04	0.50±0.06	0.52±0.06	0.09±0.03				1.3 ±0.2
2.57	0.20±0.04	0.55±0.07	0.57±0.06	0.14±0.04				1.5 ±0.2
2.77	0.13±0.05	0.52±0.06	0.56±0.06	0.16±0.04	0.07±0.02			1.4 ±0.2
2.97	0.16±0.05	0.47±0.06	0.55±0.06	0.14±0.03	0.12±0.03	0.02±0.01		1.4 ±0.2
3.16	0.20±0.05	0.41±0.05	0.50±0.06	0.15±0.03	0.08±0.02	0.13±0.04	0.03±0.01	1.5 ±0.2
3.36	0.22±0.05	0.45±0.06	0.44±0.05	0.14±0.03	0.10±0.02	0.10±0.02	0.11±0.02	1.6 ±0.2

[a] An angular distribution correction (≈18%) has been applied to the 1.75-MeV level excitation cross sections.

increased by 18–19%. No such corrections were made to the cross sections for excitation of the higher levels since the associated gamma-ray yields were low and the errors in the cross sections were relatively large.

The inelastic scattering cross sections listed in Table II were obtained by adding together the appropriate level excitation cross sections.

(3) Errors

Errors in the gamma-ray production cross sections were obtained by combining the photopeak area errors which arose due to statistical as well as background subtraction effects with errors in the multiplying factors of Eq. (1). The latter errors which were discussed individually in VNSMR add up to about 9% for the present work. The estimated photopeak area errors varied typically from 3.5 to 30%.

Reproducibility checks were done for the 0.908-MeV gamma-ray photopeak area by analyzing four separate runs at $E_n=2.18$ MeV and two runs at $E_n=2.57$ MeV. In no case did the deviation from the average exceed 6%. The estimated errors were somewhat greater than this. In a typical case they were approximately 8%. Reproducibility checks on the 1.51- and 1.75-MeV gamma-ray photopeak areas gave similar results for the 1.51-MeV gamma ray and better results for the 1.75-MeV gamma ray (≈3%).

IV. COMPARISON OF EXPERIMENT AND THEORY FOR THE LEVEL EXCITATION CROSS SECTIONS

(1) General Considerations

Much evidence has been adduced to show that the general features of reactions between low-energy neutrons and medium-weight nuclei can be described by an optical-model potential[28] provided that the spread in energy of the incident neutron beam is large enough to excite a sufficient number of states in the compound nucleus.[29] The Woods-Saxon potential[30] with absorption throughout the nuclear volume and a diffuse surface has been widely used. It has the following form:

$$V(r)=\frac{V_0(1+i\zeta)}{1+\exp[(r-R)/a]} \qquad (2)$$

where V_0 is the well depth for the real part; ζV_0 is the depth of the imaginary part of the well, $R=a_0A^{1/3}$ is the nuclear radius, r is the distance from the center of the well to the center of the neutron in the c.m. system, and a is the diffuseness parameter. This potential has been quite successful in describing such things as the dependence of incident neutron energy on total cross section (σ_t), elastic scattering cross section (σ_{el}), compound-nucleus formation cross section (σ_c), as well as the differential elastic scattering cross section [$\sigma_e(\theta)$]. The parameters of the potential can be chosen to vary smoothly from nucleus to nucleus as has been done by Campbell *et al.*[31] or they can be chosen so as to best describe the interaction of a neutron of incident energy E_n with a particular nucleus, with respect to the previously mentioned cross sections. This is essentially the approach of Beyster *et al.*[27] whose tables of transmission coefficients were used to derive theoretical results for comparison with this experiment. Unfortunately, after the submission of this manuscript it was pointed out to us by D. T. Goldman that errors have

[28] H. Feshbach, C. E. Porter, and V. F. Weisskopf, Phys. Rev. **96**, 448 (1954); and in *Proceedings of the International Conference on the Nuclear Optical Model*, Florida State University Studies No. 32 (Florida State University, Tallahasse, Florida, 1959).

[29] However, D. J. Donahue, using fast neutrons from a reactor, claims to have found a correlation between the yield of gamma rays arising from $(n,n'\gamma)$ reactions for nine elements and the $B(E2)$ values for the appropriate transitions [Phys. Rev. **128**, 1231 (1962)]. He offers no explanation for his observation and states that the mean neutron energies (2–3 MeV) make direct processes unlikely. The present investigation as well as several others using essentially monoenergetic neutrons up to 3.4 MeV (e.g., references 17–20) indicate that a compound-nucleus mechanism is predominant. See also footnote 38.

[30] R. D. Woods and D. S. Saxon, Phys. Rev. **95**, 577 (1954).

[31] E. J. Campbell, H. Feshbach, C. E. Porter, and V. F. Weisskopf, Massachusetts Institute of Technology Laboratory for Nuclear Science, Technical Report No. 73, 1960 (unpublished).

recently been found in the transmission coefficient tables of Beyster *et al.*[27] (See VNSMR for details.) Thus all of the calculations have been redone.

Many refinements to the Woods-Saxon potential have been suggested and to some extent tested. There is some theoretical justification for believing that the absorption should be concentrated at the surface of the nucleus rather than throughout the volume. Emmerich[32] has carried out a considerable number of computations on this basis. Moldauer[33] has recently investigated the theory of average neutron reaction cross sections in the resonance region using the R-matrix formalism. Spin-orbit effects which seem to be necessary to describe certain results for $\sigma_{el}(\theta)$ have been considered by Bjorklund and Fernbach.[34] Recently Goldman and Lubitz[35] did a series of calculations of $\sigma(n,n')$ for Al, Zr, and Nb, including spin-orbit effects, and concluded that they were important. Spin-orbit effects are also taken into account by Moldauer.[33] Other recent theoretical attempts to fit the previously mentioned neutron data involve the use of nonlocal potentials.[36,37]

(2) Calculation of the Level Excitation Cross Sections for the $Y^{89}(n,n')$ Reaction

Since the Beyster transmission coefficients were of doubtful correctness the theoretical calculations were redone using transmission coefficients taken from the report of Campbell, Feshbach, Porter and Weisskopf.[31] They used a Woods-Saxon form for the potential (Eq. 2). The parameters for Y^{89} were: $V_0=52$ MeV, $\zeta V_0=3.12$ MeV, $a=0.52$F and $R=(1.15\ A^{1/3}+0.4)$F $=5.53$F. These parameters were derived on the basis of a global fit of neutron scattering and absorption cross-section data. Some of the calculations were done using the spin-dependent Bjorklund-Fernbach[34] optical-model potential with the 4.1-MeV parameters. (These parameters vary relatively slowly with neutron energy.) The spin-dependent Hauser-Feshbach code of Goldman and Lublitz[35] was used for these calculations which were done by Goldman of the Knolls Atomic Power Laboratory as were most of the Campbell calculations. Finally, calculations were done using spin-dependent nonlocal potential transmission coefficients supplied by Perey of the Oak Ridge National Laboratory. These were obtained from the work of Perey and Buck.[36] Spin-independent values of $\bar{T}=[(l+1)T^{+}+lT^{-}]/(2l+1)$ were obtained according to the prescription suggested by E. Sheldon in order to provide input values for our spin-independent Hauser-Feshbach code.

Having obtained the transmission coefficients for a range of l (orbital angular momentum values from zero

[32] W. S. Emmerich, Westinghouse Research Report 6-94511-6-R19, 1958 (unpublished).

[33] P. A. Moldauer, Phys. Rev. **123**, 968 (1961).

[34] F. Bjorklund and S. Fernbach, Phys. Rev. **109**, 1295 (1958).

[35] D. T. Goldman and C. R. Lubitz, Technical Report KAPL-2163, 1961 (unpublished).

[36] F. Perey and B. Buck, Nucl. Phys. **32**, 353 (1962).

[37] F. Perey (private communication).

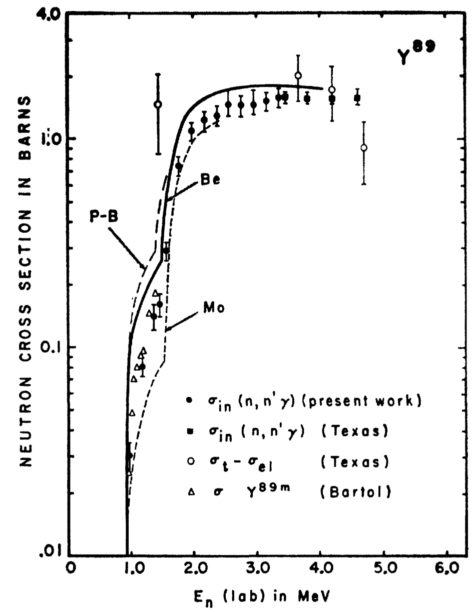

FIG. 5. Inelastic neutron scattering from Y^{89} compared with theory. The experimental points indicated by the solid circles are obtained from the present work by adding the production cross sections for the appropriate gamma rays. The points indicated by solid squares are obtained in the same way as above but using the data of Bostrom *et al.* (reference 15). The points indicated by open circles are obtained by subtracting values of σ_e obtained from the time-of-flight measurements of Bostrom *et al.* (reference 15) from values of σ_t listed in Table V of reference 15. The open triangles represent results of Swann and Metzger (reference 12) for the yield of the 16-sec 0.91-MeV gamma radiation vs neutron bombarding energy. Results of theoretical Hauser-Feshbach calculations using transmission coefficients due to Beyster *et al.* (reference 27) (Be) and Perey and Buck (reference 36) (P-B) are shown as well as results of Moldauer's (reference 44) (Mo) level width fluctuation calculations. Other theoretical curves based on the Bjorklund-Fernbach (reference 34) spin-dependent optical-model results and the spin-independent Campbell *et al.* (reference 31) results are not shown for the sake of clarity but they lie within the limits of the curves which are shown. (See text.)

to 5 versus neutron energy in the c.m. system, the next step was to assume spins and parities for the various excited levels in Y^{89}. The inelastic cross sections could then be calculated by the Hauser-Feshbach method.[35,38] For the Campbell calculations it was assumed that the spin sequence, starting with the ground state and including the 2.61-MeV level, was as follows: $1/2^-$, $9/2^+$, $3/2^-$, $5/2^-$, $5/2^+$, $7/2^+$, $9/2^+$, $3/2^-$, $5/2^-$. The spin and/or parity of one level was then varied to see what effect this would have on the cross sections for excitation of that level. Figure 6 shows the results for various spin choices. Figures 5 and 7 show results for

[38] W. Hauser and H. Feshbach, Phys. Rev. **87**, 366 (1952). This method assumes a compound-nucleus type of interaction and requires that enough levels in the compound nucleus be excited for statistical averaging to occur. Angular distribution measurements of inelastically scattered neutrons from Y^{89} using time-of-flight methods for incident neutron energies from 2.2 to 4.7 MeV have shown that a compound-nucleus model of the interaction is reasonable (references 13 and 14). The angular distributions have in no case deviated from isotropy by more than about 15%.

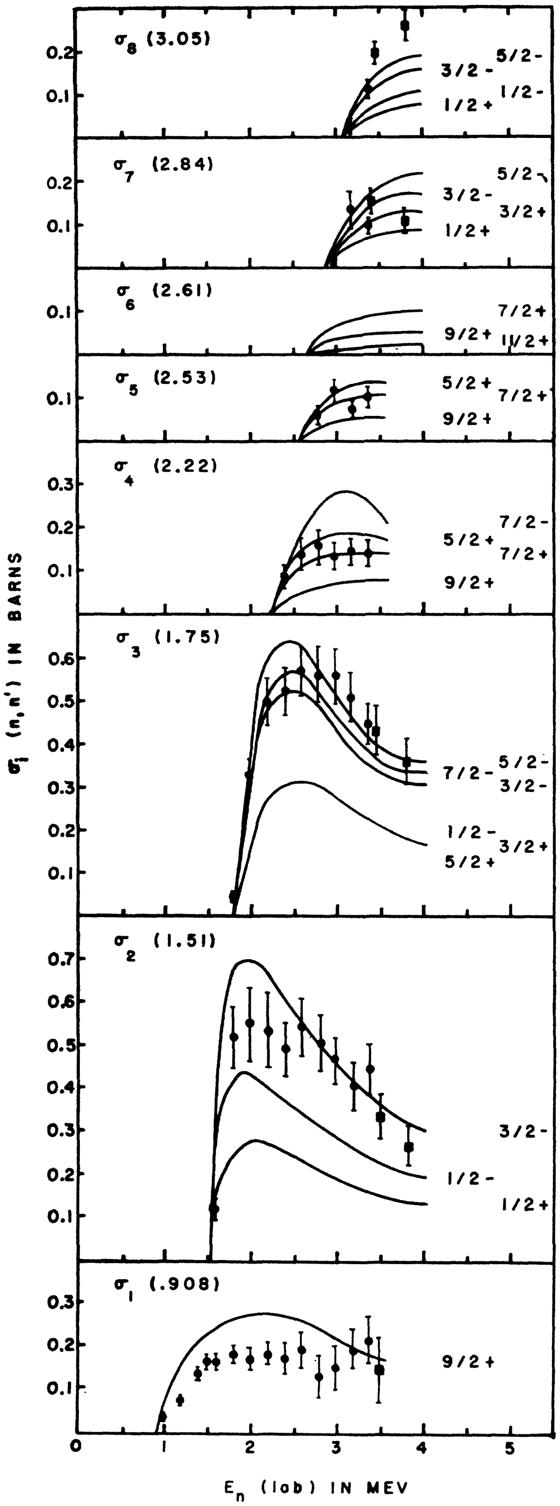

FIG. 6. Experimental excitation cross sections for levels in Y^{89} vs neutron bombarding energy compared with theory for different choices of spins and parities. The solid curves were calculated using Hauser-Feshbach theory and transmission coefficients due to Campbell *et al.* (reference 31). Most of these curves were calculated by D. T. Goldman. The spins for all levels except the one being studied were set at $1/2^-$, $9/2^+$, $3/2^-$, $5/2^+$, $7/2^+$, $9/2^+$, $3/2^-$, and $5/2^-$, starting with the ground state and the spin and parity of each level were varied in succession. The solid round dots are obtained from the present gamma-ray production cross section data at 98°, and the solid squares are obtained in a similar manner from the data of Bostrom *et al.* (reference 15). All of the 1.75-MeV level cross sections have been corrected for angular distribution effects. The cross sections for the 0.908- and 1.75-MeV levels have not been corrected for a possible contribution due to an unresolved 1.703-MeV gamma ray for $E_n > 2.6$ MeV (see text).

various theories when the spins of all levels are assumed as above. In most cases where the same calculations were done using different theories the results were very similar (Fig. 7), e.g., when $E_n = 3.5$ MeV, $5/2^-$ levels have the highest cross section according to all theories tried whereas $1/2^{\pm}$ or $9/2^+$ or $11/2^+$ levels have much smaller cross sections. It is noteworthy that in this mass region the Beyster results are quite similar to most of the other results even though the transmission coefficients may not be derivable from the quoted optical-model parameters. In general, it can be seen that for the same spin the positive-parity states are less strongly excited than the negative-parity states. This is probably because Y^{89} is near the peak of the p-wave strength function resonance[39] so the odd orbital angular momentum neutrons (odd l) have higher transmission coefficients than the even l neutrons, and, in particular, the $l=1$ transmission coefficients (T_1) are bigger than any others. At the higher incident neutron energies T_3 is next biggest. Thus, states in the compound nucleus with even parity are excited with higher probability than states with odd parity. If these states de-excite to negative-parity states of the residual nucleus, the outgoing l will be odd and the cross section will be higher than if they de-excite to positive-parity states where the outgoing l is even.

An over-all indication of the agreement between theory and experiment is obtained by comparing the experimental and calculated values for the inelastic cross section as a function of E_n. (See Fig. 5.) The general trend of the data is well described by all of the theories.

(3) Spin Assignments and Proposed Level Scheme

The ground-state spin of Y^{89} has been measured[40] as $\frac{1}{2}$ and the magnetic moment[41] (−0.137 nm) indicates that it belongs to the $p_{1/2}$ Schmidt group (−0.26 nm).

Shure and Deutsch[42] and Goldhaber *et al.*[43] have established the $M4$ character of the 0.908-MeV isomeric transition to the Y^{89} ground state. Thus the 0.908-MeV level of Y^{89} has a spin and parity of $9/2^+$. The experi-

[39] See, e.g., B. Buck and F. Perey, Phys. Rev. Letters **8**, 444 (1962).

[40] H. Kuhn, G. K. Woodgate, Proc. Phys. Soc. (London) Ser. A **63**, 830 (1950).

[41] E. Brun, J. Oesler, H. H. Staub, and C. G. Telschow, Phys. Rev. **93**, 172 (1954).

[42] K. Shure and M. Deutsch, Phys. Rev. **82**, 122 (1951).

[43] M. Goldhaber, E. der Mateosian, G. Scharff-Goldhaber, and A. W. Sunyar, Phys. Rev. **83**, 661 (1951).

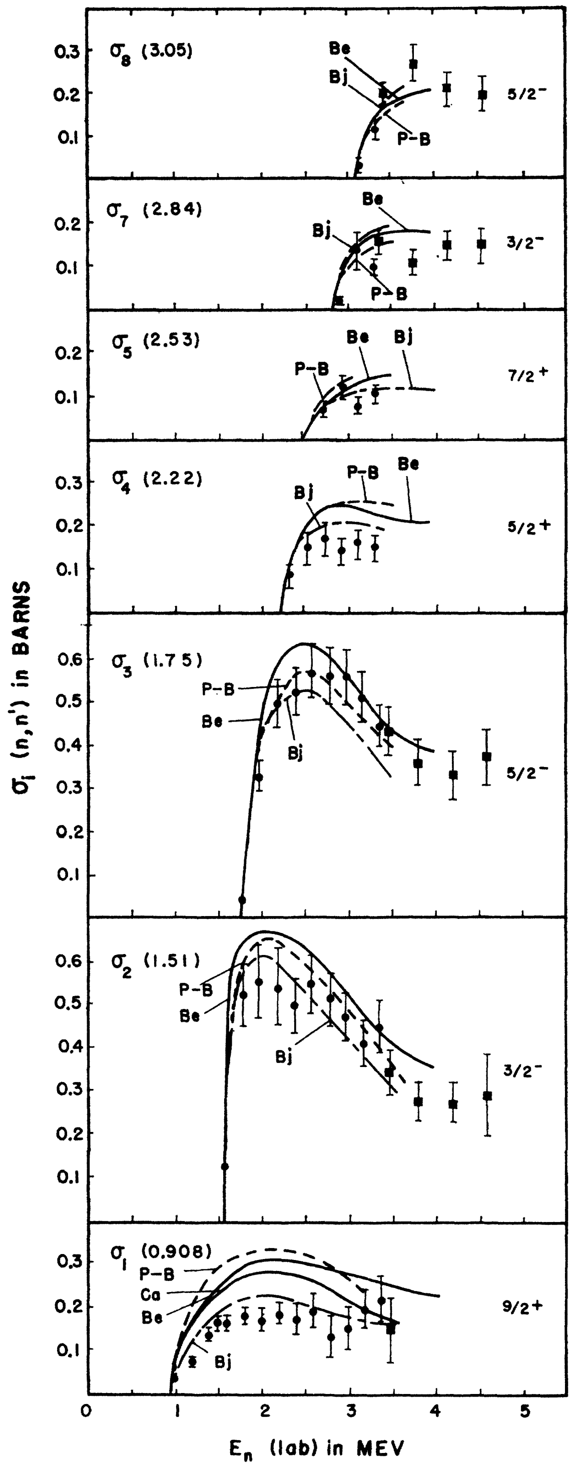

FIG. 7. Experimental excitation cross sections for levels in Y^{89} compared with different theories. The spins and parities of the levels were assumed to be as indicated in the figure. Results of Hauser-Feshbach calculations using optical-model transmission coefficients of Beyster *et al.* (reference 27) (Be) and Bjorklund and Fernbach (reference 34) (Bj) as well as the nonlocal potential transmission coefficients of Perey and Buck (reference 36) (P-B) are shown. The Beyster results are included even though the listed transmission coefficients may not follow from the assumed optical-model parameters as a matter of general interest since much use has lately been made of these tables. (See text and caption for Fig. 6.)

mental excitation cross section data for this level are shown in Fig. 6. The steady rise in cross section for excitation of this level, which starts at $E_n=2.77$ MeV, may be due to feeding from one or more higher energy levels in Y^{89} such as the 2.61-MeV level. Feeding of the 0.908-MeV level by the 2.22- and 2.53-MeV levels has already been taken into account. Theoretical curves calculated according to various theories are also shown in Figs. 6 and 7. The Bjorklund-Fernbach curve lies closest to the experimental values, while the Perey-Buck curve lies farthest from them. It is interesting that none of the theoretical calculations for this level is in satisfactory agreement with experiment, while they all are in much better agreement for the next two levels.

No evidence was found for a $9/2^+$ level at 1.50 ± 0.03 MeV which has been predicted from a study of beta-decay energy systematics.[4] Such a level, if it existed, should have been excited with about the same cross section as the 0.908-MeV level and would have decayed to that level with the emission of an 0.59 ± 0.03-MeV gamma ray. This gamma ray should then have been present in all spectra for $E_n>2.0$ MeV with an intensity comparable to that of the 0.908-MeV gamma ray, but no (0.59 ± 0.03)-MeV gamma ray was found with an intensity >0.1, the intensity of the 0.908-MeV gamma ray. Thus it is almost certain that no $9/2^+$ level at 1.50 ± 0.03 MeV exists.

Up to $E_n=1.52$ MeV, the 0.908-MeV level is the only one known to be excited so that it accounts for all of the inelastic cross section. Thus, for low bombarding energies, the data of Fig. 6 appear in Fig. 5. Also shown in Fig. 5 are the lowest bombarding energy data of Swann and Metzger[12] who measured the excitation curve for production of the metastable state. They used a quite different method than the one used in the present work. The 16-sec activity of Y^{89} was observed, and the 53-day Be^7 activity induced in the lithium target was measured to obtain an absolute calibration of their long counter. The agreement in cross-section values obtained by these two methods is well within the errors.

The next level in Y^{89} known to be excited in this work occurs at 1.51 MeV. It decays directly to the ground state and not to the 0.908-MeV state. The 1.51-MeV gamma ray is one of the most prominent in all the $(n,n'\gamma)$ spectra for $E_n>1.7$ MeV. It can be seen from Fig. 6 that a $3/2^-$ spin choice gives much better agreement between Hauser-Feshbach theory and experiment than a $1/2^+$ or a $1/2^-$ choice. The theoretical curve calculated by Moldauer[44] for a $3/2^-$ spin choice is in excellent agreement with the data. The superallowed decay of Zr^{89m} (log ft value of 4.3) establishes the spin of the 1.51-MeV level of Y^{89} as $3/2^-$ or $1/2^-$ with high probability. Shell-model theory has led to the $3/2^-$ choice

[44] P. A. Moldauer, Bull. Am. Phys. Soc. **7**, 334 (1962).

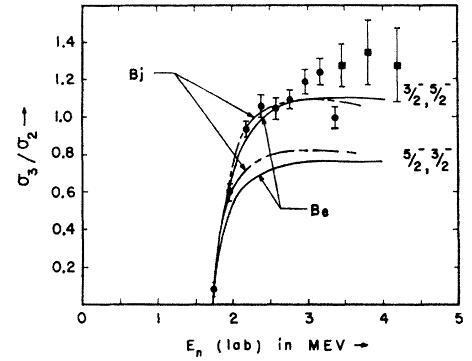

FIG. 8. Comparison of experimental results of the present work (solid dots) and of Bostrom *et al.* (reference 15) (solid squares) with theory for the ratio of the 1.75- to the 1.51-MeV (n,n') level excitation cross sections. An angular distribution correction ($\approx$18%) has been applied to the 1.75-MeV gamma-ray yield to obtain the cross section for excitation of the 1.75-MeV level. The $3/2^-$, $5/2^-$ and $5/2^-$, $3/2^-$ theoretical curves are calculated assuming these spins and parities for the 1.51- and 1.75-MeV levels, respectively, while spins and parities of other levels are assumed to be $1/2^-$, $9/2^+$, $5/2^+$, $7/2^+$, $9/2^+$, $3/2^-$, and $5/2^-$. Results of calculations using transmission coefficients due to Beyster *et al.* (reference 27) (labeled Be) and using Bjorklund and Fernbach (reference 34) spin-dependent transmission coefficients (labeled Bj) which were calculated by D. T. Goldman, are shown. Other theoretical curves based on the nonlocal potential results of Perey and Buck (reference 36), the optical-model results of Campbell *et al.* (reference 31), and the level width fluctuation theory results of Moldauer (reference 44), are not shown for the sake of clarity but lie very close to the curves which are shown. The deviation of the experimental points from theory at neutron bombarding energies above 2.6 MeV is partly due to the presence of an unresolved 1.70-MeV gamma ray in the 1.75-MeV gamma-ray peak.

for this level.[45] The branching of the 2.22-MeV level to the 1.51-MeV level as well as to the 0.908-MeV $9/2^+$ level (30 and 70%, respectively) favors a $3/2^-$ assignment for the 1.51-MeV level.

The 1.75-MeV level was the next one known to be excited. It decays directly to the ground state of Y^{89} and not with observable intensity to either the 1.51- or 0.908-MeV states. Preliminary measurements of the 1.75-MeV gamma-ray angular distribution (Sec. 2) showed that it was strongly anisotropic and indicated that it could arise from a pure $E2$ transition, in which case a $5/2^-$ assignment would be required for the 1.75-MeV level. The 1.75-MeV gamma ray is very prominent in all $(n,n'\gamma)$ spectra where $E_n>2.0$ MeV. The Hauser-Feshbach calculations give best agreement for a spin and parity value of $5/2^-$ and much worse agreement for $5/2^+$, $1/2^+$, $3/2^+$, or $1/2^-$ choices. The theoretical curve of Moldauer[44] for a $5/2^-$ choice is in excellent agreement with experiment.

Further information concerning the spins and parities of the levels at 1.51 and 1.75 MeV can be obtained by comparing the ratios of the measured cross sections to ratios of calculated cross sections. In this way, many of the experimental uncertainties associated with the determination of absolute cross sections are eliminated and some of the uncertainties in the theoretical calculations cancel out.

Figure 8 shows the experimental data as well as theoretical curves calculated with two sets of spin and parity choices for these two levels: $3/2^-$ and $5/2^-$ for the 1.51- and 1.75-MeV levels, respectively, which fits the low-energy experimental data satisfactorily, and $5/2^-$, $3/2^-$, which differs greatly from the experimental points. It does not show Moldauer's results for the ratio of the cross sections for these two levels, but they agree closely with experiment and with the previously mentioned theoretical calculations. The fact that all the different theoretical ratio calculations agree so closely with each other while the absolute cross-section calculations differ quite markedly shows clearly the advantage of the ratio method. The ratio method appears to establish the spins of these levels quite unambiguously. However, it must be used with discretion. For example, one would have more confidence in this method if cross sections for the 1.75- and 1.51-MeV levels could be compared with the 0.908-MeV level cross section, since its spin is known. However, such comparisons are not very informative, partly because the present theoretical calculations are in poor agreement with the measured cross sections for the 0.908-MeV level. The ratio method is expected to be most useful when the two states being compared have not very different energies and spins and the same parities. Unfortunately, this method is not very helpful in establishing the spins of the weakly excited gamma rays arising from higher levels in Y^{89}, since for it to be successful, accurate corrections must be made for cascades from higher levels, angular distribution corrections must be made for all gamma rays coming from or ending on that level, and the photopeak areas must be quite accurately known.

The highest levels observed in this experiment are all much less strongly excited than the 1.51- and 1.75-MeV levels. The levels at 2.22 and 2.53 MeV both decay to the 0.908-MeV first excited state of Y^{89} and not to the ground state. Therefore, they are closer in spin and parity to the 0.908-MeV level than to the ground state. As already remarked, the 2.22-MeV level also has a 30% branch to the 1.51-MeV level. The 2.22- and 2.53-MeV levels are weakly excited compared with the 1.51- and 1.75-MeV levels even for neutron energies 0.3–0.5 MeV above threshold. This is presumably because their spin and parity values are such that their excitation cross sections are low, and, indeed, the Hauser-Feshbach calculations predict low cross sections for reasonable spin choices. Such a choice for the 2.22-MeV level is $5/2^+$. Then the two gamma rays resulting from this spin assignment would be 0.71-MeV ($E1$) and 1.31-MeV ($E2$), which would compete. If its spin were $7/2^+$, the two gamma rays would be $M2$ and $E2$, $M1$, which usually do not compete. The (n,n') cross section for either of the 2.22- or 2.53-MeV levels seems too low for an assignment of either $5/2^-$ or $7/2^-$ for these states.

[45] F. J. Shore, W. L. Bendel, H. N. Brown, and R. A. Becker, Phys. Rev. 91, 1203 (1953).

The two most likely choices for the spin and parity of the 2.53-MeV level are $7/2^+$ or $9/2^+$. Both of these are compatible with the low (n,n') cross sections, and the presence of the 1.62-MeV gamma-ray transition to the 0.908-MeV level. The $7/2^+$ choice has the following difficulty: no 0.78-MeV $E1$ gamma-ray transition to the 1.75-MeV level is observed with an intensity >0.1, the intensity of the 0.71-MeV gamma ray. A $9/2^+$ choice for this level would explain the lack of an 0.78-MeV gamma ray, since the transition would then be $M2$, which would not be expected to compete with the 1.62-MeV $E2$, $M1$ transition. Other possibilties are $5/2^+$ or $9/2^-$. In the former case, $E1$ transitions of 1.02 and 0.78 MeV to levels at 1.51 and 1.75 MeV might be expected to compete with the 1.62-MeV $E2$ transition to the 0.908-MeV state. However, no 1.02-MeV gamma ray is observed with an intensity >0.1 of the intensity of the 1.62-MeV gamma ray. In the latter case, the high-energy 1.62-MeV $E1$ transition might completely dominate and the lack of an 0.78-MeV $E2$ transition might be expected. However, the measured cross section for excitation of this level seems low for $9/2^-$.

The only evidence for excitation of the 2.61-MeV level is the slight shift in the energy of the 1.75-MeV gamma-ray peak for $E_n>2.64$ MeV (Sec. III-1). If the observed shift is, indeed, caused by excitation of this level, the cross section must be large enough to make an $11/2^+$ spin assignment for this level unlikely. A $7/2^+$ assignment is less likely than a $9/2^+$ assignment, since in the former case an 0.87-MeV $E1$ gamma-ray transition to the 1.75-MeV level should be observed, and yet the intensity of such a transition is ≤ 0.1 times the intensity of the weak 0.71-MeV gamma-ray transition, while in the latter case the 0.87-MeV transition would be $M2$ and hence not observed.

The two highest energy gamma rays (2.84 and 3.05 MeV) found in this work are both due to ground-state transitions. No evidence for stop-over gamma rays was found, but some of the observed 1.32-MeV gamma radiation at the highest bombarding energies may have been due to cascades from these two levels to the 1.51- and 1.75-MeV levels, respectively. These two levels are near the maximum neutron bombarding energy used in this investigation, so relatively little information is obtained. The data of Bostrom *et al.*[15] at higher neutron bombarding energies give further information. However, no values of spin and parity for which theoretical calculations were done are ruled out. Nevertheless, it is striking that the energy difference between these levels (0.21 MeV) is so close to the energy difference between the 1.75- and 1.51-MeV levels (0.24 MeV). Also the individual levels in both pairs of levels are excited about equally, and all four levels decay directly to the Y^{89} ground state, which suggests that the higher energy pair of levels might have the same spins and parities as the low-energy pair.

Thus, on the basis of these considerations, and the results of Sec. III (1) concerning the lack of a 2.01-MeV level, the level scheme on the left-hand side of Fig. 9 is deduced. The Zr^{89} and Zr^{89m} decay schemes are shown at the right of Fig. 9.

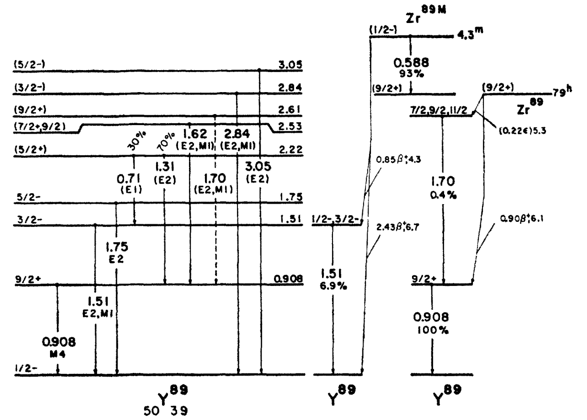

FIG. 9. Left: Proposed level scheme for Y^{89}. The spins, parities, and gamma-ray multipolarities in parentheses are suggested but not necessarily required by the present investigation. Right: Decay of 4.3-min Zr^{89m}. Extreme right: Decay of 79-h Zr^{89}. The energies of the Y^{89} gamma rays arising from the decay of Zr^{89} and Zr^{89m} have been determined as part of the present investigation.

V. DISCUSSION

Simple shell-model theory characterizes the ground state of Y^{89} as $2p_{1/2}$ and the 16-sec metastable state as $1g_{9/2}$. On this basis, the next two known levels in Y^{89} with spins and parities of $3/2^-$ and $5/2^-$ are formed by promoting a proton from the filled $2p_{3/2}$ and $1f_{5/2}$ shells, respectively, to the half-filled $2p_{1/2}$ shell and coupling the two $2p_{1/2}$ protons to zero. In fact, all of the observed levels in Y^{89} could probably be attributed to single particle or hole excitations. However, Kisslinger and Sorenson[1] have done extensive calculations on the level structures of single closed-shell nuclei such as Y^{89} using an approach suggested by superconductivity theory. They consider the influence of pairs of particles moving in a potential well on the odd particle. Thus a short-range pairing force, as well as a long-range $P_2(\cos\theta)$ force, which describes deformations of the well from a spherical shape, are taken into account. In this way the $9/2^-$ and $1/2^-$ splitting in Y^{89} is very accurately reproduced and positions of $3/2^-$ and $5/2^-$ single quasiparticle levels are predicted. The order which is predicted for these levels is correct, but the locations of the states are not correctly predicted.

Sakai[46] has suggested that certain features of the structure of Y^{89} might result from the coupling of the 39th $p_{1/2}$ proton of Y^{89} to the 2^+, 3^-, and (2^+) excited states of an Sr^{88} core. De-Shalit[5] has pointed out that Y^{89} is a nucleus where such coupling might arise. The possible identification of levels in Y^{89} with levels in Sr^{88} is shown in Fig. 10. Analogous gamma-ray transitions are also indicated in Fig. 10. The fact that no 0.78-MeV

[46] M. Sakai (private communication).

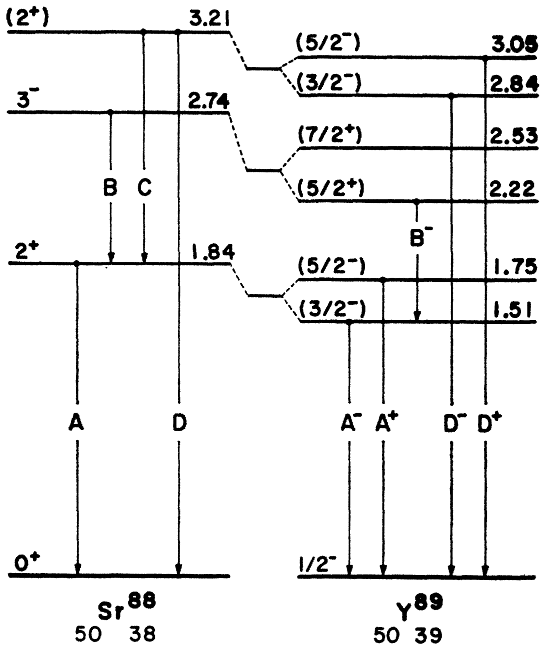

FIG. 10. Possible identification of levels in Y^{89} due to coupling of the 39th $p_{1/2}$ proton with excited levels in a Sr^{88} core. Left: Sr^{88} levels and strong gamma-ray transitions. Right: Y^{89} core plus particle levels and observed gamma-ray transitions. Center: Centers of gravity of the core-plus-particle doublets. Analogous transitions in Sr^{88} and Y^{89} are labeled with the same roman letters. Superscripts of + or − indicate the addition of +1/2 or −1/2 to the spin of the associated core state.

gamma-ray transition between the 2.53- and 1.75-MeV levels was observed casts some doubt on the identification of the 2.53-MeV level as the upper one of the 3^- doublet. The centers of gravity of the doublets of Fig. 10 are below the core-excited levels in Sr^{88}, but this is not unexpected.[5]

Since the three core levels in Sr^{88} are to some extent collective in nature, the related doublets in Y^{89} should be collective to the same extent on this model. The 15-MeV Y^{89} (d,d') reaction studies of Cohen and Price[11] may indicate that these levels are, indeed, somewhat collective, since it often happens that this reaction preferentially excites collective levels and since deuteron groups to each of the Y^{89} levels of Fig. 10 were observed. Further, the two levels of Y^{89} not associated with this model at 0.908 and 2.61 MeV did not seem to be excited in the (d,d') case. However, this may only be related to the high spins of these levels. Proton groups to some but not all of the Y^{89} levels shown in Fig. 10 were observed in the 22-MeV Y^{89} (p,p') investigation of Cohen and Rubin.[10] However, their resolution was not as good as in the (d,d') case.[11]

In conclusion, it appears that the core-excited doublet model for Y^{89} is attractive and could explain many features of the observed level structure, but much work remains to be done before it can be established or rejected.

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