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Inelastic proton scattering from ^{138}Ba and ^{144}Sm at 30 MeV*

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Differential cross sections for elastic and inelastic scattering of 30-MeV protons by ^{138}Ba and ^{144}Sm have been measured with a total energy resolution for the inelastic peaks of 7–10 keV, full width at half maximum. This permitted the observation of 20 excited states in ^{138}Ba and 18 excited states in ^{144}Sm below $E_x = 3.4$ MeV, and the determination of excitation energies accurate to 2 keV or less for these states. Based on characteristic shapes derived from angular distributions to states of known J^π, spin-parity assignments were made for the majority of the observed states. Collective-model distorted-wave Born-approximation calculations for the observed transitions were compared to the data, and deformation parameters extracted for all states to which J^π could be assigned. The energy-level structures of these nuclei, obtained by combining the present results with information in the literature, are compared to the predictions of structure calculations based on the assumption of a closed $N = 82$, $Z = 50$ core.

[NUCLEAR REACTIONS ^{138}Ba, ^{144}Sm(p,p') $E_p = 30$ MeV. Resolution 7–10 keV. Enriched targets. Measured $\sigma(\theta)$ and E_x energies for 20 states up to $E_x \sim 3.3$ MeV. Deduced optical-model parameters. DWBA analysis, deduced J^π, $\delta_L = \beta_L R$, transition strengths G_L for 12 states in each nucleus. Comparison of results to shell-model calculations.]

I. INTRODUCTION

The recent interest in the "$N = 82$" nuclei stems from a number of sources. Foremost among these is the observation that in a shell-model picture, low-lying states in these nuclei are expected to be formed predominantly from proton configurations, the neutrons having the magic number 82. Furthermore, the active proton orbits should be those of the fifth major shell, those following the magic number 50. Experimental evidence from single-proton[1,2] and -neutron[3-5] transfer reactions confirms these expectations. The limit of viability of this simple picture is indicated by the positions of the lowest-lying neutron particle-hole states found near 4 MeV in isobaric-analog-resonance experiments.[6]

Electromagnetic decay aspects of the $N = 82$ nuclei have been studied through (β, γ),[7,8] (n, γ),[9] $(n, n'\gamma)$,[10] $(\alpha, xn\gamma)$,[11] and (γ, γ')[12] experiments. These experiments have been useful in assigning precise energies to the observed excited states and in limiting the possible J^π assignments of many of these states to a few values. The $(\alpha, xn\gamma)$ studies have led to the observation of a series of isomeric 6^+ states in the even-even $N = 82$ isotones.

Charged-particle inelastic scattering studies have been limited mainly to the observation of the strongly excited states. Early experiments[13] determined the positions of the first collective 2^+ and 3^- states. The $(p, p'\gamma)$ and $(d, d'\gamma)$ reactions[14] on the even-even isotones were studied in an attempt to locate the positions of excited 0^+ states in these nuclei by observing the $E0$ conversion electrons emitted in the transition to the ground state. More recently, the reactions ^{139}La(α, α'),[15] ^{140}Ce(α, α'),[15] ^{141}Pr(α, α'),[16] ^{138}Ba(α, α),[17] ^{144}Sm(α, α'),[18] ^{144}Sm(p, p'),[18,19] and ^{144}Sm$(^3$He$, ^3$He$')$[19] have been used to study the collective nature of the strongly excited states in these nuclei.

In this paper we present results from inelastic proton-scattering experiments performed at a bombarding energy of 30 MeV on ^{138}Ba and ^{144}Sm. Use of the high-resolution system developed by Blosser *et al.*[20] resulted in a total energy resolution for the inelastic peaks of typically 7–10 keV full width at half maximum (FWHM). Excitation energies accurate to within 1 to 2 keV were extracted and found to be in good agreement with those obtained in γ-ray-decay experiments. Using empirical characteristic shapes derived from angular distributions to known states, spins and parities were assigned to the majority of the observed states. The data were also analyzed with the standard collective-model distorted-wave Born-approximation (DWBA) formalism[21] to extract the deformation parameters of the excited states. A preliminary report of this work has been published elsewhere.[22]

II. EXPERIMENTAL PROCEDURES

Our measurements were made with 30-MeV protons from the Michigan State University sector-focused cyclotron. An Enge split-pole spectrograph was used to analyze the scattered particles. The amount of beam on target was monitored both with a current integrator in conjunction with a Faraday cup, and with a 5-mm-thick silicon detector placed at 60° with respect to the incident beam. A set of removable slits located immediately prior to the spectrograph scattering chamber was used periodically to check the position of the beam on target. The typical size of the energy-dispersed beam spot was 2 mm high by 4–5 mm wide. The entrance aperture of the spectrograph was 2° wide by 1.6° high, corresponding to a solid angle of 0.98 msr. During data accumulation this entrance aperture was the only slit between the cyclotron and focal plane of the spectrograph. The energies of the proton beams obtained from the calibration of the beam-transport system magnets (uncertainty of ±0.1%) were 29.8 MeV for ^{138}Ba and 29.9 MeV for ^{144}Sm.

Angular distributions for elastic scattering and for scattering from the strong first 2^+ and 3^- states in both nuclei were measured using a 300-μm-thick solid-state position-sensitive detector mounted in the focal plane of the spectrograph. The energy resolution obtained with this system was typically 30 keV FWHM. The remainder of the inelastic scattering data was obtained with Kodak NTB 25- or 50-μm-thick nuclear emulsions placed in the focal plane of the spectrograph. Aluminum absorbers were used to shield the emulsions from all particles of greater stopping power than protons. Emulsions were exposed every 5° between 20 and 80° for ^{138}Ba and between 12 and 95° for ^{144}Sm. Two exposures were made at each angle, a short exposure to obtain data for the first 2^+ and 3^- states (for normalization purposes), and an exposure sufficiently long to obtain data with good statistics for most of the remaining states. The position-sensitive-detector data and

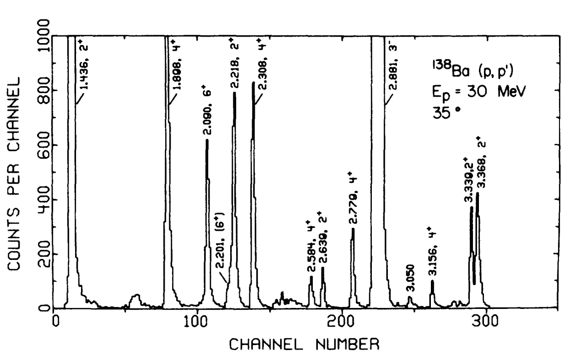

FIG. 1. Spectrum of ^{138}Ba(p,p') at 35° with resolution of about 10 keV FWHM. The broad bumps correspond to protons which scatter from Mg and Si impurities and because of kinematic differences have different planes of focus in the spectrograph. The yields of the 2^+ state at 1436 keV and of the 3^- state at 2881 keV were too intense to be counted on this plate.

the emulsion data for the 2^+ and 3^- states agreed to within the combined statistical uncertainties, so the data were combined to obtain angular distributions for these states.

Isotopically enriched compounds of $Ba(NO_3)_2$ (99.8%) and Sm_2O_3 (95.1%), obtained from Oak Ridge National Laboratory, were used in the fabrication of the targets. Each compound was placed in a Zr boat and heated in vacuum, causing reduction of the compound to the enriched metal and simultaneous evaporation of the metal onto the target backing, which consisted of a 20-μg/cm^2 carbon foil plus a 3–5-μg/cm^2 layer of Formvar supporting the carbon. The target material was evaporated over a surface 1.6 cm in diameter and appeared to be quite uniform. Typical target thicknesses ranged between 50 and 300 μg/cm^2. The targets were stored and transferred under vacuum to reduce oxidation; in air complete oxidation occurred in only a few seconds for a thin ^{138}Ba target and a few minutes for a ^{144}Sm target. Target thickness was estimated by comparing the measured elastic scattering to optical-model predictions for the scattering. The major contaminants in the targets, as determined from analysis of the inelastic scattering spectrum, were carbon, oxygen, magnesium, and silicon.

The emulsion data were all taken using the high-resolution system developed by Blosser *et al.*[20] This system relies on dispersion matching,[23] kinematic compensation, and a feedback system which compensates for possible drift of magnets in the cyclotron-beam transport system. Using the techniques described in Ref. 20 we routinely obtained resolutions of 7–10 keV FWHM at 30-MeV incident proton energy, as shown in Figs. 1 and 2. Typical beam currents on target were 100 nA for ^{138}Ba (target limited) and 900 nA for ^{144}Sm.

III. EXPERIMENTAL RESULTS

A. Energies of states in ^{138}Ba and ^{144}Sm

The techniques for measurements with nuclear emulsions described in the previous section were used to obtain precise energies for 20 excited states in ^{138}Ba and 18 states in ^{144}Sm which occurred below an excitation energy of 3.4 MeV. Peak centroids and intensities were extracted from the spectra obtained at each angle with the aid of an automatic peak-fitting program. The final adjustments to the basic energy calibration of the spectrograph were determined by fitting certain strong isolated peaks in our (p, p') spectra to excitation energies previously determined for these levels by Ge(Li) spectrometer studies of their γ-ray decays. These calibration energies, along with their errors, are noted in Table I.

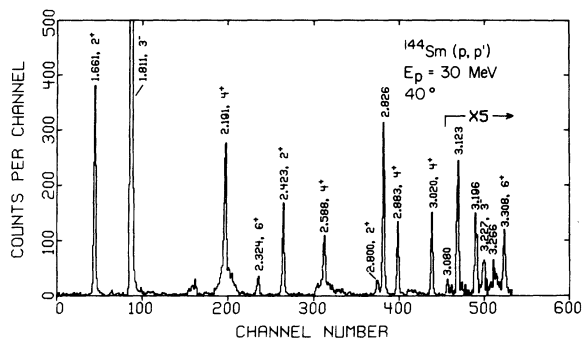

FIG. 2. Spectrum from ^{144}Sm(p,p') at 40° with resolution of about 7 keV FWHM. The broad bumps under certain of the peaks correspond to protons which scatter from Mg and Si impurities as in the ^{138}Ba spectrum. The yield of the 3^- state at 1811 keV was too intense to be counted on this plate. To the right of channel 454, the counts per channel have been multiplied by 5.

This calibration of the spectrograph was then used for interpolation to other excitation energies. The extracted energies were averaged over all angles of observation and the standard deviations in the centroids calculated. The energies we have assigned to levels in ^{138}Ba and ^{144}Sm, along with the combined random and systematic errors, are listed in Table I. The values are in excellent agreement with those from (β, γ)[7,8] work on ^{138}Ba and $(\alpha, 2n\gamma)$[11] work on ^{144}Sm.

B. Angular distributions

Angular distributions were obtained for 18 of the 20 states observed in ^{138}Ba, for 15 of the 18 states observed in ^{144}Sm, and for elastic scattering from both nuclei. The elastic scattering angular distributions from ^{138}Ba and ^{144}Sm are shown in Fig. 3. The curves through the data are optical-model calculations using the parameters of

TABLE I. Energy levels of ^{138}Ba and ^{144}Sm.

^{138}Ba		^{144}Sm	
Present work E_x (J^π) [a,b]	Previous work E_x (J^π) [c]	Present work E_x (J^π) [a,b]	Previous work E_x (J^π) [d]
1436 [e] ±1.0 2^+	1435.7±0.2 2^+	1661*[e]±1.0 2^+	1660.6± 1.0 2^+
1898*[e]±1.0 4^+	1898.4±0.3 4^+	1811 [e] ±1.2 3^-	1810.1± 0.5 3^-
2090*[e]±1.0 6^+	2090.1±0.6 (6^+)	2191*[e]±1.0 4^+	2190.6± 1.0 4^+
2201 ±2.0 (6^+)	2203.2 [f]	2324 [g] ±1.0	2323.2± 0.5 6^+
2218 ±1.0 2^+	2217.9±0.4 $(1,2^+)$	2423* ±1.0 2^+	2423.4± 1.0
2308* ±1.0 4^+	2307.4±0.3 (3,4)	2478 ±1.9	2478.3± 1.0 0^+
2415 ±1.2	2414.9±0.6 (5^+) [h]	2588 ±1.0 4^+	
2445 ±1.2	2445.4±0.3 3^+ [h]	2661 ±1.6	
	2582.8±0.6 1,2	2800 ±1.6 2^+	
2584 ±1.0 4^+		2826 ±1.8	2830 ±10
2639 ±1.2 2^+	2639.3±0.4 2	2883 ±1.9 4^+	
2779* ±1.0 4^+	2779.2±0.5 2,3,4	3020 ±2.0 4^+	
2881 [e] ±1.2 3^-	2880.5±0.6 3^-	3080 ±2.0	
(2929) [i] ±2.0	2931.1±1.0 1,2	3123 ±1.8	3123.8± 1.0 $7^{(-)}$
(2990) [i] ±2.0	2990.8±0.5 1,2,3,4	3196 ±1.9	
3050* ±1.0 (2^+)	3049.9±1.0 1,2	3227 ±2.0 3^-	
3156 ±1.2 4^+		3266 ±2.3	
	3163.5±0.8 2,3,4	3308 ±2.1 6^+	
3254 ±1.2			
3285 ±1.4			
3339 ±1.4 2^+	3339.5±1.5 1,2		
	3352.2±1.5 1,2		
3368 ±1.8 2^+	3365.9±1.0 1,2		

[a] Excitation energies in keV.
[b] Subset of levels used in energy calibration is marked with an asterisk(*).
[c] From Ref. 7, except see f and h below.
[d] From Refs. 11 and 18 and references cited therein, and Ref. 33.
[e] Used in determination of characteristic shapes.
[f] From Ref. 8.
[g] Unresolved doublet whose angular distribution is consistent with a spin 6^+ state plus a lower-spin state.
[h] From Ref. 30.
[i] These states were observed only at 20° and were very weak. See Sec. III.

Becchetti and Greenlees.[24] The elastic scattering angular-distribution data were normalized to the optical-model calculations to establish the cross-section scales for the inelastic transitions. Comparisons with calculations using other sets of optical-model parameters[25,26] result in an estimate of 10% over-all uncertainty in the assigned experimental cross sections. Relative uncertainties arising from scanning errors, monitoring errors, and statistical errors are typically 5%.

In order to obtain spins and parities from the measured angular distributions in a model-independent fashion, empirical characteristic shapes were derived for 2^+, 3^-, 4^+, and 6^+ angular distributions in the following way. Examination of angular distributions of, for example, the known 2^+ states in both ^{138}Ba and ^{144}Sm revealed that they all had essentially the same shape. Using this fact, a characteristic 2^+ shape was obtained by averaging together all of the distributions for transitions leading to known 2^+ states which are observed in both nuclei. This characteristic 2^+ shape was then used as a standard and compared to angular distributions for states of unknown J^π.

Identical techniques were applied to the angular distributions of all assigned 3^-, 4^+, and 6^+ states in these nuclei to obtain 3^-, 4^+, and 6^+ characteristic shapes. The resulting empirical characteristic shapes for 2^+, 3^-, 4^+, and 6^+ angular distributions are compared in Fig. 4. The states used in the determination of these shapes are noted in Table I. The angular-distribution data, along with the characteristic shape of the appropriate J^π which best approximates the data, are shown in Figs. 5 through 10. The remaining states, whose angular distributions are not similar to any of the characteristic shapes, are shown in Figs. 11 and 12. They may be grouped into two classes: either they are very weakly excited in this reaction, or they peak farther out in angle

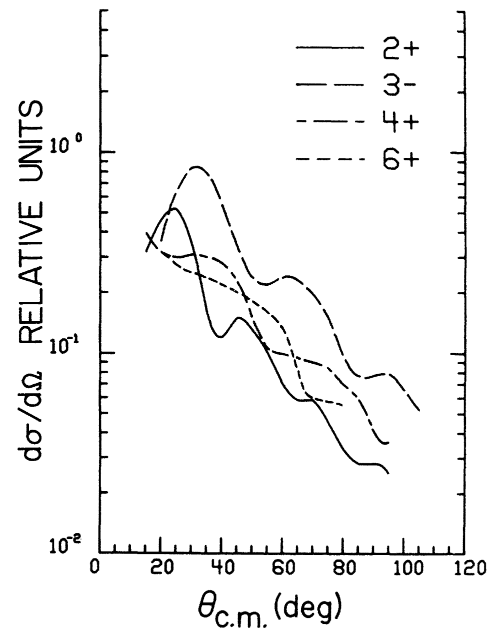

FIG. 4. Characteristic curves obtained by averaging our measured angular distributions from groups of states in ^{138}Ba and ^{144}Sm which had previously assigned J^π values.

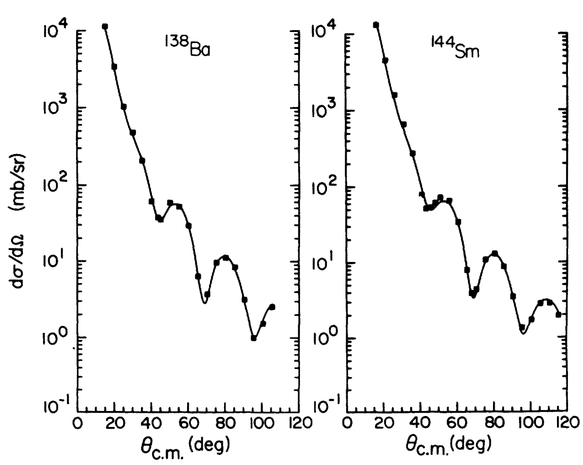

FIG. 3. Elastic scattering angular distributions measured for ^{138}Ba and ^{144}Sm. The curves are results of optical-model calculations made with the optical-model parameters of Becchetti and Greenlees (Ref. 24).

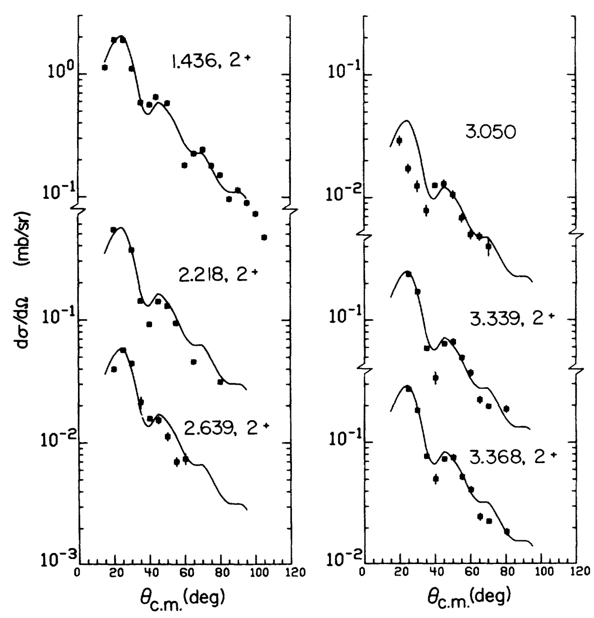

FIG. 5. States in ^{138}Ba which have angular distributions in agreement with the characteristic 2^+ shape, which is the line drawn through the data. We assign all of these states $J^\pi = 2^+$ with the exception of the state at 3050 keV.

than the 4^+ states, implying that they may be high-spin states.

Direct DWBA theory would predict L transfers of 2, 3, 4, and 6 for transitions from a 0^+ ground state to states with $J^\pi = 2^+$, 3^-, 4^+, and 6^+, respectively. There are sufficient differences between the characteristic shapes, as seen in Fig. 4, to allow us to uniquely assign an L transfer of 2,

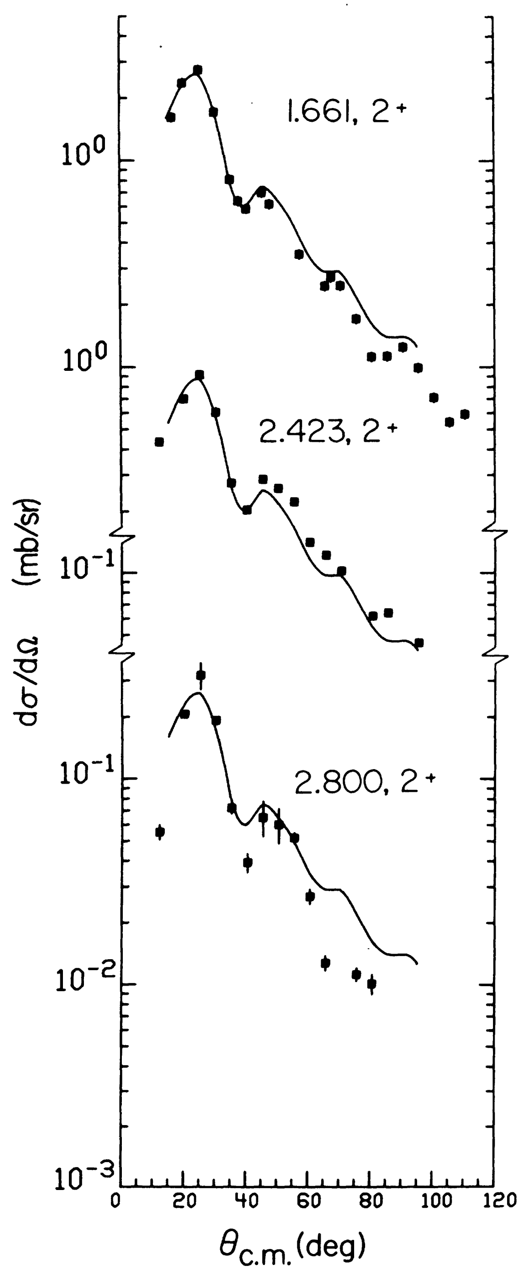

FIG. 6. States in ^{144}Sm which have angular distributions in agreement with the characteristic 2^+ shape which is the line drawn through the data. We assign all of these states $J^\pi = 2^+$.

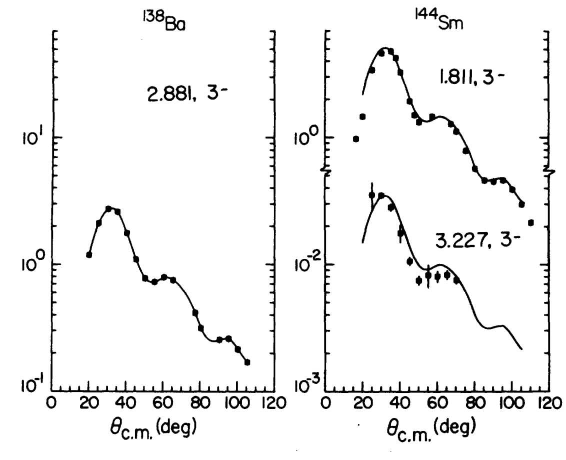

FIG. 7. States in ^{138}Ba and ^{144}Sm which have angular distributions in agreement with the characteristic 3^- shape which is the line drawn through the data. We assign these states $J^\pi = 3^-$.

3, 4, or 6 to the majority of the observed transitions. This in turn leads to assignments of $J = L$, with parity $(-1)^L$, if it is assumed that nonnormal-parity states are weakly excited. For example, an angular distribution for a state of unknown J^π which matches the 4^+ characteristic shape has an L transfer of 4. This in turn leads to a J^π assignment of 4^+, and not the nonnormal parity 3^+ or 5^+, as direct DWBA theory would also allow.

The only experimental angular distributions for nonnormal-parity transitions [transitions to states for which $\pi \neq (-1)^J$] in nuclei with mass $A > 80$ and at incident energies greater than 20 MeV of which

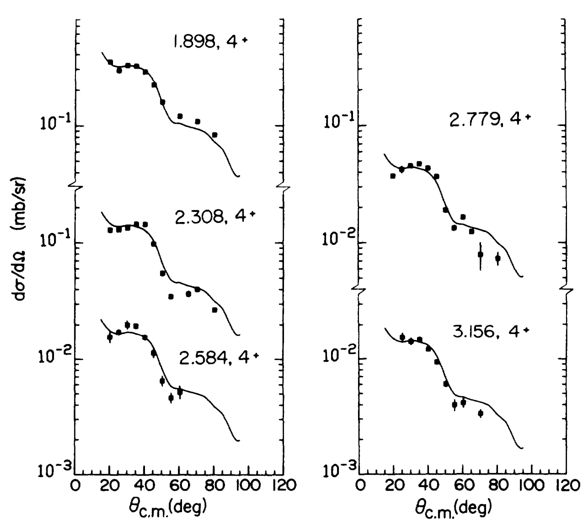

FIG. 8. States in ^{138}Ba which have angular distributions in agreement with the characteristic 4^+ shape which is the line drawn through the data. We assign all of these states $J^\pi = 4^+$.

we are aware are those for the 3^+ and (5^+) states in ^{138}Ba, which we observe, and for a 4^- state in ^{208}Pb.[27] In all cases, the cross sections are less than 20 μb/sr. The fact that so few nonnormal-parity states are observed in inelastic proton scattering is evidence in itself that cross sections to such states must be small. Microscopic model calculations for transitions to the 3^+ and (5^+) states in ^{138}Ba have been made according to the technique of Ref. 28. The resulting cross sections are approximately 1 μb/sr. Thus, both theory and experiment indicate that nonnormal-parity states (also often referred to as spin-flip states) are indeed very weakly excited in medium-energy inelastic proton scattering on heavy nuclei. Our assignments for the spins and parities of the excited states we observe in ^{138}Ba and ^{144}Sm, based on the agreement of the measured angular distributions with the empirical characteristic shapes and the assumption of negligible spin-flip probability, are given in Table I.

C. Discussion of states in ^{138}Ba

To organize the discussion of our experimental results, it is convenient to divide the levels which we observe into groups corresponding to the various J^π assignments.

1. 2⁺ states (Fig. 5)

The states at 1436, 2218, 2639, 3339, and 3368 keV are assigned $J^\pi = 2^+$. The state at 1436 keV is firmly established as 2^+ from Coulomb-excitation,[29] conversion-coefficient,[30] and (α, α') inelastic scattering measurements.[17] The state at 2218 keV is observed to have a strong decay branch to the ground state in neutron capture[9] and (β, γ)[7,8,30] decay experiments. This limits the spin to 1 or 2. Achterberg *et al.*[30] assign positive parity to this state from conversion-coefficient measurements. Thus our assignment of $J^\pi = 2^+$ is consistent with previous data. The level at 2639 keV, observed in (n, γ)[9] and (β, γ)[7,8] studies, also has a strong decay branch to the ground state, thus limiting its spin to $J = 1, 2$. However, the logft value of 7.4 for β decay from the $J = 3^-$ state of ^{138}Cs given by Carraz, Monnand, and Moussa[8] eliminates $J = 1$. The two levels at 3339 and 3368 keV also decay directly to the ground state, limiting their spins to $J = 1, 2$. Angular distributions from (α, α') studies[17] also suggest an assignment of $J^\pi = 2^+$ for these states. The angular distribution for the state we observe at 3050 keV is not in agreement with the 2^+ characteristic shape at forward angles, thus we leave its assignment tentative. Hill and Fuller[7] assign $J = 1, 2$ to this state.

2. 3⁻ states (Fig. 7)

The only 3^- state we observe in ^{138}Ba is the one previously assigned[13,17] at 2881 keV. It is the strongest state in the (p, p') spectrum, and is strongly populated in (d, d')[14] and (α, α')[17] experiments and in (n, γ)[9] studies, where it decays strongly to the 2^+ state at 1436 keV.

3. 4⁺ states (Fig. 8)

The states at 1898, 2308, 2584, 2779, and 3156 keV are assigned $J^\pi = 4^+$. The level at 1898 keV is established as 4^+ from (α, α')[17] angular distributions, $(d, {}^3\text{He})$[2] measurements which suggest an assignment of 4^+ or 6^+, and conversion-coefficient[30] studies which, when combined with the $(d, {}^3\text{He})$ work, limit the spin to 4^+.

The state at 2308 keV was assigned $J^\pi = 3^+, 4^+$ in the conversion-coefficient studies of Achterberg *et al.*[30] A $J = 3, 4$ assignment has also been suggested by (n, γ)[9] and (β, γ)[7] studies based on the strong decay to both the first 2^+ and 4^+ states. An assignment of $J^\pi = 4^+$ to this state is also consistent with the results of (α, α')[17] studies.

Hill and Fuller[7] and Mariscotti *et al.*[9] observe a state in the vicinity of the state we see at 2584 keV. Hill and Fuller limit the spin of this state to $J = 1, 2$ on the basis of a γ-ray branch to the ground state. However, the angular distribution we measure has a 4^+ shape. Thus, we believe there are two distinct levels in this vicinity, since the state seen by Hill and Fuller is clearly not a 4^+ by virtue of the γ ray to the ground state. It is informative to consider ratios of intensities

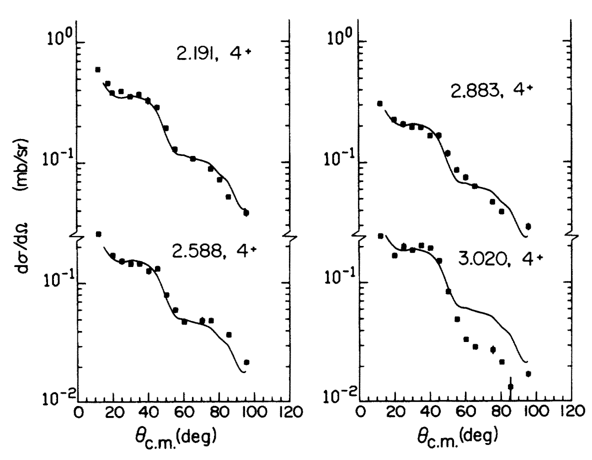

FIG. 9. States in ^{144}Sm which have angular distributions in agreement with the characteristic 4^+ shape which is the line drawn through the data. We assign all of these states $J^\pi = 4^+$.

of two γ rays depopulating this "level," as measured by Hill and Fuller in their (β, γ) work and by Mariscotti *et al.* in their (n, γ) studies:

$$\frac{I(2583 \to 1436)}{I(2583 \to 0)} = 7.8 \quad (n, \gamma),$$

$$\frac{I(2583 \to 1436)}{I(2583 \to 0)} = 2.3 \quad (\beta, \gamma).$$

Thus

$$\frac{(n, \gamma)}{(\beta, \gamma)} = 3.3. \tag{1}$$

Similar ratios for the 2583–2218-keV transition relative to the ground-state transition are also in the ratio of 3 : 1. The difference between the (n, γ) and (β, γ) ratios can be taken as an indication that the two experiments are populating two different levels with different intensities in the vicinity of 2583 keV. In addition, Hill and Fuller see a broadening of the γ-ray line connecting their state at 2583 keV with the 2445-keV state. They attribute this to the decay of the 2445-keV to the 2307-keV state, but we suggest it could also be due to a state at 2584 keV decaying to the 2445-keV state. The broadened decay line they observe could then correspond not to two but to three different transitions. We will find in Sec. V that shell-model calculations predict a 1^+-4^+ doublet near this energy, which would be consistent with the present experimental observations. A 1^+ state would decay to the ground state via an $M1$ transition, but since it is a nonnormal-parity state we would not expect to populate it strongly in (p, p'). The angular distribution we measure for this doublet would then assume the shape characteristic of the 4^+ member of the doublet.

The state at 2779 keV is observed in (β, γ),[7] but not (n, γ)[9] work and decays to both of the first excited 2^+ and 4^+ levels, thus limiting its spin to $J = 2, 3, 4$. It may also correspond to the state at 2.79 MeV observed in the $(d, {}^3\mathrm{He})$[2] experiment.

The state at 3156 keV which we observe is probably not the same state reported by Hill and Fuller[7] at 3164 keV, since the 8-keV difference in energies is outside the combined errors. However, they do assign spin limits of $J = 2, 3, 4$ to their state based on its decay to the first excited 2^+ and 4^+ states. These two experiments are the only ones which report a state near this energy.

4. 6^+ states (Fig. 10)

Angular distributions for known 6^+ states are scarce in the literature. Our standard 6^+ shape is based on the distribution for the state at 2090 keV which has been assigned 6^+ by Carraz, Monnand, and Moussa[8] on the basis of its measured half-life of 0.8 μsec. This assignment is consistent with systematics of 6^+ states in $N = 82$ nuclei; isomeric 6^+ states have been identified[31] in all the even-even isotones from ^{134}Te to ^{146}Gd. A 6^+ assignment is also consistent with the absence of this state in the (n, γ)[9] work, and its negligible feeding in the β decay of the 3^- ground state of ^{138}Cs.

The state at 2201 keV is the subject of some

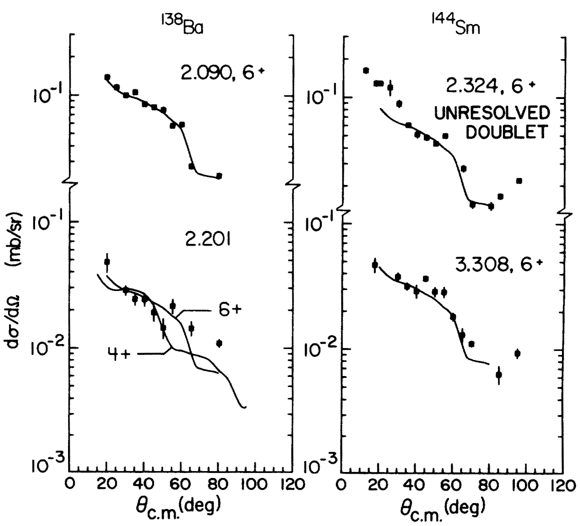

FIG. 10. Angular distributions for the previously assigned 6^+ state at 2090 keV and the weak 2201-keV member of a doublet in ^{138}Ba. Both the 4^+ and 6^+ characteristic curves are drawn through this angular distribution. The 2324-keV state in ^{144}Sm has been assigned 6^+, but due to the rise of the data at forward angles, this state may be a close-lying doublet. We assign $J^\pi = 6^+$ to the 3308-keV state in ^{144}Sm.

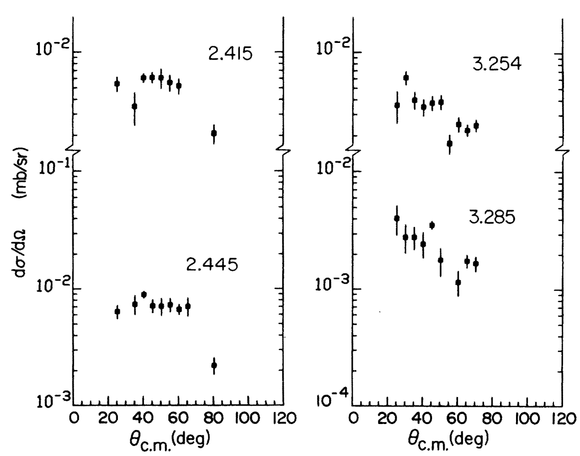

FIG. 11. Angular distributions of states in ^{138}Ba for which no J^π assignment could be made from this work. Spins of 5^+ and 3^+ have been suggested for the states at 2415 and 2445 keV, respectively (Ref. 30).

controversy. Carraz, Monnand, and Moussa[8] propose that this state has $J^{\pi}=(5^-)$, while Achterberg *et al.*[30] propose $J^{\pi}=(4^+,5^+)$, based on measurement of $\log ft$ values from the decay of $^{138}Cs^{m,g}$ and the assumption of $J^{\pi}=3^-$, (6^-) for the ground and isomeric states, respectively, of ^{138}Cs. This state is quite weak in our spectra, and not well resolved from the strong 2^+ at 2218 keV. Our angular distribution is not inconsistent with any of the tentative assignments. Both the 4^+ and 6^+ characteristic shapes are drawn through the angular distribution for this state in Fig. 10. We would favor a (6^+) assignment for this state, biased by the predictions of shell-model calculations as well as by the shape of the angular distribution.

5. *Other states (Fig. 11)*

We make no J^{π} assignments for the states we observe at 2415, 2445, 3254, and 3285 keV. The transitions to these states are all very weak, the largest cross section at any angle being less than 10 μb/sr. Achterberg *et al.*[30] have assigned $J^{\pi}=3^+$ to the state at 2445 keV, based on angular-correlation and conversion-coefficient measurements. They also suggest a $J^{\pi}=5^+$ assignment for the state at 2415, based on $\log ft$ values of the β decay feeding it from $^{138}Cs^{m,g}$. Our angular distributions for these states, by virtue of their magnitudes, support nonnormal-parity assignments. The two remaining states at 3254 and 3285 keV were not seen in previous work on this nucleus, and our angular distributions do not shed any light on possible J^{π} assignments for them. The 2929- and 2990-keV states which were observed only at 20° are very weak $[\sigma(20°)<1\ \mu b/sr]$ and are therefore not likely to be low-spin normal-parity states. Hill and Fuller[7] suggest spins of $J=1,2$ and $1,2,3,4$, respectivly, for these states.

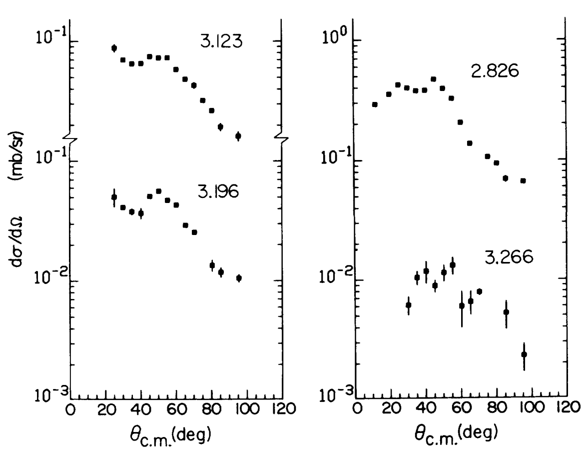

FIG. 12. Angular distributions of states in ^{144}Sm for which no J^{π} assignment could be made from this work. The state at 3123 keV has been assigned $J^{\pi}=7^{\pm}$ in Ref. 11.

D. Discussion of states in ^{144}Sm

1. *2^+ states (Fig. 6)*

The states at 1661, 2423, and 2800 keV are assigned $J^{\pi}=2^+$. The 1661-keV level is the first excited state in ^{144}Sm: Its J^{π} value is firmly established from Coulomb excitation,[32] (β,γ)[33] studies, and (α,α') and (p,p')[18] experiments. Barker and Hiebert[18] also assign a 2^+ state at 2.45 ± 0.2 MeV via (p,p') and (α,α') reactions, which we assume corresponds to our level at 2423 keV. The state at 2800 keV is here assigned $J^{\pi}=2^+$ from comparison of its angular distribution with the 2^+ characteristic shape. It has also been observed weakly in the β^+ decay[33] of the 1^+ ground state of ^{144}Eu.

2. *3^- states (Fig. 7)*

The states at 1811 and 3227 keV are assigned $J^{\pi}=3^-$. The state at 1811 keV is well established to have $J^{\pi}=3^-$ from (α,α') and (p,p') experiments,[18] and it is the strongest state observed in our ^{144}Sm spectra. The angular distribution of the previously unobserved state at 3227 keV is very similar to that of the 1811-keV state, as well as to the angular distribution for the collective 3^- state in ^{138}Ba.

3. *4^+ states (Fig. 9)*

The states at 2191, 2588, 2883, and 3020 keV are assigned $J^{\pi}=4^+$. The level at 2191 keV has previously been assigned $J^{\pi}=4^+$ on the basis of γ-ray systematics,[31] and recent (α,α') and (p,p') experiments[18] support this assignment. We assume that this is the level at 2.21 ± 0.02 MeV observed in (d,d') and (p,p') studies.[14] The states at 2588, 2883, and 3020 keV have not been previously reported. They are in good agreement with the characteristic 4^+ shape, with the possible exception of the 3020-keV state which falls off somewhat too rapidly for angles larger than 50°. These 4^+ assignments are consistent with the fact that Kownacki *et al.*[11] have not observed these states in the ^{142}Nd$(\alpha,2n)^{144}$Sm reaction which preferentially populates states with $J\geq8$. Studies of the β decay of the ^{144}Eu 1^+ ground state[33] also show no evidence for levels at these energies which is in agreement with our 4^+ assignments since population of 4^+ states via this decay would be unique second forbidden.

4. 6^+ states (Fig. 10)

The Stockholm group[31] has assigned the state at 2324 keV a spin-parity of 6^+, based on its lifetime of 0.88 sec. This agrees with systematics of 6^+ states in the $N = 82$ nuclei. However, our angular distribution for this state is only in qualitative agreement with the characteristic 6^+ shape due to the rise of the data at forward angles. This could be due to a very close-lying low-spin state, which would cause the experimental angular distribution to rise at forward angles. This possibility is supported by the fact that the FWHM of this peak is consistently 10–15% larger than that of other nearby peaks. We also assign $J^\pi = 6^+$ to the previously unobserved state at 3308 keV on the basis of the shape of its angular distribution.

5. Other states (Fig. 12)

We make no J^π assignments for the states we observe at 2826, 3123, 3196, and 3266 keV. The state at 3123 keV has been assigned $7^{(\pm)}$ by the Stockholm group[11] in their search for high-spin states with the ^{142}Nd(α, $2n\gamma$)^{144}Sm reaction and coincidence techniques. Our angular distribution for this state is consistent with a high-spin state: If this is the same state seen by the Stockholm group, we would favor a 7^- rather than a 7^+ assignment as it is fairly strongly excited. The angular distributions for the levels at 2826 and 3196 keV also peak at large angles suggestive of high-spin states, but the Stockholm group did not find levels at these energies. The 2800- (2^+) and 2826-keV levels are seen as a doublet in the (α, α') and (p, p') work of Barker and Hiebert.[18] The 2826-keV level is interesting because of its strong inelastic scattering cross section; unfortunately it is not possible to make a spin assignment to it. We also note in passing the similarity of the 3123- and 3196-keV angular distributions. Finally, the state at 3266 keV has not been observed previously, and is excited very weakly in the present experiment. The angular distribution for this state does not allow us to make any suggestions for its spin and parity.

IV. DWBA ANALYSIS

Essential ingredients in any DWBA calculation are the optical-model potential parameters which describe the elastic scattering in the entrance and exit channels. A number of optical-model parameter studies[24–26] have been made for 30-MeV protons incident on nuclei with A between 40 and 208. However, there is a large gap from tin ($A \sim 120$) to lead ($A = 208$) for which very little precise elastic scattering data exists, and thus no information for this region was included in the optical-model studies. It was not clear, therefore, that the parameters which these studies predict would properly account for the elastic scattering from ^{138}Ba and ^{144}Sm.

Fortunately, parameters predicted by the previous studies[24–26] yielded results which are in very good agreement with our elastic scattering data. For example, the optical-model parameters of Becchetti and Greenlees[24] predict elastic scattering angular distributions for ^{138}Ba and ^{144}Sm consistent with experiment within a χ^2 per point of 3.4 and 5.3, respectively, while Sets I and II from Satchler's analysis[25] yield fits of almost equal quality. The optical-model parameters used in the DWBA calculations to be described in the following sections were determined by adjusting the values of the standard global parameters to best fit the present Ba and Sm elastic scattering data. The final best-fit parameters are given in Table II. The sensitivity of the calculated inelastic scattering cross sections to the choice of optical-model parameters was investigated by making comparative calculations with the parameter sets of Refs. 24 and 25. Relative to the elastic scattering cross sections the results were essentially identical.

Conventional collective-model[20] DWBA calculations deforming both the real and imaginary terms of the optical-model potential were carried out for all of the transitions observed in ^{138}Ba and ^{144}Sm. We extracted deformation parameters β_L' for all states with assigned J^π values by normalizing the calculated angular distributions to the measured distributions with a χ^2 fitting program. The forward-angle data were most strongly weighted in these fits. The resulting β_L' values were used to estimate the strengths $B(EL)$ of the corresponding transitions between the ground state and the state of interest. Coulomb excita-

TABLE II. Optical-model parameters used in the DWBA analyses of inelastic scattering on ^{138}Ba and ^{144}Sm. The units of length are fm, the units of potential strengths are MeV. The notation is that of Ref. 24.

	^{138}Ba	^{144}Sm
r_c	1.20	1.20
V_R	54.80	56.10
r_R	1.14	1.13
a_R	0.75	0.75
W_V	3.00	2.70
r_I	1.33	1.33
a_I	0.67	0.67
W_{SF}	6.86	6.72
V_{so}	6.10	6.40
r_{so}	1.14	1.12
a_{so}	0.75	0.75

tion was not included in the form-factor calculations. Test cases showed that its inclusion would not have altered the extracted deformation parameters by more than 4% for $J^\pi = 2^+$ and 3^-, and negligibly for higher-spin transfers.

The formalism of Bernstein[34] has been designed to extract equivalent electromagnetic isoscalar-transition rates from inelastic α-scattering data. However, the method can be applied to our results if it is assumed (1) that spin- and isospin-flip amplitudes are small and (2) that the contribution from the interior of the nucleus, which contributes to proton but not to α inelastic scattering, can be neglected. There is some evidence that these are not unreasonable assumptions on the average, since deformation lengths $\delta' = \beta' R'$ obtained from inelastic proton and α scattering are often in good agreement.[18, 34] The isoscalar-transition rates are calculated (in single-particle units) from the equation[34]

$$G_L = \frac{(Z\beta_m)^2(3+L)^2}{4\pi(2L+1)} , \qquad (2)$$

where β_m, the mass-deformation parameter, is obtained from the prescription[34]

$$\beta' R' = \beta_m R_m , \qquad (3)$$

β' is obtained from the relation $\sigma_{\text{expt}}/\sigma_{\text{thy}} = (\beta')^2$, R' is the imaginary radius obtained from optical-model fits to elastic scattering, and $R_m = 1.2A^{1/3}$ is the cutoff radius for a uniform-charge-density model of the nucleus.

Figures 13 and 14 show our measured angular distributions for the lowest-lying 2^+, 3^-, 4^+, and 6^+ states in ^{138}Ba and ^{144}Sm along with the collective-model DWBA predictions for these states. As seen in Figs. 13 and 14, the predicted angular distributions are in good agreement with the data for the 2^+ and 3^- states, but the agreement deteriorates as one goes to the higher-spin states. Results of calculations for the remaining states observed in our measurements are not shown, since our use of characteristic shapes indicated that all experimental angular distributions for a given J^π have very similar shapes. The empirical observation that the shapes of the angular distributions appear to be independent of excitation energy in the energy range from 1 to 3.5 MeV is consistent with the results of the collective-model DWBA calculations.

The results of these collective-model analyses are given in Table III. The small size of the deformation parameters, except for the lowest 3^- states, is an indication that the states are not strongly collective. The results of previous studies of inelastic scattering on ^{138}Ba and ^{144}Sm are compared with our results in Table IV. Values of both $\beta' R'$ and G_L are listed. The most intensely studied transition in this group is that leading to the first excited 2^+ state in ^{144}Sm. The values of $\beta_2' R'$ extracted for this transition by the various workers have a maximum scatter of 15%. This sort of consistency seems typical for the other 2^+ and 4^+ transitions for which comparisons can

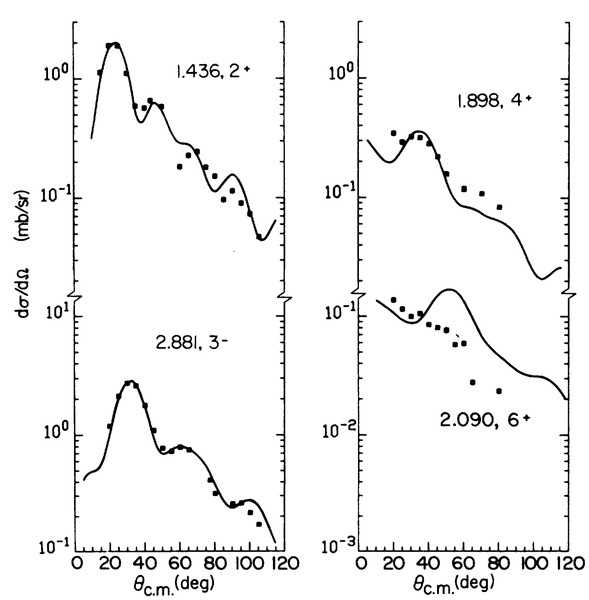

FIG. 13. Results of collective-model calculations for inelastic scattering on ^{138}Ba for the lowest 2^+, 3^-, 4^+, and 6^+ states.

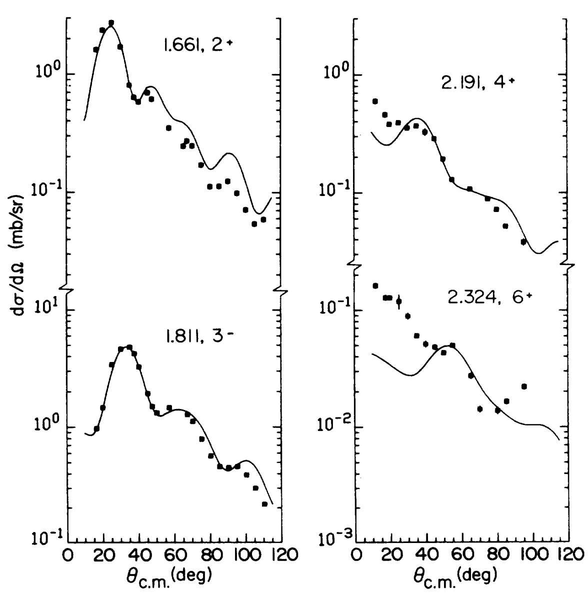

FIG. 14. Results of collective-model calculations for inelastic scattering on ^{144}Sm for the lowest 2^+, 3^-, 4^+, and 6^+ states. The curve for the 2.324-MeV state is for $\beta_L R' = 0.15$ (see Table III).

TABLE III. Deformation lengths and transition strengths for ^{138}Ba and ^{144}Sm from this work.

^{138}Ba				^{144}Sm			
E_x energy (keV)	J^π	$\beta_L R'$ (fm)	$G(L)$	E_x energy (keV)	J^π	$\beta_L R'$ (fm)	$G(L)$
1436	2^+	0.43	6.1	1661	2^+	0.46	8.7
2218	2^+	0.23	1.7	2423	2^+	0.29	3.5
2639	2^+	0.07	0.2	2800	2^+	0.14	0.8
3339	2^+	0.15	0.7	1811	3^-	0.87	34.0
3368	2^+	0.17	1.0	3227	3^-	0.07	0.3
2881	3^-	0.73	18.9	2191	4^+	0.33	5.8
1898	4^+	0.31	4.1	2588	4^+	0.21	2.3
2308	4^+	0.21	1.9	2883	4^+	0.25	3.2
2584	4^+	0.08	0.2	3020	4^+	0.23	2.8
2779	4^+	0.12	0.6	2324	(6^+)	0.11 [a]	1.0
3156	4^+	0.07	0.2			0.18 [a]	2.8
2090	6^+	0.30	6.3	3308	6^+	0.15	1.8
2201	(6^+)	0.15	1.7				

[a] These numbers represent the extremes of possible fits to the data.

be made, but the available evidence for the 3^- transitions does not agree with this trend. The values of $\beta_3' R'$ measured with $Z=2$ projectiles are uniformly lower than those measured with protons and by significant amounts.

Coulomb-excitation measurements of $B(E2)$ for the ground- to first-excited-state transitions in ^{138}Ba and ^{144}Sm yield values of 442 ± 18 and 500 ± 75 e^2 fm^4, respectively. These values correspond to 10.0 ± 0.4 and 11.0 ± 1.8 single-particle units. Comparison with the values of $G(L)$ obtained from nuclear inelastic scattering indicates that the latter are only 60–80% of the magnitudes obtained by the direct electromagnetic probes. This failure of the two types of experiments to yield the same answers seems to occur only in this region of the Periodic Table.[17,34]

As one adds protons outside a closed core, one might expect that the fraction of the collective strength found in the low-lying states will increase and that this increase will be reflected in the inelastic scattering cross sections. Barker and

TABLE IV. Summary of deformation lengths and G_L values for states in ^{138}Ba and ^{144}Sm from various reactions.

	J^π	E^* (MeV)	Reaction	Beam energy (MeV)	$\delta_L' = \beta_L' R'$ (fm)	G_L	Reference
^{138}Ba	2^+	1.436	(p,p')	30	0.43	6.1	Present work
	2^+	1.436	(α,α')	50	0.42	5.6	17
	4^+	1.898	(p,p')	30	0.31	4.1	Present work
	4^+	1.898	(α,α')	50	0.30	3.6	17
	2^+	2.218	(p,p')	30	0.23	1.7	Present work
	2^+	2.19	(α,α')	50	0.19	1.2	17
	4^+	2.308	(p,p')	30	0.21	1.9	Present work
	4^+	2.27	(α,α')	50	0.19	1.4	17
	3^-	2.881	(p,p')	30	0.73	18.9	Present work
	3^-	2.88	(α,α')	50	0.58	11.6	17
	2^+	3.339	(p,p')	30	0.15	0.7	Present work
	(2^+)	3.34	(α,α')	50	0.18	1.0	17
^{144}Sm	2^+	1.661	(p,p')	30	0.46	8.7	Present work
	2^+	1.66	(p,p')	30	0.44	7.4 [a]	18
	2^+	1.659	(p,p')	50	0.41	6.4	19
	2^+	1.66	$(^3He,^3He')$	53	0.47	8.5	19
	2^+	1.66	(α,α')	50	0.43	7.0	18
	3^-	1.811	(p,p')	30	0.87	34.0	Present work
	3^-	1.81	(p,p')	30	0.82	27.6 [a]	18
	3^-	1.82	$(^3He,^3He')$	53	0.71	20.7	19
	3^-	1.81	(α,α')	50	0.71	20.8	18
	4^+	2.191	(p,p')	30	0.33	5.8	Present work
	4^+	2.19	(p,p')	30	0.32	4.9 [a]	18
	4^+	2.19	(α,α')	50	0.30	4.2	18
	2^+	2.423	(p,p')	30	0.29	3.5	Present work
	2^+	2.45	(p,p')	30	0.29	3.2 [a]	18
	2^+	2.45	(α,α')	50	0.26	2.5	18

[a] The quantities G_L listed in Ref. 18 for (p,p') are wrong due to an arithmetic error. The corrected values are given above. Private communication from J. H. Barker.

Hiebert[17, 18] have noted such an increase in strength for the lowest-lying 3^- state but have found no increase for the lowest-lying 2^+ state. To check on this expectation with our more complete data, we have summed the strengths found for the 2^+, 3^-, and 4^+ states in Figs. 6–10, with the results shown in Table V. The summed strengths of the 2^+ excitations in ^{144}Sm are 30% greater than in ^{138}Ba while the 3^- and 4^+ strengths are about a factor of 2 greater in ^{144}Sm. The only unassigned states ($E_x \leq 3.3$ MeV) with substantial strength are in ^{144}Sm and these probably have $L \sim 4$, which would tend to increase the ^{144}Sm/^{138}Ba ratio for the higher spins. The sample of 6^+ states is so small that no reliable conclusions can be drawn, but the ratio is less than 1 if the cross sections in Fig. 11 are assigned to be 6^+.

It has been suggested[34] that a better measure of the intrinsic strengths is the energy weighted sum $\sum E_x G_L$. The ratios of these sums are also tabulated in Table V. The ratio for the 2^+ states is essentially unchanged, while that for the 3^- states is now near unity and that for the 4^+ states is somewhat increased.

V. COMPARISON OF OBSERVED SPECTRA WITH NUCLEAR-STRUCTURE CALCULATIONS

As is well known, analysis of the variations of nuclear parameters as a function of mass number indicates that the nucleon numbers 50 and 82 correspond to major shell closures. It follows that a theoretical treatment of the structure of the lowest-lying energy levels of $^{138}_{56}$Ba$_{82}$ and $^{144}_{62}$Sm$_{82}$ might logically be based on the assumption of an inert core consisting of 50 protons and 82 neutrons. The structural features of the states here in question would arise in this picture from the couplings of the 6 (^{138}Ba) and 12 (^{144}Sm) protons outside the $N = 82$, $Z = 50$ core. As mentioned in the Introduction, neutron- and proton-stripping and pickup studies in this region show that this picture of the "$N = 82$" nuclei is basically valid.

TABLE V. Ratio of excitations below $E_x = 3.3$ MeV by (p,p') in ^{138}Ba and ^{144}Sm.

J^π	2^+	3^-	4^+
$\dfrac{\sum_i G_i\,(^{144}\text{Sm})}{\sum_i G_i\,(^{138}\text{Ba})}$	1.35	1.81	2.02
$\dfrac{\sum_i E_i G_i\,(^{144}\text{Sm})}{\sum_i E_i G_i\,(^{138}\text{Ba})}$	1.36	1.14	2.44

There are at present two lines of theoretical investigation of the $N = 82$ nuclei. Calculations in the framework of the BCS model have been carried out by Rho,[35] by Waroquier and Hyde,[36] and by Freed and Miles.[37] Conventional shell-model calculations have been carried out by Wildenthal[38–40] and interesting truncation schemes suggested by his work have been investigated by Hecht and collaborators.[41, 2] All of these investigations have employed one truncation or another of the full $g_{7/2}$-$d_{5/2}$-$d_{3/2}$-$s_{1/2}$-$h_{11/2}$ basis space which the general shell-model picture (and the relevant proton-transfer experiments) suggest as the correct space for dealing with the $Z > 50$ proton excitations. The spectra predicted by the various calculations are very similar both in qualitative appearance and in quite some quantitative detail.

Shown in Fig. 15 is a comparison of the experimental spectrum for ^{138}Ba derived from the present and from previous experimental work and a theoretical spectrum, calculated with a modified surface δ interaction (MSDI) which was shown by Wildenthal and Larson[40] to accurately account for the spectra of the lightest-mass $N = 82$ nuclei.

The first comment on the comparison is that up through 2.7-MeV excitation energy, all predicted positive-parity excited states have sure or plausible counterparts in the experimental spectrum, with the exception of the first excited 0^+ state, predicted to come at 2.22 MeV excitation. Conversely, there are no "extra" experimental states of positive parity in this region. The agreement as regards excitation energies is reasonably good throughout. The failure of any experimental work to identify the excited 0^+ level is not, as yet, too distressing. In particular, the present (p, p') reaction is known to excite such states, especially in medium and heavy nuclei, very weakly.

Not only is the *number* of levels experimentally identified in the low-energy region of the spectrum in good agreement with the theoretical predictions, but also the breakdown of these levels into groups of different spin values. The present results clarify this correspondence in several aspects. The identities of the second and third 2^+ states at 2.218 and 2.639 MeV are confirmed by our $L = 2$, $J^\pi = 2^+$ assignments which supplement the previous $J = 2$ assignments. The higher-lying experimental states assigned $J^\pi = 2^+$ are not easily correlated with states in the theoretical spectrum and it seems likely that some of the 2^+ states predicted to come at 3.0 MeV and higher excitation energy are not observed in the present experiment.

The second, third, and fourth experimental 4^+ states are all identified in the present work. Two of these states had been observed previously but did not have unique J assignments. The third 4^+

is a level not previously observed. Again, these experimental levels come at energies which correspond closely to predicted 4^+ states in the model spectrum. In particular, the discovery of the 2.58-MeV 4^+ state resolves what would otherwise be the outstanding discrepancy in the theory-experiment relationship. The fifth experimentally assigned 4^+ comes at an energy (3.16 MeV) at which the density of theoretical levels has increased to the point at which level-to-level correspondences can no longer be made with reasonable certainty.

Two $J^\pi = 6^+$ states are predicted to occur in the low-energy part of the spectrum of ^{138}Ba. The lowest of these model states apparently corresponds to the 2.090-MeV state whose 6^+ character was deduced previously only from its isomeric decay behavior and its systematic relationship to similar states in neighboring nuclei. The present data provide an independently based confirmation of this assignment and suggest that the second predicted 6^+ state occurs experimentally at 2.201 MeV.

The so-called "unnatural-parity" states with $J^\pi = 1^+$, 3^+, and 5^+ have, as has been discussed, weak (p, p') cross sections and indistinctive angu-

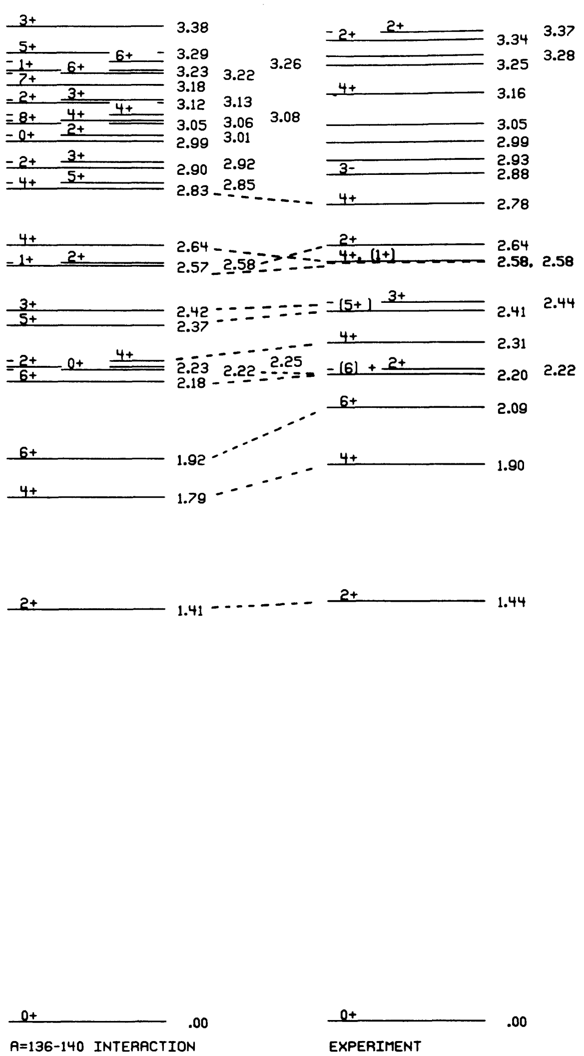

FIG. 15. Comparison of results of the shell-model calculation discussed on Sec. V with experimentally known energy levels in ^{138}Ba.

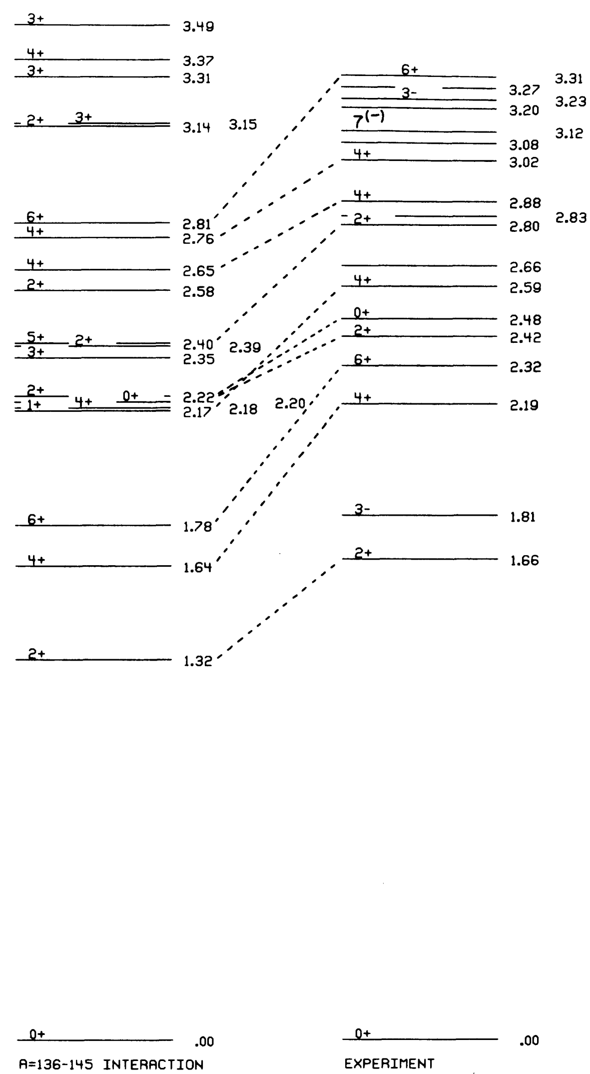

FIG. 16. Comparison of results of the shell-model calculation discussed in Sec. V with experimentally known energy levels in ^{144}Sm.

lar distributions. As such, our data do not provide positive information about these states. However, as discussed in Sec. III, the present results combined with previous assignments for the 2.415-, 2.445-, and 2.583-MeV states lead us to expect that the J^π values for these states are, respectively, 5^+, 3^+, and 1^+. This spin sequence and the energy position of this triplet of states are consistent with the theoretical predictions.

The results obtained in the present experiment on ^{144}Sm constitute a proportionally greater advance in the knowledge of this system than was the case for ^{138}Ba, because the previous knowledge of ^{144}Sm was quite sketchy. The composite spectrum which includes the present results still seems less complete than does the ^{138}Ba spectrum. One aspect that is more advanced in ^{144}Sm is that the excited 0^+ state is known, occurring at 2.478 MeV. We observed this level in our spectra but at too few angles and too weakly to be able to obtain an angular distribution for it.

The experimental spectrum of ^{144}Sm is compared to a theoretical spectrum in Fig. 16. The calculation is based on the model-space and MSDI parameters of Ref. 38. This calculation for ^{144}Sm is formally analogous to that shown for ^{138}Ba, but it is expected to be quite inferior to the ^{138}Ba calculations as regards its correspondence to the physical system. This is because the model basis space used for both calculations allows essentially only two-hole configurations for ^{144}Sm as opposed to a much more comprehensive set of configurations for ^{138}Ba. Nonetheless, although the details of the energy-level agreements and wave-function features for ^{144}Sm are not nearly so good as for ^{138}Ba, the number of levels and their basic sequence and spacing seems valid.

Our experimental results confirm the identity of the counterpart at 2.423 MeV of the second predicted 2^+ state and identifies the third 2^+ at 2.800 MeV. A fourth 2^+ state should, on the basis of extrapolating the theoretical predictions, occur around 3.0 MeV excitation, but we cannot identify such a state in our results. This is a somewhat troublesome point. We also locate and assign three new 4^+ states, the second, third, and fourth in the spectrum. All four 4^+ states come at experimental excitation energies consistent with the spacings in the model spectrum, and the theoretical results imply that there are no other unidentified 4^+ states in the first 3 MeV of excitation in the experimental spectrum.

As discussed in Sec. III, our results are not inconsistent with the previous 6^+ assignment to the 2.324-MeV state, but cannot be considered as completely confirmatory either. The first 6^+ state predicted in the model spectrum is located relative to the first 2^+ and 4^+ states much as is observed experimentally. Unlike ^{138}Ba, the second 6^+ state in ^{144}Sm is predicted to come considerably above the first in excitation energy. A possible candidate for the second 6^+ is observed in our results at 3.308 MeV excitation, but the number of unidentified and missing levels in the experimental region below this energy makes it impossible to draw a firm correspondence in this case.

It might be speculated that the unidentified number of the (6^+)-(?) doublet at 2.32 MeV is the 1^+ state predicted to occur in the 0^+-4^+-2^+-1^+ quadruplet at 2.2 MeV in the theoretical spectrum. If so, the energy shift between calculated and observed excited states is less than average. Likewise, the weak unidentified level at 2.66 MeV might be either of the unnatural-parity (3^+ and 5^+) states predicted at 2.4 MeV or the missing 2^+ state.

VI. CONCLUSIONS

The present results indicate that high-resolution (p, p') experiments on medium and heavy nuclei permit observation of almost all low-lying energy levels. Moreover, the angular distributions for inelastic scattering to natural-parity states appear to be quite stable in shape for a given L transfer, and hence provide a medium for assigning not only L and π to residual states, but also J, since observation indicates spin-flip contributions above ~20 μb/sr can be ruled out.

The precise energies from the present work and the spin-parity assignments based on the observed (p, p') angular distributions provide very productive complements to the body of precision data previously available on ^{138}Ba and ^{144}Sm from γ-ray-detection studies, since the mechanisms, initial states of transitions, and selection rules are different. In the many cases in which the existence of a state was previously known but only limits on its spin and nothing of its parity determined, the matching of the (p, p') results with the γ-decay results permits fixing both J and π. In the cases where states were unknown prior to this work, the (p, p') data permitted conclusions about: excitation energies to ±2 keV or better; often the assignment of π and L, and, to high probability, J on the basis of the observed angular distributions; and finally, the extent of coupling to the ground state via a multipole of order J from the over-all magnitudes of the observed angular distribution.

The comparison of the present results for ^{138}Ba with both the rather complete experimental picture previously available and the apparently quite successful theoretical spectrum based upon a $Z=50$,

$N = 82$ core leads to the conclusion that all the low-lying levels except the first excited 0^+ state are well accounted for.

The theoretical calculations for ^{144}Sm are not as definitive as for ^{138}Ba, but the qualitative features predicted for this system are mostly observed in the composite of present and previous work. The lack of γ-ray studies of detail comparable to those for ^{138}Ba leaves the completeness of the present catalog of states below 3 MeV in some question. It is possible that the 10 new levels found in the present study do not exhaust the list of those actually occurring in this range.

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