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g factor of 4_1^+ states in the $N=82$ isotones ^{136}Xe and ^{138}Ba

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The g factors for the 4_1^+ states in ^{136}Xe and ^{138}Ba were measured using the method of time-integral perturbed angular correlation. The levels of interest were populated by the decay of mass-separated ^{136}I and ^{138}Cs. g factors of 0.80 ± 0.15 and 0.80 ± 0.14 were measured for the 4_1^+ states in ^{136}Xe and ^{138}Ba, respectively. The above results, along with those for the g factors in the 4_1^+ state in ^{140}Ce and the 6_1^+ states in ^{134}Te and ^{138}Ba, are well described by a shell-model calculation in which the effective elemental proton g factors are $g_l'=1.12$ and $g_s'=4.12$.

I. INTRODUCTION

The $N=82$ isotones have been extensively studied both experimentally and theoretically. Wildenthal[1,2] pointed out the suitability of these nuclei for shell-model calculations which were carried out using the modified surface delta interaction (MSDI) to parametrize the two-body part of the shell-model Hamiltonian. In other theoretical approaches Freed and Miles[3] have calculated the low-lying states of the odd-mass $N=82$ isotones using the quasiparticle Tamm-Dancoff approximation. Detailed calculations of the level structure of the $N=82$ isotones ^{135}I through ^{141}Pr have been carried out by Baldridge and coworkers.[4,5] They took the Brueckner G matrix from the Reid soft-core potential as the leading contribution to the effective two-proton interaction. Static $M1$ and $E2$ moments as well as level energies and transition probabilities have been calculated for the even-even $N=82$ isotones by Waroquier and Heyde.[6] Also $g(4_1^+)$ values for ^{134}Te through ^{144}Sm were calculated. They employed a surface delta interaction (SDI) and a Gaussian force as the residual proton-proton interaction.

For the even-even $N=82$ isotones the existing experimental data are for the most part quite comprehensive, with the exception of static magnetic dipole and electric quadrupole moments. In particular, the only known g factor for a low-lying 2_1^+ or 4_1^+ state for these nuclei is $g(4_1^+)$ for ^{140}Ce, which has been measured[7] by several groups. We report here measurements of the g factors of the 4_1^+ states in ^{136}Xe and ^{138}Ba. Together with the known value for ^{140}Ce we obtain for the first time systematics for $g(4_1^+)$ for the even-even $N=82$ isotones. This information along with the measured $g(6_1^+)$ for ^{134}Te (Ref. 8) and ^{138}Ba (Ref. 9) provides a sensitive test of shell-model calculations.

II. EXPERIMENTAL METHODS

The measurements were performed at the TRISTAN fission product separator[10,11] which operates on-line to the High-Flux Beam Reactor at Brookhaven National Laboratory. Large activities of fission products with masses 136 and 138 were produced by a FEBIAD-type ion source and deposited on an aluminized Mylar tape. The tape was subsequently moved to transport the activity to a counting position between the pole pieces of an electromagnet. The activity accumulation and counting times were adjusted according to the half-life of the parent isotope (^{136}I and

^{138}Cs, respectively). The magnetic field was 1.72 and 1.83 T for the Xe and Ba measurements, respectively.

The half-lives of the 4_1^+ states in ^{136}Xe and ^{138}Ba are known to be 1.32 and 2.17 ns, respectively.[12,13] Therefore, the integral perturbed angular correlation method can be used for g-factor measurements. The experimental system consisted of four Ge detectors (with efficiencies of 17–20%) placed at ~8 cm from the center of the pole pieces (see Fig. 1). The electronic and data acquisition systems were set in such a way that γ-γ coincidences between any of the six pairs of detectors were recorded as address triplets on magnetic tape. The four-detector system has been described in detail elsewhere.[14]

Two different experiments were carried out for each of the isotopes studied: (a) an unperturbed angular correlation measurement to determine the coefficients A_{22}, A_{44} in the Legendre polynomial expansion; (b) a time-integral perturbed angular correlation measurement to determine the g factor. For each experiment, a different set of angles between the detector pairs was chosen. For the unperturbed correlations, the detectors were set in such a way that angles of 90°, 105°, 120°, 135°, 150°, and 165° were obtained between the various pairs. For the perturbed correlations the detectors were set so that between four pairs we had 130° (for ^{136}Xe) or 140° (for ^{138}Ba). For the particular γ-γ correlations which were used to determine the g factors of these two nuclei, the expected effect is nearly maximal at these two angles. We thus had about four times more statistics per unit time as compared with a two-detector system.

III. RESULTS

A. Unperturbed angular correlations

Partial decay schemes of ^{136}Xe (Ref. 15) and ^{138}Ba (Ref. 16) which are relevant to the present work are given in Fig. 2. No γ-γ correlations have been reported to date for ^{136}Xe. The spin assignments for levels up to 2 MeV are from systematics and β-decay data, and are confirmed by our results for the unperturbed γ-γ correlations (see the following). For ^{138}Ba, some spin assignments were obtained from γ-γ correlation measurements.[17]

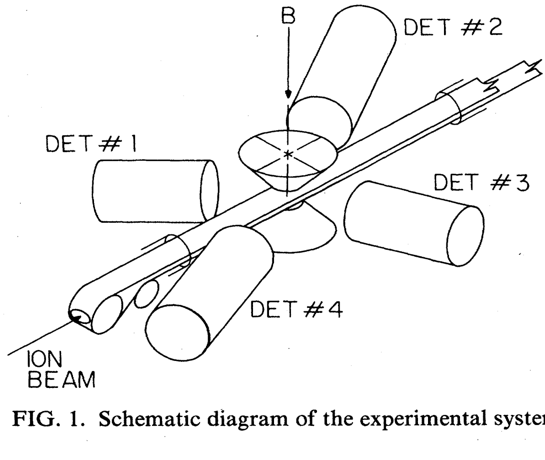

FIG. 1. Schematic diagram of the experimental system.

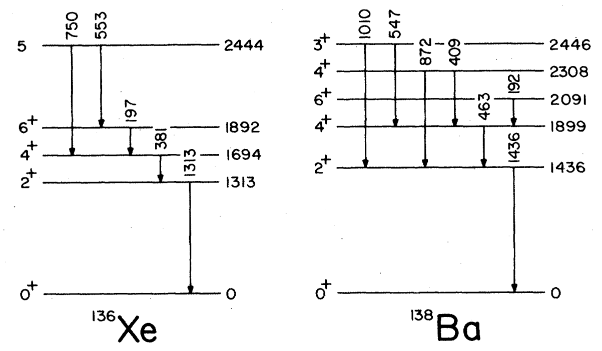

FIG. 2. Partial decay schemes of ^{136}Xe and ^{138}Ba relevant to the present work.

We measured unperturbed γ-γ correlations for some of the cascades in Fig. 2. In Fig. 3 we present some of the measured correlations. The solid lines are best fits to Legendre polynomial expansions up to and including $P_4(\cos\theta)$. The coefficients A_{22}, A_{44} of the polynomial expansion are given in Table I. In the case of ^{138}Ba, our results agree with those of Basinger *et al.*[17] and confirm their spin assignments. The results for the 381-1313-keV and 197-381-keV cascades in ^{136}Xe are consistent with 4^+-2^+-0^+ and 6^+-4^+-2^+ assignments, respectively. The A_{22}, A_{44} coefficients for the 750-381-keV cascade in ^{136}Xe are consistent with the spin sequences 3^+-4^+-2^+ or 5^+-4^+-2^+. The $J=3$ possibility can be ruled out since a γ transition is observed from this level to the 6_1^+ level but not the 2_1^+ level.[15] We therefore assign $J=5$ to the 2444-keV level.

Among all the cascades in Table I in which 4_1^+ is the

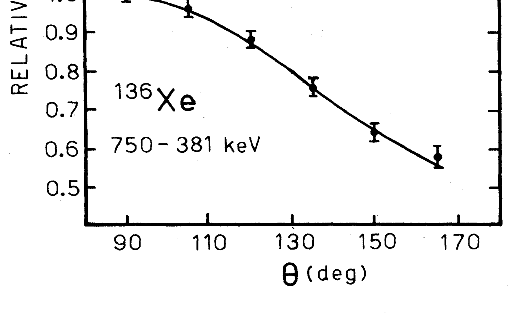

FIG. 3. Measured angular correlations for the 409-463-keV and 750-381-keV cascades in ^{138}Ba and ^{136}Xe, respectively. The solid lines are fits to a Legendre polynomial expansion including $P_2(\cos\theta)$ and $P_4(\cos\theta)$.

TABLE I. Results of the unperturbed angular correlations measurements.

Isotope	Cascade (keV)	Present results[a] A_{22}	Present results[a] A_{44}	Previous measurements[b] A_{22}	Previous measurements[b] A_{44}	Spin sequence
^{136}Xe	381-1313	0.083 ± 0.015	$-0.02\ \pm0.02$			4^+-2^+-0^+
	197-381	0.080 ± 0.020	0.004 ± 0.020			6^+-4^+-2^+
	750-381	-0.410 ± 0.010	0.003 ± 0.030			5-4^+-2^+
^{138}Ba	409-463	0.192 ± 0.010	$-0.02\ \pm0.03$			4^+-4^+-2^+
	409-(463)-1436	0.194 ± 0.004	-0.008 ± 0.020	0.211 ± 0.037	0.009 ± 0.040	4^+-4^+-2^+-0^+
	872-1436	0.126 ± 0.020	-0.006 ± 0.030	0.130 ± 0.031	-0.024 ± 0.034	4^+-2^+-0^+
	1010-1436	-0.096 ± 0.032	0.014 ± 0.045	-0.084 ± 0.020	-0.010 ± 0.022	3^+-2^+-0^+
	547-(463)-1436	-0.034 ± 0.010	0.001 ± 0.014	0.053 ± 0.022	0.004 ± 0.025	3^+-4^+-2^+-0^+

[a] A_{22} and A_{44} are the coefficients of the Legendre polynomials $P_2(\cos\theta)$ and $P_4(\cos\theta)$, respectively.
[b] See Ref. 17.

intermediate state, two have quite large A_{22} coefficients, namely 750-381 keV in ^{136}Xe and 409-463 keV in ^{138}Ba. These cascades are thus suitable for perturbed angular correlation measurements. Also one can use the γ-skip-γ cascades 750-(381)-1313 (^{136}Xe) and 409-(463)-1463 (^{138}Ba), in which one of the transitions is unobserved, as these cascades have the same correlations as those already indicated and can be used to improve the statistics of the measurement.

B. Perturbed angular correlations

The half-lives of the 4_1^+ states in ^{136}Xe and ^{138}Ba are suitable for integral perturbed angular correlation measurements of their g factors. Experimentally, we measured the double ratio:

$$R(\theta)=\left[\frac{I(\theta,B)}{I(\theta,-B)}\bigg/\frac{I(-\theta,B)}{I(-\theta,-B)}\right]^{1/2},$$

where $I(\theta,B)$ is the number of counts for the given γ-γ cascade at angle θ with magnetic field B up. The advantage of using this ratio is that it does not depend on normalization involving detector efficiency, geometry, beam intensity, and counting time with field up and down. Several sources of systematic errors are thus eliminated.

The angular correlation coefficients were corrected for solid angle attenuation using information given by Camp and van Lehn.[18] The magnetic field at the site of the Xe or Ba nuclei (stopped in the aluminized tape) was taken to be equal to the applied magnetic field. Extranuclear perturbations from electric field gradients are not expected because of the cubic structure of aluminum. Also, a large number of unperturbed correlations were measured to date[14,19] using the same tape, and good agreement with theoretical values was found. This indicates that extranuclear perturbations, if at all present, are smaller than the statistical errors.

For a given γ-γ correlation, $R(\theta)$ has a maximum at an angle $\theta_{\max}$, which depends on A_{22} and A_{44}. For the cascades considered in this work $\theta_{\max}\sim145°$. The experimental results for ^{136}Xe and ^{138}Ba are described in the following.

1. g factor of the 4_1^+ state in ^{136}Xe

The ratios $R(\theta)$ for several cascades in ^{136}Xe were measured at $\theta=130°$ with an external static magnetic field of 1.72 T. The results are given in Table II. The g factor of the 4_1^+ state was deduced from the average value

$$R(130°)=0.856\pm0.022$$

for the double ratios of the 750-381-keV and 750-(381)-1313-keV cascades, using the known formula of the perturbed angular correlations.[20] The g factor obtained is

$$g(4_1^+)=0.80\pm0.15\ .$$

A consistency check of the experimental value of $R(\theta)$ was obtained by deducing the double ratio for the 381-1313-keV and 197-381-keV cascades. In both cases $R(130°)$ values close to 1.00 are expected. For the first cascade the half-life of the intermediate 2^+ state is very short ($T_{1/2}=0.41$ ps) and no shift in the angular correlation pattern is expected. For the second cascade the anisotropy is weak ($A_2=0.08$), and therefore the expected effect is small, i.e., $R(130°)\approx1.031$. From Table II we see that both results are in very good agreement with the above-mentioned predictions, thus indicating that systematic errors, if present, are smaller than the statistical errors.

TABLE II. Results of the perturbed angular correlation measurements.

Isotope	Cascade	$R(\theta)$	$g(4_1^+)$
^{136}Xe[a]	381-1313	1.000 ± 0.030	
	197-381	1.031 ± 0.027	
	750-381	0.868 ± 0.033	0.80 ± 0.15
	750-(381)-1313	0.844 ± 0.030	
^{138}Ba[b]	463-1436	1.002 ± 0.008	
	1010-1436	1.001 ± 0.014	
	547-463	0.982 ± 0.017	
	409-463	1.094 ± 0.010	0.80 ± 0.14
	409-(463)-1436	1.097 ± 0.013	

[a] $B=1.72$ T, $\theta=130°$.
[b] $B=1.83$ T, $\theta=140°$.

TABLE III. Measured and calculated g factors for 2_1^+, 4_1^+, and 6_1^+ states in the $N=82$ isotones.

Nucleus	J^π	g (experimental)	Calculated with free proton g factors	Calculated with effective proton g factors[a]
^{134}Te	2^+		0.58	0.85
	4^+		0.57	0.84
	6^+	0.846 ± 0.025[b]	0.55	0.82
^{136}Xe	2^+		0.66	0.90
	4^+	0.80 ± 0.15[c]	0.58	0.84
^{138}Ba	2^+		0.78	0.98
	4^+	0.80 ± 0.14[c]	0.67	0.90
	6^+	0.98 ± 0.02[d]	0.83	1.01
^{140}Ce	2^+		1.05	1.15
	4^+	1.11 ± 0.04[e]	0.99	1.11

[a] $g_l' = 1.12$ and $g_s' = 4.12$.
[b] Reference 8.
[c] This work.
[d] Reference 9.
[e] Reference 7.

2. g factor of the 4_1^+ state in ^{138}Ba

In this case an external static magnetic field of 1.83 T was used. The double ratio $R(\theta)$ was measured at 140°. The results of $R(\theta)$ for several cascades are summarized in Table II. The g factor of the 4_1^+ state was deduced from $R(140°)$ for the 409-463-keV and 409-(463)-1436-keV cascades. The average value of $R(\theta)$ was 1.095 ± 0.009. The value obtained for g is

$$g(4_1^+)=0.80\pm0.14 \ .$$

Consistency checks were provided by the three other cascades in Table II, and again $R(\theta)$ values close to 1.000 were obtained, as expected.

IV. DISCUSSION

All g factors which have been measured for 4_1^+ states in the $N=82$ isotones are given in Table III along with those for the 6_1^+ states in ^{134}Te and ^{138}Ba. Table III also gives the results of a shell-model calculation for the above g factors as well as those for the 2_1^+ states in ^{134}Te, ^{136}Xe, ^{138}Ba, and ^{140}Ce.

A. Shell model calculations

Wave functions for the states of interest were obtained from a shell-model calculation which was carried out for the $N=82$ nuclei ^{133}Sb to ^{148}Dy. The model space consisted of all $g_{7/2}$, $d_{5/2}$, $d_{3/2}$, $s_{1/2}$, and $h_{11/2}$ configurations outside of a closed ^{132}Sn core. The only restrictions were that a maximum of four protons were allowed in the $h_{11/2}$ orbit, and that only configurations with overall seniority less than or equal to 4 were considered. Values for the individual matrix elements of the two-body Hamiltonian and for the single-particle energies were fitted using a set of approximately 150 well-determined energy levels for the $N=82$ isotones. A description of this fit, and the detailed results of the shell model calculation, will be reported by two of us (H.K. and B.H.W.) in a future publication.

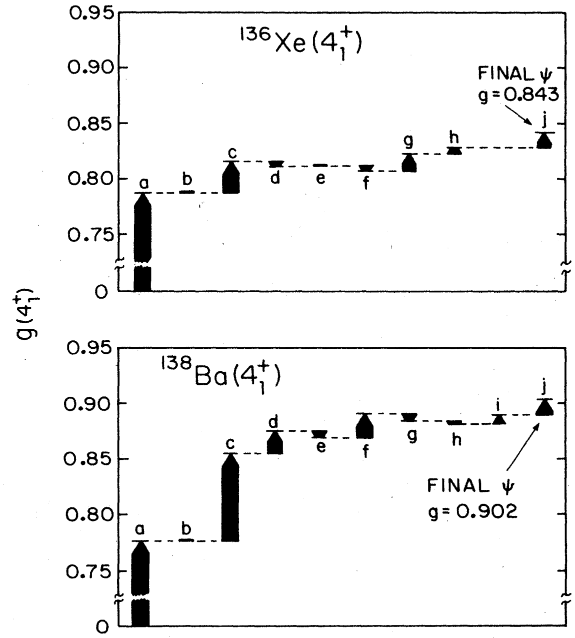

FIG. 4. Contributions to $g(4_1^+)$ in ^{136}Xe and ^{138}Ba from various components of the 4_1^+ wave function. For ^{136}Xe the components are the following: a—$(g_{7/2})_4^4$; b—$(g_{7/2})_4^2(d_{5/2})_0^2$); c—$(g_{7/2})_{7/2}^3(d_{5/2})_{5/2}^1$; d—$(g_{7/2})_4^2(h_{11/2})_0^2$; e—$(g_{7/2})_4^2(d_{3/2})_0^2$; f—$(g_{7/2})_{5/2}^3(d_{3/2})_{3/2}^1$; g—$(g_{7/2})_0^2(d_{5/2})_4^2$; h—$(g_{7/2})_{7/2}^1(d_{5/2})_{5/2}^3$. For ^{138}Ba the components are the following: a—$(g_{7/2})_4^6$; b—$(g_{7/2})_4^4(d_{5/2})_0^2$; c—$(g_{7/2})_{7/2}^5(d_{5/2})_{5/2}^1$; d—$(g_{7/2})_{7/2}^2(d_{5/2})_{5/2}^3$; e—$(g_{7/2})_4^4(h_{11/2})_0^2$; f—$(g_{7/2})_0^4(d_{5/2})_4^2$; g—$(g_{7/2})_4^2(d_{5/2})_0^4$; h—$(g_{7/2})_4^4(d_{3/2})_0^2$; i—$(g_{7/2})_{7/2}^3(d_{5/2})_{5/2}^1$.

It has been established[8] in the case of the g factor for the 6_1^+ state in ^{134}Te that the use of configuration-mixed shell-model wave functions along with elemental proton g factors is not sufficient to give the correct $g(6_1^+)$. This is due to the neglect of core polarization effects.[8,21] We have chosen to incorporate these effects by determining one set of effective orbital and spin proton g factors g_l' and g_s'. These were determined by fitting the ground state g factors for ^{139}La and ^{141}Pr, which are $g(7/2^+)=2.78$ and $g(5/2^+)=4.28$, respectively,[22] to the configuration-mixed wave functions already described. These wave functions are very pure for the ground states of ^{139}La and ^{141}Pr, which is consistent with spectroscopic factors obtained from single-proton transfer reactions.[23] Fits to the experimental g factors for ^{139}La and ^{141}Pr yield $g_l' = 1.12$ and $g_s' = 4.12$.

The above-mentioned effective proton g factors g_l' and g_s' were next used to calculate g factors for the 2_1^+ and 4_1^+ states in ^{134}Te, ^{136}Xe, ^{138}Ba, and ^{140}Ce and the 6_1^+ states in ^{134}Te and ^{138}Ba using the appropriate configuration-mixed shell-model wave functions. The results are given in Table III.

B. Conclusions

The $g(4_1^+)$'s measured in this work are in good agreement with calculations presented graphically by Waroquier and Heyde.[6] As can be seen from the results presented in Table III, the known $g(4_1^+)$ values for ^{136}Xe, ^{138}Ba, and ^{140}Ce and the $g(6_1^+)$ for ^{134}Te and ^{138}Ba can all be reproduced using one set of effective elemental-proton g factors that appear to adequately reproduce the core polarization effects for all four nuclei. It is interesting to examine the contributions of the various components of the wave functions to the magnetic moments of the 4_1^+ states in ^{136}Xe and ^{138}Ba. This is illustrated in Fig. 4. In both cases more than 75% of the contribution to the g factor comes from a single component of the wave function.

In summary, we have measured $g(4_1^+)$ for ^{136}Xe and ^{138}Ba and created systematics for $g(4_1^+)$ in the $N=82$ isotones. The results are well described by calculations employing configuration-mixed shell-model wave functions and a single set of effective-proton g factors that account in an empirical fashion for core polarization effects.

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