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Photoneutron Cross Sections for Ba^{138} and N^{14}†

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Photoneutron cross sections, including $\sigma[(\gamma,n)+(\gamma,pn)]$, $\sigma(\gamma,2n)$, and $\sigma(\gamma,3n)$ for Ba^{138} and $\sigma[(\gamma,n)+(\gamma,pn)]$ for N^{14}, were measured with monoenergetic photons from threshold to 29 MeV. The partial cross sections were determined by neutron multiplicity counting, and the average neutron energies for both single- and double-photoneutron events were determined simultaneously with the cross-section data by the ring-ratio technique. The N^{14} data, when combined with data from other laboratories, appears to show that the (γ,pn) process dominates the decay of the giant resonance in this nucleus. The giant-resonance parameters for Ba^{138} are nearly the same as those for Pr^{141}, which has the same (magic) neutron number.

INTRODUCTION

Photoneutron cross sections for Ba^{138} and N^{14} were measured as part of a continuing survey to examine the influence of the characteristics of nuclei on the giant resonance. One of the key elements in the survey is $_{56}Ba^{138}$ which has a closed neutron shell ($N=82$) and which differs from $_{59}Pr^{141}$ (measured previously at this laboratory[1]) by three protons. The question to be resolved is whether the giant-resonance parameters for these two nuclei are the same, since the giant-resonance decay is dominated by neutron emission.

The Ba^{138} sample was in the form of $Ba(NO_3)_2$. It therefore was necessary to measure first the photoneutron cross section for N^{14} in order to obtain the Ba^{138} cross section. (The oxygen contribution was determined from previous measurements.[2,3]) Although the N^{14} nucleus is interesting in its own right (it is self-conjugate, odd-odd, and light), its photoexcitation and subsequent decay are very complex, involve several reaction channels, and require a much more comprehensive study than was done in the present experiment. The present contribution, however, determines several quantities of interest vital to that study, and gives an over-all view of the N^{14} giant resonance.

Some work has been done previously on N^{14}, albeit with continuous bremsstrahlung sources, including a $N^{14}(\gamma,n)$ activation measurement by King, Haslam, and Parsons,[4] a $N^{14}[(\gamma,n)+(\gamma,pn)+2(\gamma 2n)]$ yield measurement by Fast *et al.*,[5] a $N^{14}(\gamma$, charged particle) cloud-chamber experiment by Komar, Krzhemenek, and Yavor,[6] a $N^{14}(\gamma,p)$ spectrum measurement by Kosiek, Maier, and Schlüpmann,[7] and a $N^{14}(\gamma, \text{total})$ absorption measurement by Bezić *et al.*[8] Other work under way includes a $C^{13}(p,\gamma)$ experiment by Reiss, O'Connell, and Paul,[9] and several other bremsstrahlung experiments,[10–13] as well as $N^{14}(\gamma,\gamma')$ deexcitation-γ-ray-spectrum measurements by Baglin *et al.*[14] and by Thompson, Stewart, and Thomson.[15] All this work taken together soon should provide us with a much more detailed description of the photodisintegration of N^{14}; the present measurement, however, is the only one done with monoenergetic photons, and thus makes its unique contribution.

No previous work has been published on Ba^{138}.

EXPERIMENT

The source of radiation was the monoenergetic photon beam created by the annihilation in flight of fast positrons from the linear accelerator.[16] The neutron detector consisted of 48 BF_3 tubes embedded in a 2-ft paraffin cube. This detector is about 40% efficient, enables one to measure the neutron multiplicities in order to determine the $(\gamma, 2n)$ and $(\gamma, 3n)$ cross sections independently and simultaneously, and, by means of the ring-ratio-technique,[17,18] to determine the average energy of the photoneutrons and hence, the detector efficiency for each data point and for each neutron multiplicity. The photon energy resolution varied from less than 300 keV at 10 MeV to about 400 keV at 30 MeV,[1] corresponding to the use of a 0.030-in. Be annihilation target. The absolute cross-section scale was determined to 7% by a photon-beam intensity calibration done with the aid of an 8-in. ×8-in. NaI(Tl) γ-ray spectrometer. The energy scale was determined to $\frac{1}{4}$% from high-resolution (1%) and fine-gridded measurements of the locations of the 17.28-MeV peak in the $O^{16}(\gamma, n)$ cross section, the thresholds for neutron emission from O^{16} to the first and third excited states of O^{15}, and the $(\gamma, 2n)$ thresholds for many nuclei.

The Ba^{138} sample consisted of 100 g of Ba^{138} enriched to 99.80% isotopic purity in the form of $Ba(NO_3)_2$ in a thin-walled Lucite container. Appropriate subtractions for the contributions of the oxygen and Lucite were carried out with the help of previous measurements made at this laboratory[2,3,19]; the nitrogen contaminant required the present measurement of the $N^{14}[(\gamma,n)+(\gamma,pn)]$ cross section. This was done with a 125-g cyanoguanidine ($C_2H_4N_4$) sample; again, the appropriate subtractions for the carbon and the Lucite container were made.[19]

The threshold energies for the various photoneutron reactions are shown in the plots by arrows. As can be seen in Table I, the values obtained in the present experiments agree, within the experimental limits, with the values from Mattauch, Thiele, and Wapstra.[20]

TABLE I. Thresholds for photoneutron reactions (in MeV).

Reaction	Experimental	From Ref. 20
$Ba^{138}(\gamma, n)$	8.5 ± 0.1	8.54 ± 0.07
$Ba^{138}(\gamma, 2n)$	15.6 ± 0.1	15.49 ± 0.07
$Ba^{138}(\gamma, pn)$	···	17.54 ± 0.09
$Ba^{138}(\gamma, p2n)$	···	24.15 ± 0.10
$Ba^{138}(\gamma, 3n)$	···	24.72 ± 0.10
$N^{14}(\gamma, n)$	10.5 ± 0.1	10.553 ± 0.001
$N^{14}(\gamma, pn)$	···	12.497 ± 0.001

RESULTS AND DISCUSSION

N^{14}

The average neutron energy $\bar{E}_n$ for $[(\gamma,n)+(\gamma,pn)]$ events for N^{14}, derived from the ring-ratio data mentioned above, is shown as a function of photon energy in Fig. 1. The value for $\bar{E}_n$ rises from 4.5 MeV at a photon energy E_γ of 20 to 8 MeV at $E_\gamma = 27$ MeV. A least-squares straight-line fit to the data also is shown in Fig. 1, which, if extrapolated down to $\bar{E}_n = 0$ (through a region of low cross section and poor statistics) would intersect the abscissa at a photon energy within 0.5 MeV of the (γ, n) threshold.

The total photoneutron cross section for N^{14} (Fig. 2) contains contributions both from the (γ, n) and (γ, pn) processes [the $(\gamma, 2n)$ threshold is 30.64 MeV, above the range of the present measurement]. The combined $[(\gamma,n)+(\gamma,pn)]$ cross section measured here begins to rise rapidly only above 18 MeV, reaches its maximum value of 15 mb at 23.3 MeV, and exhibits structure at about 19, 20.5, and 26 MeV, and perhaps elsewhere, both below 18 and above 26 MeV. Also, the main

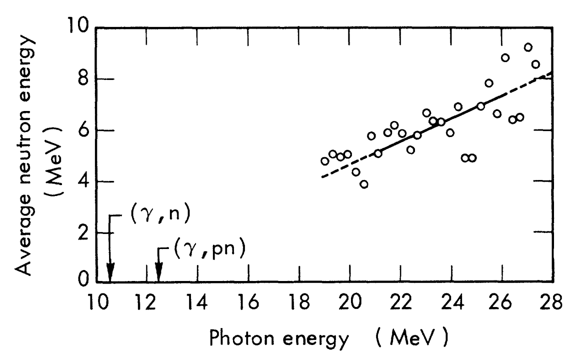

FIG. 1. Average neutron energy for $N^{14}[(\gamma,n)+(\gamma,pn)]$ events derived from the ring-ratio data and plotted as a function of photon energy (see text). The thresholds (arrows) are from Ref. 20.

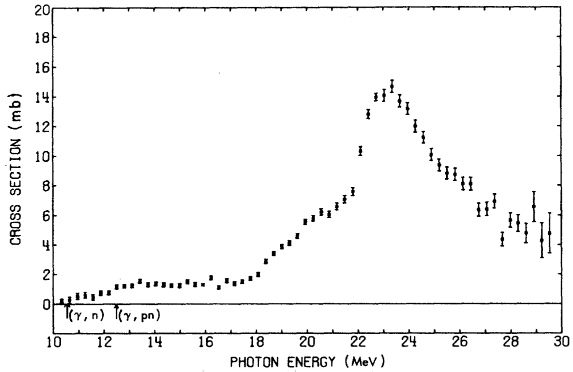

FIG. 2. Total photoneutron cross section for N^{14}, $\sigma[(\gamma,n)+(\gamma,pn)]$. The $(\gamma,2n)$ threshold is above the range of the present measurement.

peak at 23.3 MeV appears to be split between two absorption levels. This observation is verified by the $C^{13}(p,\gamma)$ measurement of Ref. 9, the neutron spectrum of Ref. 11, and also by a careful examination of the data of Refs. 4, 7, 8, and 13 [which are (γ,n), (γ,p), (γ,total), and (γ,p) measurements, respectively]. The 19- and 20.5-MeV peaks are also seen in the data of Refs. 4, 7, 9, 11, and 13. Since the primary motive for measuring this cross section was to extract the Ba^{138} cross sections from the $Ba^{138}(NO_3)_2$ data, the resolution used was coarse, and no doubt a better-resolution experiment would enhance the appearance of such structure as exists in the N^{14} cross section.

Although many decay channels are energetically possible for the deexcitation of the N^{14} giant-resonance states, only a few do not involve neutron emission. Since $E1$ excitation of a self-conjugate nucleus at low momentum transfer requires $\Delta T = +1$, the (γ,d), (γ,α), and (γ, Li^6) reactions are forbidden by the isospin selection rule. Furthermore, the non-neutron-producing reactions (γ,t), (γ, He^3), and (γ, Li^7) are expected to be unimportant. This leaves only the $N^{14}(\gamma,p)$ reaction to the ground or to one of the first three excited states of C^{13} as decay modes which do not involve neutron emission, since more highly excited states in C^{13} populated by (γ,p) reactions lie above the $C^{13}(\gamma,n)$ threshold and hence will almost surely emit a neutron in preference to a γ ray. [Likewise, all N^{13} states other than the ground state lie above the $N^{13}(\gamma,p)$ threshold, and hence will almost surely decay predominantly by proton emission.] Consequently, the major fraction of the N^{13} giant-resonance decays probably involve a neutron, and hence should be detected in the present experiment. This is partly confirmed by the magnitudes of the cross sections reported in Refs. 7 and 9, both of which indicate that the (γ,p_0) cross section

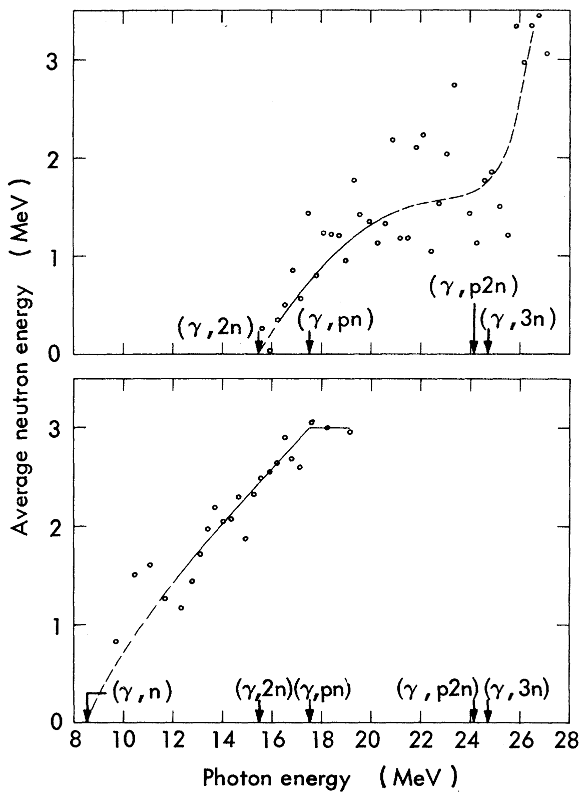

FIG. 3. Average neutron energies for Ba^{138} derived from the ring-ratio data: (top) for $[(\gamma,2n)+(\gamma,p2n)]$ events; (bottom) for $[(\gamma,n)+(\gamma,pn)]$ events.

is about 20% of the $[(\gamma,n)+(\gamma,pn)]$ cross section reported here (and also in Ref. 5, whose cross-section results are about 10% smaller than ours). Furthermore, since the $N^{14}(\gamma,n)$ cross section of Ref. 4 also is about 20% of the present $[(\gamma,n)+(\gamma,pn)]$ cross section, it appears that the $N^{14}(\gamma,pn)$ processes, proceeding through states in either N^{13} or C^{13}, account for the bulk, (probably about 60%) of the giant-resonance decays. Finally, the present measured integrated cross section is 97.6 MeV mb up to 29.5 MeV, or 46.5% of the classical dipole sum-rule value with no exchange corrections. Since this represents about 75% of the total photon absorption cross section, only slightly more than three fifths of the sum-rule value is exhausted up to this photon energy.

Ba^{138}

The average neutron energies $\bar{E}_n$ for $[(\gamma,n)+(\gamma,pn)]$ and for $[(\gamma,2n)]$ events for Ba^{138}, derived from the ring-ratio data, are shown as functions of photon energy in Fig. 3. The statistics are perhaps best indicated by the scatter of the data points. Where solid curves are drawn, the data are relatively good; the dashed curves indicate less certainty. The average energy for single-photoneu-

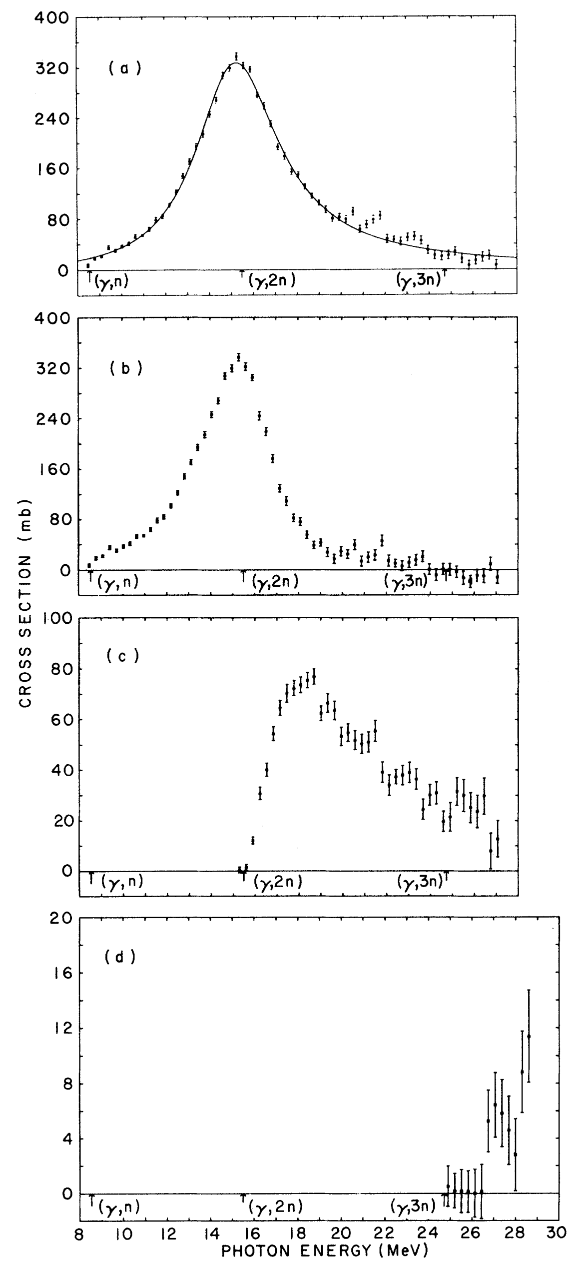

FIG. 4. Photoneutron cross sections for Ba^{138}. (a) Total photoneutron cross section $\sigma[\gamma, n) + (\gamma, pn) + (\gamma, 2n) + (\gamma, 3n)]$. The solid line is a Lorentz-curve fit to the giant-resonance data (12–19 MeV). (b) Single-photoneutron cross section $\sigma[\gamma, n) + (\gamma, pn)]$. (c) Double-photoneutron cross section $\sigma[\gamma, 2n) + (\gamma, p2n)]$. (d) The $(\gamma, 3n)$ cross section.

tron events $\bar{E}_n(1)$ rises gradually from threshold to a maximum of 3 MeV at the (γ, pn) threshold, then appears to level off a bit, possibly resulting from the opening of the (γ, pn) reaction channel. The fact that $\bar{E}_n(1)$ continues to rise above the $(\gamma, 2n)$ threshold probably results from the fact that $(\gamma, 2n)$ events bleed off the lowest-energy neutrons. (For other examples of these phenomena, see Refs. 18 and 21.) The values for $\bar{E}_n(1)$ at the peak of the giant resonance (15.26 MeV; see below) is 2.4 MeV. The average energy for double-photoneutron events $\bar{E}_n(2)$ rises gradually from threshold to about 1.5 MeV at 21 MeV, appears to level off a bit, and then seems to rise rapidly to about 3 MeV for photon energies above the $(\gamma, 3n)$ threshold.

The Ba^{138} photoneutron cross sections are shown in Fig. 4. The total photoneutron cross section $\sigma[(\gamma, n) + (\gamma, pn) + (\gamma, 2n) + (\gamma, 3n)]$ [Fig. 4(a)] exhibits the single-peaked shape typical of the giant resonance in spherical nuclei. Other structure is apparent at 21.6 and 23.3 MeV, and, less definitely, at 9.3 and 20.5 MeV. The single-photoneutron cross section $\sigma[(\gamma, n) + (\gamma, pn)]$ [Fig. 4(b)] reaches a peak of 336 mb at 15.3 MeV, then decreases rapidly to small values by 19.5 MeV, 4 MeV above the $(\gamma, 2n)$ threshold, in keeping with similar behavior observed for nearly every medium or heavy nucleus studied at this laboratory, and with the prediction of the statistical model. The $(\gamma, 2n)$ cross section [Fig. 4(c)] rises rapidly from threshold to a maximum value of 77 mb at 18.7 MeV, then decreases gradually, with some indications of structure between 19 and 27 MeV. The $(\gamma, 3n)$ cross section [Fig. 4(d)] remains small for a region of 1.5 MeV above threshold, then rises to about 10 mb at 29 MeV, the limit of the present measurement.

The total photoneutron cross section was fitted with a Lorentz curve whose parameters are $E_m = 15.26 \pm 0.02$ MeV, $\sigma_m = 327 \pm 3$ mb, and $\Gamma = 4.61 \pm 0.08$ MeV (the fitting interval used is 12–19 MeV; the χ^2 value for the fit is 2.47; the uncertainties given result from the fitting procedure only and do not include systematic errors). The nuclear symmetry energy K computed from E_m and Γ (see Ref. 18) is 26.2 MeV, in keeping with the values of K for other nuclei in this mass region. The integrated cross section computed from σ_m and Γ is 2.37 MeV b; the measured integrated cross section up to 27.1 MeV is 2.04 MeV b, or 102% of the sum-rule value. The partial integrated cross sections are $\sigma_{\text{int}}[(\gamma, n) + (\gamma, pn)] = 1.55$ MeV b and $\sigma_{\text{int}}(\gamma, 2n) = 0.49$ MeV b. The ratio of $\sigma_{\text{int}}(\gamma, 2n)$ to $\sigma_{\text{int}}(\gamma, \text{total})$ is 0.24 ± 0.03, roughly in agreement with the value of 0.19 ± 0.03 for Pr^{141} (Ref. 1), confirming that this important shell-model parameter[22] is a function of neutron (and not proton) number. The integrated moments of the measured total photoneutron cross section are $\sigma_{-1} = 131$ mb and $\sigma_{-2} = 8.72$ mb MeV^{-1}.

It is interesting to compare the giant resonance for this nucleus with that for Pr^{141}. Figure 5

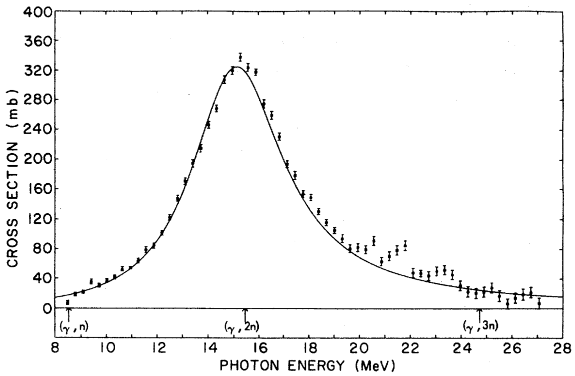

FIG. 5. Total photoneutron cross section for Ba^{138} (data points). The solid line is a Lorentz-curve fit to the Pr^{141} giant-resonance data of Ref. 1 (see text).

shows the Ba^{138} total photoneutron cross section [the data of Fig. 4(a)], together with the best Lorentz-curve fit ($\chi^2 = 0.77$) to the Pr^{141} data of Ref. 1. These latter data were reanalyzed with the same fitting interval as the Ba^{138} data; the new Lorentz parameters for Pr^{141} are $E_m = 15.15 \pm 0.01$ MeV, $\sigma_m = 324 \pm 2$ mb, and $\Gamma = 4.42 \pm 0.05$ MeV, barely differing from the values reported in Ref. 1. One can see immediately that the two cross sections are nearly the same, which shows once again that it is the neutron and not the proton number that dominates the shape of the giant resonance for medium-heavy and heavy nuclei.

Finally, Fig. 6 shows the ratio of the $(\gamma, 2n)$ cross section to the total photoneutron cross section for a few MeV above the $(\gamma, 2n)$ threshold, together with a theoretical fit based on the statistical model. The two parameters determined by such a fit are the level density a in Ba^{137} in the range of excitation energy from 7.0 to 13.1 MeV, and the shell-plus-pairing-effect parameter Δ, which is a correction to the ground-state energy

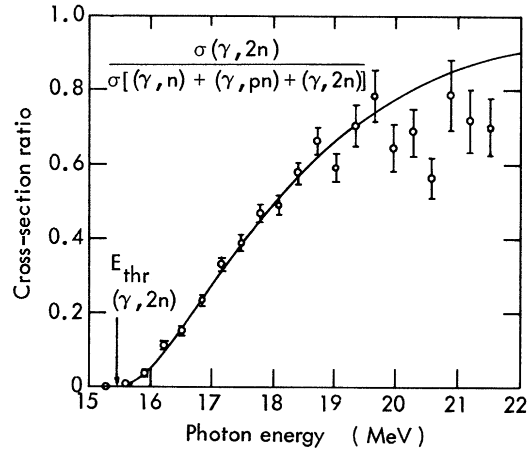

FIG. 6. Ratio of the $(\gamma, 2n)$ to the total photoneutron cross section for Ba^{138}. The solid line is derived from the theoretical expression for the nuclear density of states given in Ref. 23, evaluated for a level-density parameter $a = 5.3\ \mathrm{MeV}^{-1}$, and including a shell-plus-pairing-effect parameter $\Delta = 2.0$ MeV.

of Ba^{137} (see Ref. 17). Using the Ericson[23] formula for the density of states ρ, the present data yield best values for $a = 5.3\ \mathrm{MeV}^{-1}$ and $\Delta = 1.8$ MeV; using the Blatt and Weisskopf[24] formula, $a = 1.4\ \mathrm{MeV}^{-1}$ and $\Delta = 2.2$ MeV. This demonstrates once again that although a is strongly dependent on the functional form of ρ, Δ is not, and thus the value of 2.0 ± 0.2 MeV can be trusted as a measure of shell and pairing effects on the nuclear level density for Ba^{137}.

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Study of the Levels in ^{140}La Using the ^{139}La$(n,\gamma)^{140}$La Reaction*

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The levels in ^{140}La have been studied following thermal-neutron capture in ^{139}La using Ge(Li), Si(Li), curved-crystal, and coincidence spectrometers. The neutron binding energy of ^{140}La was determined as 5161.1 ±1.0 keV. The data, when combined with the previous ^{139}La-$(d,p)^{140}$La study, allow the assignment of the first 14 states up to 581.060 keV to the mixed configurations $\pi g_{7/2}\,\nu f_{7/2}$ and $\pi d_{5/2}\nu f_{7/2}$. The energies of states in keV (spin parity) are: 0 (3^-), 29.965 (2^-), 34.656 (5^-), 43.811 (1^-), 48.865 (6^-), 63.171 (4^-), 103.803 (6^-), 162.656 (2^-), 272.311 (4^-), 284.634 (7^-), 318.214 (3^-), 322.003 (5^-), 467.505 (1^-), 581.060 (0^-). Comparisons of γ-ray branching ratios and (d,p) cross sections with the predictions of a quasiparticle model for odd-odd nuclei allow a relatively uncompromised solution for the state vectors for the first 14 states. The success of this model implies that there is little phonon or four-quasiparticle admixture through the level at 581.060 keV. A detailed experimental study of additional levels up to 1055 keV has been performed.

I. INTRODUCTION

The experimental study of odd-odd nuclei is difficult not only because the high level density requires maximum resolution but also because the strong negative pairing energy and 0^+ ground state of parent even-even nuclei make decay scheme studies less fruitful than some other approaches. In spite of these difficulties a number of decay scheme studies[1-6] of ^{140}Ba have been attempted yielding excitation energies and spin assignments for six low-spin states in ^{140}La.

The high-energy γ-ray spectrum following thermal-neutron capture by ^{139}La has been studied by Groshev,[7] who used a magnetic Compton spectrometer. Giannini *et al.*,[8] using a NaI scintillation spectrometer, report four lines in the spectrum below 277 keV. Both the low- and high-energy por-