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$Ba^{138}(n, \gamma)Ba^{139}$ Reaction and Evidence for Direct Capture*

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The γ radiation emitted following thermal-neutron capture in Ba^{138} has been studied both in singles and coincidence with 9-cm^3 and 20-cm^3 Ge(Li) detectors and a 9-cm^3 Ge(Li)-NaI detector combination at the Brookhaven research reactors. γ rays of the following energies (in keV) and relative intensities (given in parentheses) were assigned to Ba^{139}: 295 (<1), 352 (<1), 454.67 (27), 627.26 (100), 666.5 (1.5), 1047.4 (3), 1076 (<1), 1105 (2), 1420.1 (5), 1500 (<1), 1558.0 (2.5), 1854.0 (3), 1952.3 (3), 2242.0 (5), 2522.5 (2.5), 2537.0 (3), 2567 (3), 2594.1 (8), 3432 (<1), 3641.4 (20), and 4096.1 (60). All but one of these transitions were incorporated in a level scheme for the Ba^{139} nucleus with levels at the following energies (in keV): 627.26±0.10, 1081.9±0.2, 1292.6±1.0, 1420.1±1.0, 1952.3±1.0, 2129.3±1.2, 2156.4±2.0, 2186.4±1.9, and 2481.4±1.2. The level at 1292 keV which is excited in the Ba^{138} (d, p) reaction is shown to be a doublet of levels at 1284.0 and 1292.6 keV, of which only the 1292.6-keV member is observed to be populated in the Ba^{138} (n, γ) reaction. The neutron separation energy was found to be 4723.4±0.7 keV. The strengths of the primary γ rays and proton groups in the (n, γ) and (d, p) reactions, respectively, have been compared, and a strong correlation, with a correlation coefficient of 0.95, was observed. This correlation is discussed in terms of the common unique parent assumption of Lane and Wilkinson. It is seen to be consistent with this assumption and yields evidence for direct capture. It is shown that the theory of radiative capture of Lane and Lynn predicts a cross section for direct capture in Ba^{138} which is comparable to the observed total thermal-neutron-capture cross section $\sigma_{th}=0.35\pm0.15$ b.

I. INTRODUCTION

The β and γ radiations from Cs^{139} have been studied by several investigators.[1-6] The short half-life (9.5 min) [7] of Cs^{139} and the fact that it is normally obtained as a fission product hinder such radioactive decay studies. Wasson[2] was the first to report two γ rays of energies 0.63 and 1.28 MeV in this decay, whose existence was later confirmed by Wahlgren and Meinke.[3] Aksenov, Brodkin, Bushuev, and Polikarpov[4] reported two additional intense γ rays of energies 1.9 and 3.4 MeV, and several weaker γ rays. Zherebin, Krylov, and Polikarpov[5] constructed a decay scheme based on γ-γ and β-γ coincidences as well as the singles γ-ray spectrum. The results reported here are in complete disagreement with their decay scheme. Recently, Alväger, Naumann, Petry, Sidenius, and Thomas[6] reported on-line studies of mass separated fission products of Xe in which they assigned two γ rays of energies 626.6 and 1284.0 keV to Ba^{139}.

Several studies[8-11] of the $Ba^{138}(d,p)Ba^{139}$ reaction have been carried out, which helped to obtain information on the shell structure of nuclei near the $N=82$ closed neutron shell.

Further information on the energy levels of Ba^{139} has been obtained by von Brentano, Marquardt, Wurm, and Zaidi[12] and Morrison, Williams, Nolen, and von Ehrenstein[13] in their studies of the isobaric analog resonances observed in proton elastic and inelastic scattering from Ba^{138}.

Measurements of the polarization of protons scattered from Ba^{138} have been made by Veeser, Ellis, and Haeberli[14] in order to determine the spins and parities of isobaric analog states in La^{139}. They observed analog states corresponding to the ground state and excited states at 0.627, 1.085, 1.435, and 1.705 MeV in Ba^{139} to which they assigned spins and parities of $\frac{7}{2}-$, $\frac{3}{2}-$, $\frac{1}{2}-$, and $\frac{5}{2}-$, respectively.

The present investigation consists of a study of the γ radiation emitted in the $Ba^{138}(n,\gamma)Ba^{139}$ reaction.

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[1] *Nuclear Data Sheets*, compiled by K. Way *et al.* (Printing and Publishing Office, National Academy of Sciences—National Research Council, Washington, D.C., 1964).

[2] J. Wasson, MIT Laboratory for Nuclear Science Progress Report, 1958 (unpublished).

[3] M. A. Wahlgren and W. W. Meinke, J. Inorg. Nucl. Chem. **24,** 1527 (1962).

[4] V. A. Aksenov, E. B. Brodkin, A. V. Bushuev, and V. I. Polikarpov, Soviet J. At. Energy **13,** 877 (1963).

[5] E. A. Zherebin, A. I. Krylov, and V. I. Polikarpov, Yadern. Fiz. **3,** 981 (1966) [English transl.: Soviet J. Nucl. Phys. **3,** 717 (1966)].

[6] T. Alväger, R. A. Naumann, R. F. Petry, G. Sidenius, and T. Darrah Thomas, Phys. Rev. **167,** 1105 (1968).

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[8] R. H. Fulmer, A. L. McCarthy, and B. L. Cohen, Phys. Rev. **128,** 1302 (1962).

[9] F. W. Bingham and M. B. Sampson, Phys. Rev. **128,** 1796 (1962).

[10] J. Rapaport and W. W. Buechner, Phys. Letters **18,** 299 (1965), and private communication.

[11] C. A. Wiedner, A. Heusler, J. Solf, and J. P. Wurm, Nucl. Phys. **A103,** 433 (1967), and private communication.

[12] P. von Brentano, N. Marquardt, J. P. Wurm, and S. A. A. Zaidi, Phys. Letters **17,** 124 (1965); S. A. A. Zaidi, P. von Brentano, K. Melchior, P. Rauser, and J. P. Wurm, in *Isobaric Spin in Nuclear Physics,* edited by J. D. Fox and D. Robson (Academic Press Inc., New York, 1966), p. 798.

[13] G. C. Morrison, N. Williams, J. A. Nolen, Jr., and D. von Ehrenstein, Phys. Rev. Letters **19,** 592 (1967).

[14] L. Veeser, J. Ellis, and W. Haeberli, Phys. Rev. Letters **18,** 1063 (1967); L. Veeser and W. Haeberli, Nucl. Phys. **A115,** 172 (1968).

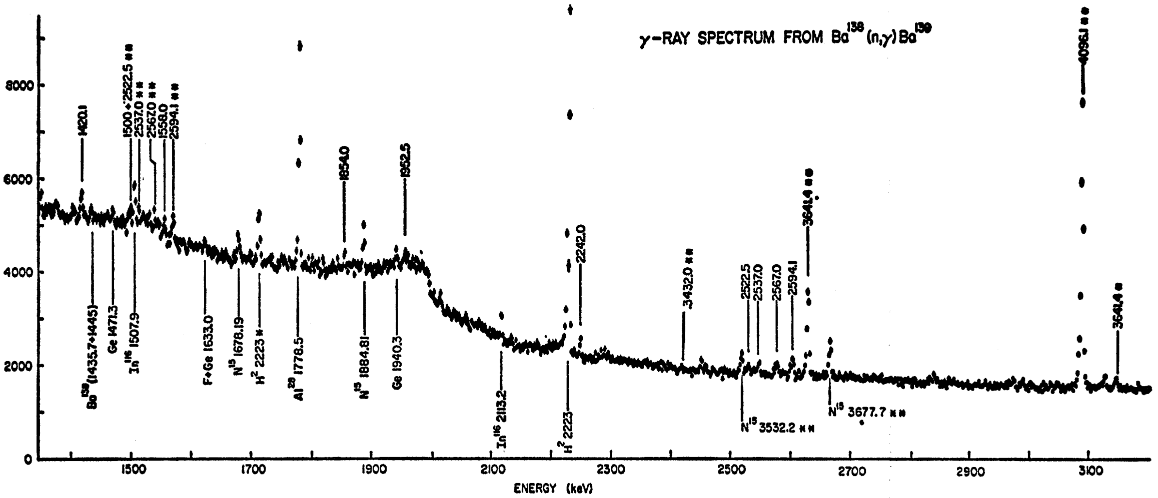

FIG. 1. The γ-ray spectrum (1.3–3.1 MeV) from thermal-neutron capture in a $Ba(NO_3)_2$ target enriched in Ba^{138}. This spectrum was accumulated in ~12-h running time with a 20-cm^3 Ge(Li) detector and a diffracted thermal-neutron beam at the HFBR. The lines assigned to Ba^{139} are labeled above the peaks. Background and impurity lines of known origin are indicated below the peaks. Single and double asterisks indicate one- and two-escape peaks, respectively.

Singles γ-ray and γ-γ coincidence spectra were studied (Sec. II) and a level scheme for Ba^{139} was constructed (Sec. III) on the basis of the experimental information now available on Ba^{139}. A discussion of the level scheme is presented in Sec. IV. The relative reduced transition probabilities of the primary γ rays feeding levels in Ba^{139} were compared with the strengths[10,11] of excitation of these levels in the (d, p) reaction. A strong correlation was observed. The significance of this correlation is discussed below in Sec. V.

II. EXPERIMENTAL METHODS AND RESULTS

A. Equipment

The target material consisted of 6.2 g of $Ba(NO_3)_2$ enriched in Ba^{138} with the following isotopic composition[15]: 99.8% Ba^{138}, 0.2% Ba^{137}, <0.02% Ba^{136}, <0.02% Ba^{135}, <0.01% Ba^{134}, <0.01% Ba^{132}, and <0.01% Ba^{130}. For thermal neutrons the contributions of the Ba isotopes of masses 130, 135, 137, and 138 to the capture cross section are <0.2, <0.3, 2.0, and 97.5%, respectively. The contributions of the other isotopes are negligible. The sample was enclosed in a Teflon capsule and irradiated in an external neutron beam with an intensity of $\sim 8\times 10^6$ neutrons/cm^2 sec from the Brookhaven graphite research reactor (BGRR). The neutron beam was collimated to a diameter of 10 mm in both the singles and coincidence runs.

Singles γ-ray spectra were obtained with a Ge(Li) detector[16] with an active volume of ~9 cm^3. The γ-γ coincidence spectra were obtained with a 3×3-in. NaI(Tl) detector and the Ge(Li) diode in 180° geometry.

In an additional experiment at the Brookhaven high flux beam reactor (HFBR) the same enriched Ba^{138} sample was enclosed in an aluminum capsule and irradiated in a diffracted thermal-neutron beam ($E_n = 0.048$ eV) with an intensity of $\sim 10^6$ neutrons/sec from a neutron monochromator. In this experiment the γ-ray singles spectrum was obtained with a 20-cm^3 Ge(Li) detector.[16]

The electronic equipment used in the handling and storage of the pulses from these detectors and the procedure applied in the analysis of the data have been described in an earlier publication.[17]

B. Energy and Intensity Measurements

The singles γ-ray spectrum between 0 and 4.5 MeV emitted in the $Ba^{138}(n, \gamma)Ba^{139}$ reaction was investigated in five runs with a total duration of 52 h. Figure 1 shows the γ-ray singles spectrum from 1.3 to 3.1 MeV. This spectrum was obtained in 12-h counting at the HFBR with the 20-cm^3 Ge(Li) detector.

The main problem encountered in the study of this reaction is the relatively small thermal-neutron-capture cross section of Ba^{138} (0.35 b).[18] Because of the small cross section many background lines were observed with an intensity equal to or higher than the intensity of the Ba^{139} γ rays. In order to identify the γ rays

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[15] Stable Isotopes Division, Oak Ridge National Laboratory, Oak Ridge, Tenn.

[16] The Ge(Li) detectors were fabricated by H. Kraner of the Brookhaven National Laboratory Instrumentation Department.

[17] M. A. J. Mariscotti, W. Gelletly, J. A. Moragues, and W. R. Kane, Phys. Rev. **174**, 1485 (1968).

[18] M. D. Goldberg, S. F. Mughabghab, S. N. Purohit, B. A. Magurno, and V. M. May, Brookhaven National Laboratory Report No. BNL 325, 1966 (unpublished).

belonging to the background, the neutron capture singles spectrum was carefully compared with a background spectrum with the same energy dispersion taken with a piece of graphite in the target position. Concurrent studies of the γ rays from the $Ba^{137}(n, \gamma)Ba^{138}$ and $Ba^{135}(n, \gamma)Ba^{136}$ reactions[17,19] also helped in the assignment of the observed lines.

The energies of the observed lines were obtained by comparison with accurately known standard lines from reference sources and from the $N^{14}(n, \gamma)N^{15}$ reaction in the $Ba(NO_3)_2$ target. In order to eliminate the effect of drifts the capture γ-ray spectrum was recorded together with the γ-ray spectrum from the reference sources. At intervals during the measurement the same spectrum was routed into a separate section of the analyzer memory together with a set of pulser peaks from a precision pulser[20] to correct for nonlinearities.

TABLE I. Energies and relative intensities of γ rays observed in the $Ba^{138}(n, \gamma)Ba^{139}$ reaction.

E_γ (keV)	I_γ (relative)
295 ± 5 [a]	<1
352 ± 5 [a]	<1
454.67 ± 0.10 [b]	27 ± 2
627.26 ± 0.10 [b]	100 ± 5
666.5 ± 1.5	1.5 ± 0.8
1047.4 ± 1.5	3 ± 2
1076.0 ± 2.0	<1
1105.0 ± 2.0	2 ± 1
1420.1 ± 1.0	5 ± 2
1500 ± 2 [a]	<1
1558.0 ± 1.0	2.5 ± 1.5
1854.0 ± 1.0	3 ± 2
1952.3 ± 1.0	3 ± 2
2242.0 ± 1.0	5 ± 1
2522.5 ± 1.5 [c]	8.5 ± 1.5
2537.0 ± 1.5	3 ± 1
2567.0 ± 2	3 ± 1.5
2594.1 ± 1.0	8 ± 1
3432.0 ± 2.0	<1
3641.4 ± 0.7 [b]	20 ± 3
4096.1 ± 0.7 [b]	60 ± 7

[a] γ ray doubtful. These γ rays were only observed in the γ-γ coincidence measurements. They are obscured by background lines in the γ-ray singles spectra.

[b] Energies used to determine the binding energy.

[c] Not included in the level scheme.

TABLE II. A comparison of the sum of the energies (in keV) of transitions constituting a cascade with the energies of the corresponding crossover transitions. The individual transition energies E_i and E_j are given in columns 1 and 2, their sum in column 3 and the energy of the corresponding crossover transition in column 4.

E_i	E_j	E_i+E_j	$E_{\mathrm{crossover}}$
2594.1 ± 1.0	1047.4 ± 1.5	3641.5 ± 1.8	3641.4 ± 0.7
2537.0 ± 1.5	1558.0 ± 1.0	4095.0 ± 1.8	4096.1 ± 0.7
2242.0 ± 1.0	1854.0 ± 1.0	4096.0 ± 1.0	
3641.4 ± 0.7	454.67 ± 0.10	4096.07 ± 0.71	

In the low-energy region the precisely known 411.795 ± 0.009 keV[21] and 661.627 ± 0.020 keV[22] γ rays of Au^{198} and Cs^{137} were used to obtain accurate energy values of 454.67 ± 0.10 and 627.26 ± 0.10 keV for the two intense low-energy γ rays of Ba^{139}.

The well-known Co^{60} γ rays of energies 1173.23 ± 0.04 and 1332.48 ± 0.05 keV[23] and the γ rays from the $N^{14}(n, \gamma)N^{15}$ reaction[24] were used as calibration lines in the energy range 1–4.5 MeV.

The relative intensities of the observed γ rays were obtained with the use of efficiency curves for the Ge(Li) detectors, which were determined according to a method described elsewhere.[25]

The energies and relative intensities of the γ rays assigned to Ba^{139} are listed in Table I.

Table II shows a comparison of the sum of the energies of transitions in cascade with the energies of the corresponding crossover transitions.

C. γ-γ Coincidences

Two separate γ-γ coincidence runs were made at the BGRR with the 9-cm^3-Ge(Li) detector and a 3×3-in.-NaI(Tl) scintillation counter. The energy regions covered in the two runs were 1.9–3 and 1.3–3.1 MeV for the γ rays detected in the Ge(Li) diode and 0–1.4 and 0–1.5 MeV for the γ rays detected in the NaI(Tl) detector, respectively. The pulses from both detectors

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[19] The results of the Ba^{137} (n, γ) reaction studies will be presented in a separate publication [W. Gelletly, J. A. Moragues, M. A. J. Mariscotti, and W. R. Kane, Phys. Rev. (to be published)].

[20] The pulser was designed by A. Z. Schwarzschild; its main component is a Kelvin Varley Voltage Divider: Dekapot (Electronic Scientific Industries Inc., Model CA 1463).

[21] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **45**, 177 (1963).

[22] Deduced [J. A. Moragues, P. Reyes-Suter, and T. Suter, Nucl. Phys. **A99**, 652 (1967)] from the ratios of the $B\rho$ of the K conversion line of the 662-keV transition [R. L. Graham, G. T. Ewan, and J. S. Geiger, Nucl. Instr. Methods **9**, 245 (1960)] of Cs^{137} and the K and L conversion lines of the 412-keV transition of Au^{198} (Ref. 21).

[23] G. Murray, R. L. Graham, and J. S. Geiger, Nucl. Phys. **63**, 353 (1965).

[24] R. C. Greenwood, Phys. Letters **27B**, 274 (1968).

[25] W. R. Kane and M. A. Mariscotti, Nucl. Instr. Methods **56**, 189 (1967).

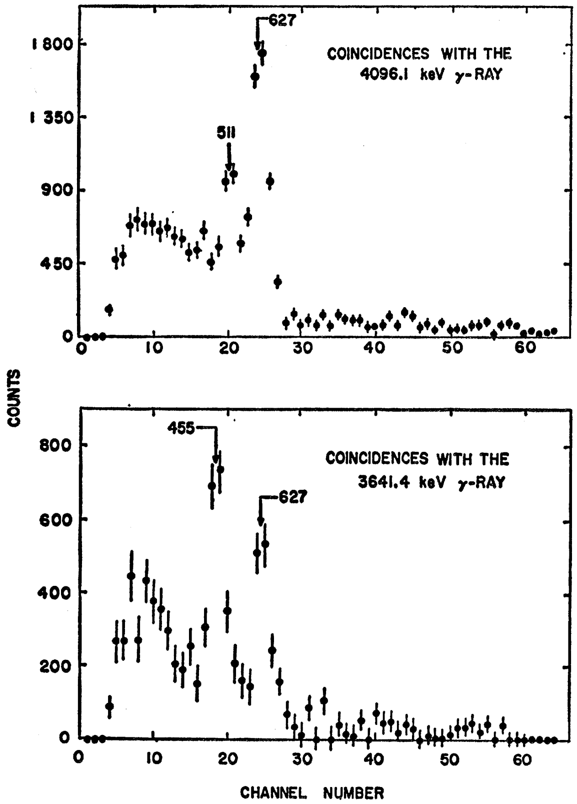

FIG. 2. Net coincidence spectra from the 3×3-in. NaI detector gated with the two-escape peaks of the 4096.1- and 3641.4-keV γ rays, which were detected in the 9-cm^3-Ge(Li) detector. Each spectrum was obtained as a computer output from the program PALMUD [M. A. J. Mariscotti, Brookhaven National Laboratory Report No. BNL 10904 (unpublished)], which summed the spectrum slices associated with the gating γ ray and subtracted an equal number of background slices. It should be noted that random coincidences have not been subtracted.

ranged over 256 and 64 channels, respectively, and were stored in the 16 384-channel memory of a two-dimensional TMC analyzer. The analysis of the data was carried out in the manner described in Ref. 17.

Because of the small thermal-neutron-capture cross section the coincidence spectra, which were accumulated in runs of 5-day duration, contained relatively few counts. Consequently the coincidence data served mainly to confirm the positions assigned to γ rays in the level scheme on the basis of energy fits. Only the dominant 4096.1–627.26 and 3641.4–454.67–627.26 cascades appear strongly in the coincidence spectra. The net spectra in coincidence with the two-escape peaks of the 4096.1- and 3641.4-keV γ rays are shown in Fig. 2.

Where relevant, details of the coincidence results are discussed in Sec. III.

III. CONSTRUCTION OF THE LEVEL SCHEME

Veeser *et al.*[14] have shown that the state in La^{139} which is the isobaric analog of the ground state of Ba^{139} has spin and parity $\frac{7}{2}-$ from measurements of the polarization of protons scattered from Ba^{138}. Their measurement confirms the earlier assignment[1] based on the expected shell-model configuration and on the analogy with Ce$_{83}{}^{141}$ and Nd$_{83}{}^{143}$. Since the capture state has spin and parity $\frac{1}{2}+$ we do not expect to observe a transition from the compound state to the ground state.

Levels in Ba^{139} at 0.63 and 1.08 MeV have been observed in the Ba^{138}(d, p)Ba^{139} reaction.[8–11] From the proton scattering experiments, Veeser *et al.*[14] were able to assign spins and parities of $\frac{3}{2}-$ and $\frac{1}{2}-$, respectively, to the isobaric analogs of these levels. On the basis of these assignments one should expect strong $E1$ transitions to these levels from the capture state in the thermal-neutron-capture reaction.

In the low-energy region of the γ-ray spectrum we see two intense γ rays of energies 627.26 and 454.67 keV. The former energy and the sum of these two energies are in good agreement with the energies of the levels mentioned above. The energy of the latter γ ray also agrees very well with the difference in energy (454.7 keV) of the intense 4096.1- and 3641.4-keV γ rays (see Table II), which are therefore assumed to be primary transitions to the first and second excited states of Ba^{139}. The coincidence measurements confirm these assumptions (see Fig. 2).

These assumptions lead to a value of 4723.4±0.7 keV for the neutron separation energy, obtained from the 4096.1–627.26 keV and 3641.4–454.67–627.26 keV cascades. This result is in good agreement with the binding energy 4717±10 keV given by Mattauch, Thiele, and Wapstra.[26]

The remainder of the level scheme was constructed by assigning certain γ rays as primary transitions and placing the outgoing transitions on the basis of energy combinations. The resulting level scheme of Ba^{139} is shown in Fig. 3.

The results of the (n, γ) and (d, p) energy measurements are in good agreement if the assumption is made that there exists a systematic error of +6 keV in the (d, p) measurements.[11] If the (d, p) energy measurements are adjusted downwards by this amount then the two sets of energy values agree within the stated error (±5 keV) of the (d, p) measurements.

Comments on the levels populated in the Ba^{138}(n, γ)Ba^{139} reaction follow:

A. Levels at 627.26±0.10 keV and 1081.9±0.2 keV

These states, the first and second excited states in Ba^{139}, were established in the manner described above. The existence of the intense 4096.1- and 3641.4-keV primary transitions to these levels supports the $\frac{3}{2}-$ and $\frac{1}{2}-$ spins and parities assigned by Veeser *et al.*[14]

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[26] J. H. E. Mattauch, W. Thiele, and A. H. Wapstra, Nucl. Phys. **67**, 32 (1965).

The 627.26-keV γ ray, which is the strongest transition observed in the neutron-capture γ-ray spectrum, was observed earlier in studies of the radioactive decay[1–6] of Cs^{139}. The 454.67-keV γ ray was reported by Aksenov *et al.*[4] In agreement with expectations from the spin and parity assignments, no crossover γ ray of 1082 keV was observed by us.

B. Level at 1292.6±1.5 keV

A level at 1292.6 keV is suggested by the observation in the present experiment of a weak primary transition of energy 3432 keV and a 666.5-keV transition to the first-excited state. It was not possible to determine whether the possible 893.8- and 836.7-keV transitions from the 2186.4- and 2129.3-keV levels exist because of the presence in the spectrum of background lines of the same energy. An upper limit of 1% of the intensity of the 627.26-keV γ ray could be placed on the intensities of both transitions. It was also impossible to detect the presence of the possible 1292.6-keV ground-state transition because of the presence of the intense 1293.4-keV In^{116} line[27] in the background. The observation of the primary transition from the $\frac{1}{2}+$ capture state and the outgoing 666.5-keV transition to the $\frac{3}{2}$ level at 627.26 suggests spin $\frac{1}{2}$ or $\frac{3}{2}$ for this level.

Wiedner, Heusler, Solf, and Wurm[11] report a level at 1292 keV which is excited in their (d,p) reaction studies. They arbitrarily assign spin $\frac{3}{2}$ and $l_n = 1$ for this level, which would be consistent with our results, although they note that the proton angular distribution shows more structure than expected at backward angles, which would be more consistent with $l_n \geq 3$. At the same time the distorted-wave Born approximation (DWBA) calculation for spin $\frac{1}{2}$ or $\frac{3}{2}$ does not reproduce this structure.

These inconsistencies may be resolved by the fact that the most intense γ ray observed in the decay of Cs^{139} has an energy of 1284.0±2.0 keV.[6] This transition is thought to be the ground-state transition from a level at 1284 keV. This level is clearly different from that observed in the present experiment. Since two close-lying levels at 1284 and 1292.6 keV would not be resolved in the (d, p) reaction studies the resulting proton angular distribution would be complex. The existence of both levels would thus explain the inconsistencies in the (d, p) measurements.

C. Levels at 1420.1±1.0 and 1952.3±1.0 keV

γ rays of energies 1420.1 and 1952.3 keV were observed in the γ ray singles spectra. These γ ray energies lie within ±5 keV of the adjusted energies (see above) of the 1430- and 1956-keV levels which were established in the (d, p) reaction studies.[8–11] Accordingly they may be identified as the ground-state transitions from levels at 1420.1 and 1952.3 keV. No primary transitions to these levels were observed, although the two-escape peak of the possible 2771.1-keV primary transition to the 1952.3-keV level would have been obscured by the presence of an In^{116} background line.

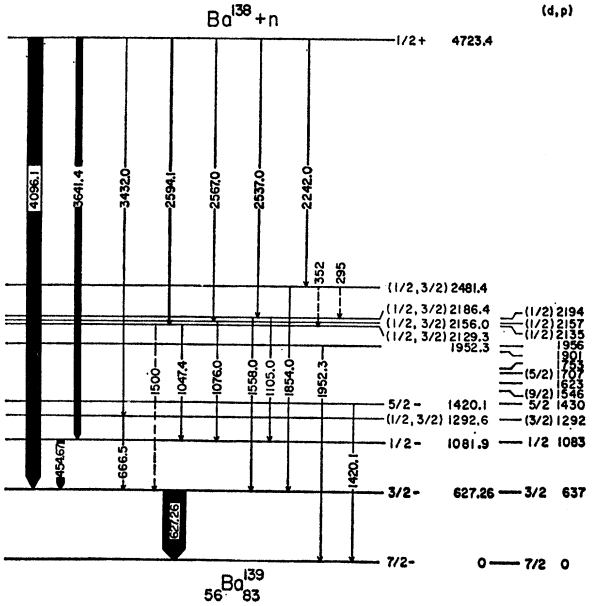

FIG. 3. Level scheme of Ba^{139} obtained from the Ba^{138} (n, γ) reaction. The dashed lines represent transitions about which there is some doubt. The 295- and 352-keV γ rays are only placed on the basis of the coincidence data (see Sec. III G). The 1500-keV γ ray is masked by the presence of the two-escape peak of the 2522.5-keV ray. Its existence is inferred from the known two-escape–full-energy peak ratio for our detector. The levels indicated by short solid lines on the right-hand side of this figure are those observed in the (d, p) reaction studies of Wiedner *et al.* (Ref. 11).

The results of the charged particle reaction studies indicate that the spin and parity of the 1420.1-keV level is $\frac{5}{2}-$. The absence of a primary transition from the $\frac{1}{2}+$ capture state and the existence of the transition to the $\frac{7}{2}-$ ground state are both consistent with this assignment.

The spin and parity of the 1952.3-keV level have not been established.

D. Level at 2129.3±1.2 keV

The 2594.1-keV transition populates this level. A 1047.4-keV transition fits between this level and the second excited state. A weak 1500-keV transition may also be placed between this state and the first excited state. However, the determination of the intensity of the 1500-keV γ ray is complicated by the accidental overlap of its full-energy peak with the two-escape peak of the 2522.5-keV γ ray. The existence of the 1500-keV transition was inferred from the fact that the observed

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[27] W. John and R. W. Jewell, in *International Conference on Nuclear Physics with Reactor Neutrons*, edited by F. E. Throw (Argonne National Laboratory, Argonne, Illinois, 1963), Report No. ANL-6769, p. 143.

two-escape–full-energy peak intensity ratio for the 2522.5-keV γ ray was larger than expected from the known ratio for our detector. The placing of this transition was supported by the relative intensities of the 627.26-, 454.76-, and 1047.4-keV transitions as observed in coincidence with the 2594.1-keV γ ray.

No ground-state transition was observed.

This level may be identified with the 2135-keV level seen in the charged particle reaction studies.[10,11] A spin of $\frac{1}{2}$ or $\frac{3}{2}$ for this level is suggested by the observation of the primary transition from the $\frac{1}{2}+$ capture state. Spin $\frac{1}{2}$ has been provisionally assigned by Wiedner *et al.*[11] on the basis of their (d, p) reaction studies.

E. Level at 2156±2 keV

This level is populated from the capture state by the 2567-keV transition. It is observed to decay by the weak 1076-keV transition to the $\frac{1}{2}-$ state at 1081.9 keV. It is noteworthy that these two transitions were only observed in the γ-ray spectrum of higher quality which was obtained at the HFBR with the diffracted neutron beam from the neutron monochromator. In the spectra taken at the BGRR the 1076-keV transition could not be seen above the background and the 2567-keV transition was obscured by a Na^{24} impurity line. The latter was also partially obscured by an unknown background line in the spectrum taken at the HFBR.

This level may be identified with the 2157-keV level which is weakly excited in the (d, p) reaction.[10,11] As in the case of the 2129-keV level a spin of $\frac{1}{2}$ or $\frac{3}{2}$ is suggested by the observation of the primary transition from the $\frac{1}{2}+$ capture state. This is consistent with the provisional assignment of spin $\frac{1}{2}$ made by Wiedner *et al.*[11] on the basis of their (d, p) reaction studies.

F. Level at 2186.4±1.9 keV

This level is populated by the 2537.0-keV primary transition and is observed to decay by the 1558.0- and 1105-keV transitions to the first and second excited states.

This level may be identified with that observed in the (d, p) reaction studies[10,11] at 2194 keV. As in the case of the previous level, a spin of $\frac{1}{2}$ or $\frac{3}{2}$ is consistent with the existence of the primary transition and the results of the (d, p) reaction studies.

G. Level at 2481.4±1.2 keV

The energy sum 2242.0+1854.0+627.26=4723.26 keV, equal to the neutron separation energy, implies the existence of a level in Ba^{139} populated by either the 2242.0- or 1854.0-keV transitions. Two lines of energies about 300 and 350 keV were observed to be in coincidence with the 2242.0-keV γ ray. It appears probable that these two transitions proceed from a level at 2481.4 keV to the 2129.3- and 2186.4-keV levels, respectively. γ rays with energies 352 and 295 keV were observed in the $Ba^{138}(n, \gamma)Ba^{139}$ singles spectrum. However, two lines with the same energies and comparable intensities also appear in the background spectrum (graphite target).

This level may be identified with the 2.49-MeV level observed in the (d, p) reaction.[8–10] The observation of the primary transition to this level favors spin $\frac{1}{2}$ or $\frac{3}{2}$ inferred from the $l=1$ assignment of Bingham and Sampson[9] and Rapaport and Buechner[10] rather than the $l=3$ assignment of Fulmer, McCarthy, and Cohen.[8]

IV. DISCUSSION OF THE LEVEL SCHEME

The level scheme of Ba^{139}, which is shown in Fig. 3, reveals a simple and reasonably consistent picture. The ground state and first and second excited states correspond to those found as isobaric analog resonances in the elastic and inelastic proton scattering experiments[12–14] on Ba^{138}. As expected from the spins and parities assigned to these analog resonances by Veeser *et al.*[14] the capture state decays predominantly to the first and second excited states and not to the ground state.

One test of the consistency and completeness of the level scheme is the balance in intensity between the transitions out of the capture state and those into the ground state. These intensities are found to agree within 8%.

All of the levels observed in the thermal-neutron-capture reaction, and reported here may be identified with levels previously reported from (d, p) reaction studies.[8–11]

The 2522.5-keV γ ray, which we identified as belonging to the $Ba^{138}(n, \gamma)Ba^{139}$ reaction, could not be placed in the Ba^{139} level scheme. If it is assumed to be a primary transition no γ rays were found to depopulate the resulting level.

V. CORRELATIONS BETWEEN $Ba^{138}(n, \gamma)$ AND $Ba^{138}(d, p)$ REACTIONS

When the formation of a compound nucleus takes place in neutron capture, the spectrum of primary γ rays has the form

$$E_\gamma^3 \rho(E_l), \qquad (1)$$

where E_γ is the energy of the photon which populates the level of energy E_l, and ρ denotes the level density. The primary transitions are assumed to be $E1$.

Groshev, Demidov, Lutsenko, and Pelekhov[28] and other authors[29] surveyed the known spectra of γ rays emitted following neutron capture. In the case of

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[28] L. V. Groshev, A. M. Demidov, V. N. Lutsenko, and V. I. Pelekhov, in *Proceedings of the Second United Nations International Conference on the Peaceful Uses of Atomic Energy, Geneva, 1958* (United Nations, Geneva, 1958), Vol. 15, p. 138.

[29] See, for instance, the review article of G. A. Bartholomew, Ann. Rev. Nucl. Sci. **11**, 259 (1961).

nuclei near magic numbers they found that the contribution of the high-energy radiation to the total spectrum increases considerably. This shift of the "center of gravity" of the spectrum toward higher energy is particularly marked in nuclei near the double closed shell at $Z=82$, $N=126$ and cannot be explained by assuming any reasonable change in the rate of increase of the level density with energy. Since states with a predominant p-shell configuration are expected to be strongly populated by s-wave neutron capture and the subsequent emission of $E1$ radiation, this anomalous spectrum distribution has been interpreted[30] by assuming that the "effective" level density $\rho(E_l)$ in (1) is modified by the presence of p states near the ground state of the residual nucleus, as in the lead region and in light nuclei.

Since the amount of p-shell configuration mixing can be inferred from the results of (d, p) reactions, Groshev *et al.*[28] analyzed the existing data on those light nuclei $(A<60)$ where both (n,γ) and (d,p) studies had been carried out. In their analysis they compared the strengths with which a given final state is populated in both the (n,γ) and (d,p) reactions.

In the case of even-odd nuclei (even-even target) this analysis revealed that a strong correlation exists between these strengths whenever the (d,p) results indicate that $l_n=1$ for the final state.

Further evidence of the influence of the p states on the primary γ-ray intensities is given by the decrease in energy of the levels which are strongly populated in neutron capture as we go from Si^{29} through S^{33}, Ca^{41}, Ti^{49} up to Cr^{53}, Fe^{57}, Ni^{59}, and Ni^{60} (for which the ground-state transitions are the strongest) as the orbits fill up and the ground states of these nuclei approach the p shell.

These findings strongly support the assumption that for light nuclei, as for nuclei in the lead region, the influence of p states is very important. Furthermore, the strong correlation observed with the results of (d,p) reactions suggests a reaction mechanism which is not consistent with the usual assumption that neutron capture proceeds through the formation of a compound nucleus.

Ba^{139} lies in a region intermediate between light $(A<60)$ and heavy $(A\sim 208)$ nuclei and it is interesting to compare the (n,γ) and (d,p) results in this case.

Table III shows the strengths $G_{n\gamma}$ and G_{dp} with which the levels of Ba^{139} are excited in the (n,γ) and (d,p) reactions, respectively. These values are given in columns 2, 3, and 4. In the first case, we have used

$$G_{n\gamma}\propto (I_\gamma/E_\gamma{}^3), \qquad (2)$$

where I_γ is the γ-ray intensity obtained from Table I. In the second case, the quantity G_{dp} has been obtained from Refs. 10 and 11 as indicated in columns 3 and 4 of Table III. If S is the spectroscopic factor[31] and J_f the spin of the final state then

$$G_{dp}=(2J_f+1)\,S. \qquad (3)$$

Column 5 shows the spectroscopic factor S for those cases where a known J_f allows one to calculate it from Eq. (3) and column 6 gives the l_n values deduced from the angular distributions of the outgoing protons in the (d,p) reaction.

Only the $l_n=1$ states are observed to be fed in the (n,γ) reaction. The strong correlation between the (n,γ) and (d,p) strengths for these states is readily apparent from the measured values of the ratio $G_{n\gamma}/G_{dp}$, which are listed in column 7 of Table III. If we exclude the case of the 1292-keV level because the 1284- and 1292.6-keV levels are not resolved in the (d,p) measurements (see Sec. III B), then, within the errors, the remaining values of $G_{n\gamma}/G_{dp}$ are consistent with the relation

$$G_{n\gamma}/G_{dp}=\text{const.} \qquad (4)$$

One measure of the correlation between $G_{n\gamma}$ and G_{dp} is the product-moment coefficient of correlation

$$\rho=\frac{\sum(G_{n\gamma}-\bar{G}_{n\gamma})(G_{dp}-\bar{G}_{dp})}{[\sum(G_{n\gamma}-\bar{G}_{n\gamma})^2\sum(G_{dp}-\bar{G}_{dp})^2]^{1/2}}\,.$$

We find $\rho=0.95$ for the observed values of $G_{n\gamma}$ and G_{dp}. This value indicates a strong correlation with only a small probability $(<0.3\%)$ that the observed values are consistent with a zero correlation.

The total transition strength G_{dp} to the $3p_{3/2}$ subshell is expected to be 4. If one associates the 627.26-keV state with this configuration, the value G_{dp} (627 keV) shown in column 3 or 4 indicates that only about one-half of the $3p_{3/2}$ strength goes to this level. The same fraction is observed in the case of the second excited state at 1081.9 keV which one could identify with the $3p_{1/2}$ configuration.

The correspondence between $G_{n\gamma}$ and G_{dp} values shown in Table III is similar to that already observed in light nuclei[28,32] and it seems to indicate the predominance of direct capture in the $Ba^{138}(n,\gamma)$ reaction. The direct capture mechanism is probably enhanced in this case by the fact that Ba^{139} has a single neutron outside the $N=82$ closed shell.

An explanation of these observed correlations between the (n,γ) and (d,p) strengths has been suggested by Lane and Wilkinson[33] and later developed by

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[30] G. A. Bartholomew, P. I. Campion, I. W. Knowles, and G. Manning, paper presented at the Colloquium on Nuclear Interactions of Neutrons, International Union of Pure and Applied Physics, New York, 1957 (unpublished).

[31] M. H. Macfarlane and J. B. French, Rev. Mod. Phys. **32**, 567 (1960).

[32] L. V. Groshev, A. M. Demidov, and N. Shadiev, Yadern. Fiz. **3**, 444 (1966) [English transl.: Soviet J. Nucl. Phys. **3**, 319 (1966)].

[33] A. M. Lane and D. H. Wilkinson, Phys. Rev. **97**, 1199 (1955).

TABLE III. Comparison of strengths of the primary γ rays and proton groups in the (n,γ) and (d,p) reactions, respectively.

Level energy (keV)	(n,γ) data $G_{n\gamma}\propto I_\gamma/E_\gamma^3$ (arb. units)	(d,p) data $G_{dp}=(2J_f+1)S$ [b]	[c]	S [c]	l_n	ratio[a] $G_{n\gamma}/G_{dp}$
0		6.2	6.1	0.76	3	
627.26	100±10	1.8	1.96	0.49	1	53±11
1081.9	48±7	0.79	0.82	0.41	1	59±14
1284			0.32	0.08		
1292.6	3±2				1	...[d]
1420.1		1.6	1.4	0.24	3	
1546			6.0	0.60	5	
1707			1.4	0.24	3	
2129.3	53±13	0.58	0.42	0.21	1	106±47
2156	20±10	0.26	0.12	0.06	1	108±80
2186.4	22±7	0.43	0.26	0.13	1	64±40
2481.4	51±10	0.60			1	85±33

[a] An average of the G_{dp} values from Refs. 10 and 11 was used to calculate this ratio. We have assigned errors of 10, 20, and 30% to this quantity for the 627- and 1081-, 2129- and 2481-, and 2157- and 2186-keV levels, respectively.

[b] Reference 10.

[c] Reference 11.

[d] See Sec. III B.

Bockelman.[34] Since the matrix elements which appear in these two types of nuclear reaction only involve single-particle transitions the system of n nucleons is conveniently described in terms of a complete set of functions $[\varphi_{J_p}(n-1)\times\varphi_j]_{JM}$ which represent $(n-1)$ nucleons coupled to J_p (the other quantum numbers are implicitly included) and in turn coupled to one odd nucleon with spin j to form the total spin J. Hence for the wave function of the n nucleons we write

$$\Psi(JM)=\sum_{J_p}(J_p|\}J)[\varphi_{J_p}(n-1)\times\varphi_j]_{JM}, \qquad (5)$$

where the summation extends over all possible (antisymmetric) states $\varphi_{J_p}(n-1)$ (parent states) of the $(n-1)$ particles compatible with the total spin J. The numerical coefficients $(J_p|\}J)$ are the coefficients of fractional parentage[35] (c.f.p.).

The wave function (5) is particularly useful for calculating the reduced matrix elements of one-particle operators. In general such a reduced matrix element reduces to[33,35]

$$\langle J_f\|\mathcal{O}\|J_i\rangle=n\langle \mathrm{sp}\rangle\sum_{J_p}\omega_{j_p}(J_p|\}J_f)(J_p|\}J_i), \qquad (6)$$

where $\langle \mathrm{sp}\rangle$ indicates the reduced single-particle matrix element and the weighting coefficients ω_{J_p} involve Racah coefficients. Because of the orthogonality of the parent states $\varphi_{J_p}(n-1)$ the sum in (6) only contains those parent states which are common to the initial and final states.

As Lane and Wilkinson pointed out, the stripping reaction can be imagined as the exchange of a nucleon between the colliding nuclei outside the surface of the target nucleus. Hence in the (d,p) reaction we can think of the initial state as the system "(target nucleus)+(neutron)." By its nature, this total state has only one parent, the state of the target nucleus, and is described by a single term in (5). Accordingly the reduced matrix element, which is given by the overlap of this initial state and the final state, and takes the form of Eq. (6) with $\mathcal{O}$ being the unit operator, reduces to a single term. This term is proportional to the corresponding c.f.p. in the expansion (5) of the final state.

In the case of neutron capture both the initial and final states will have, in general, many terms in (5). However, if the initial state has, in a particular case, a unique parent state and this corresponds, as in the (d,p) case, to the ground state of the target nucleus, a correlation between (n,γ) and (d,p) strengths must obviously be expected since the matrix elements in both cases will be proportional to the same c.f.p. Such a situation, in which both reactions have a common unique parent in the initial states, is likely to occur when the ground state of the target nucleus is a closed neutron shell state. Using the expressions given by Lane[36] and Lane and Radicati[37] for the reduced widths γ_{dp}^2 and $\gamma_{n\gamma}^2$ (the squares of the corresponding reduced matrix elements) of the two reactions, where γ_{dp}^2 is proportional to the spectroscopic factor[31] S and $\gamma_{n\gamma}^2$ is

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[34] C. K. Bockelman, Nucl. Phys. **13**, 205 (1959).

[35] A. de Shalit and I. Talmi, *Nuclear Shell Theory* (Academic Press Inc., New York, 1963).

[36] A. M. Lane, Proc. Phys. Soc. (London) **A66**, 977 (1953).

[37] A. M. Lane and L. A. Radicati, Proc. Phys. Soc. (London) **A67**, 167 (1954).

proportional to the (n, γ) strength $G_{n\gamma}$ (2), one finds,[34] in the case of an even-even target and $l_n=1$, that

$$\gamma_{n\gamma}^2/\gamma_{dp}^2 \propto (2J_f+1) \tag{7}$$

and therefore

$$\gamma_{n\gamma}^2/(2J_f+1)\gamma_{dp}^2=\text{const} \tag{8}$$

in agreement with the experimental result (4).[38] Thus, although one cannot conclude that the present experimental results are definite evidence of direct capture, they are, nevertheless, wholly consistent with the common unique parent assumption proposed by Lane and Wilkinson.[33]

More recently, Lane and Lynn[39] have presented a comprehensive study of the theory of radiative capture based on dispersion theory. In this description the wave function of the initial state is proportional to the amplitude of an incoming wave minus the product of the amplitude of an outgoing wave and the diagonal element of the scattering matrix

$$U_{c,c}=\exp(-2i\varphi_c)\{1+i\sum[\Gamma_{\lambda c}/(E_\lambda-E-\tfrac{1}{2}i\Gamma_\lambda)]\}, \tag{9}$$

where φ_c is a phase angle, $\Gamma_{\lambda c}$ is the partial width of the level λ for the channel c, E_λ and Γ_λ are the energy and total width of the level λ, and E is the energy of the initial state. The first and second terms in (9) give the respective contributions of the hard sphere scattering and of the resonant scattering to the cross section. The contribution of the latter splits into two parts. The internal part is obtained when the matrix element is evaluated in the region $r<R$, where r is the separation between the projectile and the target and R is the interaction radius. The internal part corresponds to the usual compound-nucleus cross section. The evaluation of the matrix element in the external region $r>R$, on the other hand, gives rise to the second part of the resonant cross section, which is called channel resonance.

Finally, the hard sphere contribution leads to the "direct" or "potential" capture cross section. Both the channel resonance and potential capture cross sections are functions of the strength of the single-particle p-wave configuration in the final state. To evaluate the direct or potential capture cross section one has to assume a model. The simple strong absorption model assumes that there is no appreciable free motion of the projectile inside the target and neglects the contribution of far away resonances. When the final state has a single-particle p-wave configuration the direct capture cross section, which one obtains by applying this model, is

$$\sigma(\text{hard sphere})=\frac{0.062}{R\epsilon'}\left(\frac{Z}{A}\right)^2\theta^2y^2\left(\frac{y+3}{y+1}\right)\text{(in b)}, \tag{10}$$

where ϵ' is the neutron energy in eV and $y=kR$ (k is the wave number corresponding to the binding energy of the final state). The dimensionless reduced width θ^2 is related to $\gamma_{n\gamma}^2$ by

$$\theta^2=\gamma_{n\gamma}^2(\hbar^2/MR^2)^{-1}, \tag{11}$$

where M is the reduced mass. If (10) is to be taken as an estimate of the total cross section for direct capture we may assume $\theta^2\sim 1$. The result for the $Ba^{138}(n, \gamma)$ reaction is

$$\sigma(\text{hard sphere})\sim 0.2 \text{ b},$$

which is reasonably close to the experimental thermal-neutron-capture cross section[18]

$$\sigma_{\text{expt}}(\text{thermal})=0.35\pm0.15 \text{ b},$$

indicating that most of the capture appears to be direct or potential capture. It is noteworthy that the first known resonance in $Ba^{138}(n, \gamma)$ is at 31.7 keV [18] and its contribution to the thermal cross section is <0.004 b. The nonexistence of low-lying resonances favors the predominance of the direct capture.

In conclusion, we may say that the observed correlation between our data and those obtained in the (d, p) reaction studies is in agreement with the explanation proposed by Lane and Wilkinson,[33] that the initial states in the (n, γ) and (d, p) reactions have a common unique parent state. Such a description is, of course, contrary to the compound-nucleus model. The assumption that direct capture is predominant in the present case is further supported by the direct capture cross-section estimate obtained from the work of Lane and Lynn.[39]

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[38] It should be noted that Eq. (4) stands in contradiction to the conclusions of Bockelman (Ref. 34) and of Comfort (this reference). In our opinion the disagreement with the conclusion in Ref. 34 stems from an incorrect association of the (n, γ) strength (here called $G_{n\gamma}$) with $(2J+1)\gamma_{n\gamma}^2$ and the disagreement with Comfort is due to the erroneous association of the (d, p) strength (G_{dp}) with the reduced neutron width γ_{dp}^2. We also find that Eq. (4) of Ref. 34 is correct rather than Eq. (1) of Comfort. [See the erratum to J. R. Comfort, Phys. Rev. Letters **20**, 941 (1968); **21**, 1030 (1968).]

[39] A. M. Lane and J. E. Lynn, Nucl. Phys. **17**, 563 (1960); **17**, 586 (1960).