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$E2/M1$ Multipole Mixing Ratios of Gamma Transitions in the "Quasispherical" Nucleus Xe^{132}†

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The $E2/M1$ multipole mixing ratios $\delta(\gamma) = \langle I_f \| \vec{j}_N \vec{A}_2^{(E)} \| I_i \rangle / \langle I_f \| \vec{j}_N \vec{A}_1^{(M)} \| I_i \rangle$ of 10 γ transitions in the quasispherical nucleus Xe^{132} have been measured by means of γ-γ directional correlations observed with two coaxial Ge(Li) detectors. Spin assignments have been made for the levels at 1963 keV (4^+), 2110 keV (4^+), 2112 keV (6^+), 2395 keV (4^+), 2584 keV (5^+), 2589 keV (3), 2614 keV (4^+), and 2839 keV (5^+). In addition, previous spin assignments for levels below 1900 keV were confirmed. Based on the proposed spin assignments, the following values of the quadrupole-dipole mixing ratios were obtained (energies in keV): $\delta(506) = -1.3 \pm 0.4$, $\delta(523) = -0.25 \pm 0.15$, $\delta(630) = +5.3^{+2.1}_{-1.0}$, $\delta(727) = -0.32 \pm 0.04$, $\delta(955) = -0.15 \pm 0.05$, $\delta(1136) = +0.9 \pm 0.3$, $\delta(1143) = -(0.04^{+0.09}_{-0.04})$, $\delta(1173) = -0.40 \pm 0.15$, $\delta(1291) = +0.01 \pm 0.08$, and $\delta(1399) = +0.07 \pm 0.02$. The results are discussed in terms of the collective vibrational model and in terms of a quasirotational model. However, these models are of limited value in explaining the experimental data concerning the level structure and multipole transitions of Xe^{132}.

I. INTRODUCTION

The work reported in this paper gives additional results in our systematic survey of $E2/M1$ multipole mixing ratios of γ transitions in the "quasispherical" nuclei of the mass region $100 < A < 150$. The interpretation of the excited states of even-even nuclei in this mass region in terms of collective vibrations about a spherical equilibrium shape is unable to account for the observed quadrupole moments of the excited 2^+ (one-phonon) states and for the substantial magnetic dipole ($M1$) admixtures that have been observed in the γ transitions between these "vibrational" states.[1,2]

Several attempts have been made to understand the structure of "quasispherical" nuclei on the basis of a microscopic description[3,4] in terms of quasiparticle states plus a quadrupole force. The effect of this force is determined by the quasiparticle random-phase approximation which leads to the vibrational phonon states (i.e., a pair of fermions is treated as a boson). The calculation of magnetic dipole transition matrix elements is difficult in this approach and no reliable computations of these quantities are available as yet.

More recently an interpretation of the excited states of quasispherical nuclei in terms of quasirotational bands has become fashionable.[5,6] The $2^{+\prime}$ state is then explained as the lowest state of a γ-vibrational band. This interpretation, however, does not explain the substantial $M1$ admixtures observed in the γ transitions between the quasirotational-band members.

It seems clear that the "vibrational" aspects play an important role in the description of the gross structure of the first few excited states of quasispherical nuclei, and it also seems to be true that some higher excited states of these very same nuclei have properties usually ascribed to members of a rotational band. This is especially true for the nuclei in the Xe region.[7]

An attempt to understand the large $M1$ admixtures in γ transitions between "vibrational" states has been made by Korolev,[8] who treated the quasispherical nuclei on the basis of a simple extra-pair model, in which the nuclei are described as a magic core plus one or more zero-spin nucleon pairs, which interact with the core and excite collective degrees of freedom. Nuclear excitations are treated as excitations of a pair in a potential well plus phonon excitations of the core.

Grechukhin[9] showed that magnetic dipole transitions in even-even nuclei with collective quadrupole-type excitations do not depend on the specific structure of the collective Hamiltonian, but are very sensitive to the admixture of single-particle excitations of the collective state. Hence, the $E2/M1$ mixing ratio may serve as a measure of the purity of separation of the nuclear collective quadrupole degrees of freedom and the admixture of single-particle excitations in nuclear states.

The rate of magnetic dipole transitions in even-even nuclei was computed by Greiner[10] on the basis of a model in which it is assumed that the proton distribution in nuclei is somewhat less deformed than the neutron distribution, because the pairing force acting between protons is larger than that acting between the neutrons.

The most successful approach towards an understanding of the structure and of the properties of nuclear states in quasispherical and quasideformed regions has been made by Kumar and Baranger,[11] who explore in detail the potential-energy surfaces and mass parameters of the quadrupole motion on the basis of the pairing-plus-quadrupole force and then solve the Bohr Hamiltonian numerically. Extensive calculations have been made for the mass region $182 \leqslant A \leqslant 196$. The $E2/M1$ mixing ratios δ predicted by this model in the $A \sim 190$ region agree surprisingly well with the experimental results.[12] For similar calculations in the $A \sim 120$ mass region the coupling to quasiparticle states must probably be taken into account and such calculations have not been performed, but may be available soon.[13]

A systematic experimental investigation of $E2/M1$ mixing ratios of γ transitions in the quasispherical nuclei may provide a clue to a better understanding of the microscopic structure of these nuclei. Some trends – especially with regard to the sign of the $E2/M1$ amplitude ratio δ – seem to emerge, as more and more data become available. For instance, the mixing ratios

$$\delta = \frac{\langle 2^+ \| \vec{j}_N \vec{A}_2^{(E)} \| 2^{+\prime} \rangle}{\langle 2^+ \| \vec{j}_N \vec{A}_1^{(M)} \| 2^{+\prime} \rangle}$$

of the $2^{+\prime}$ to 2^+ γ transitions in the even-even $_{44}$Ru, $_{46}$Pd, $_{48}$Cd, $_{52}$Te nuclei that have been measured so far (Ru^{104}, $Pd^{106, 108, 110}$, $Cd^{106, 108, 110, 112, 114, 116}$, $Te^{122, 124, 126}$) are all negative.[1,2,14-17] Unfortunately no reliable mixing-ratio data on the corresponding transitions in the even-even $_{50}$Sn isotopes are available as yet, except for Sn^{116}, where $\delta \simeq 0$.[18,19] The mixing ratios of the $2^{+\prime}$ to 2^+ transitions in $_{54}Xe^{126}$ and $_{54}Xe^{128}$, however, are positive: $\delta = +9.1$[2,20] and $\delta = 6.4$,[21] respectively. The present work shows that the mixing ratio of the corresponding transition in Xe^{132} is also positive ($\delta = +5.3$). This change of sign of δ from the Te to the Xe isotopes may possibly be related to the fact that in the Te isotopes the 4^+ states are below the $2^{+\prime}$ states in energy, whereas the 4^+ states are above the $2^{+\prime}$ states in all Xe isotopes (see Fig. 1). A similar relationship between the signs of the quadrupole moments of the 2^+ states and the relative positions of the $2^{+\prime}$ and the 4^+ states in quasispherical nuclei has been suggested by Kumar.[22]

Before definite systematic trends of δ can be established, however, more accurately determined mixing ratios must be available, especially for the even-even $_{44}$Ru, $_{50}$Sn, and $_{56}$Ba isotopes, and for some $_{52}$Te and $_{52}$Xe isotopes. Such measurements are presently in progress in the Purdue Tandem Accelerator Laboratory.

The present investigation of γ-γ directional correlations from the decay of I^{132} was undertaken in order to measure the $E2/M1$ mixing ratios of γ transitions in Xe^{132} and to gain insight into the nature of the excited states of Xe^{132}.

II. LEVEL STRUCTURE OF Xe^{132}

The energy levels and γ transitions in Xe^{132} relevant to the present investigation are presented in Fig. 2. The structure of the excited states seems to conform to the pattern expected on the basis of the vibrational model, with the appearance of one-, two-, and three-phonon levels; according to this model, the 668-keV level is interpreted as the one-phonon level, the 1298- and 1440-keV levels are members of the 0^+, 2^+, 4^+ two-phonon triplet, and some of the levels in the energy range 1804 to 2112 keV would be interpreted as members of the 0^+, 2^+, 3^+, 4^+, 6^+ three-phonon quintuplet. In support of this interpretation, γ transitions changing the phonon number by two units are in general observed to be reduced in intensity relative to those

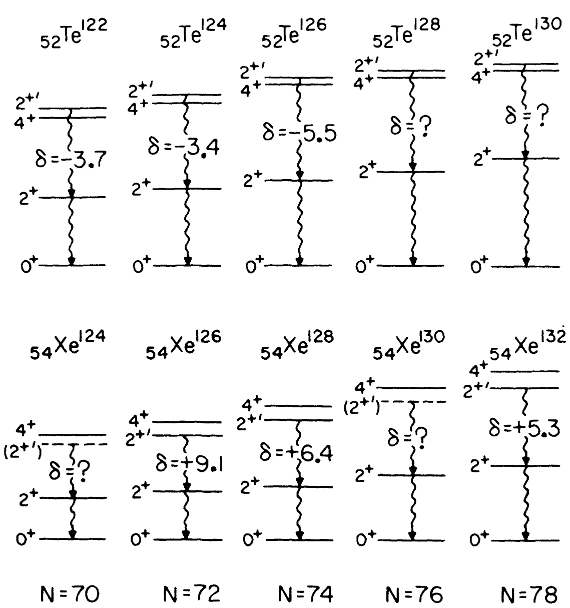

FIG. 1. The "one-phonon" and "two-phonon" states and the $E2/M1$ mixing amplitude ratios in even-even Te and Xe isotopes.

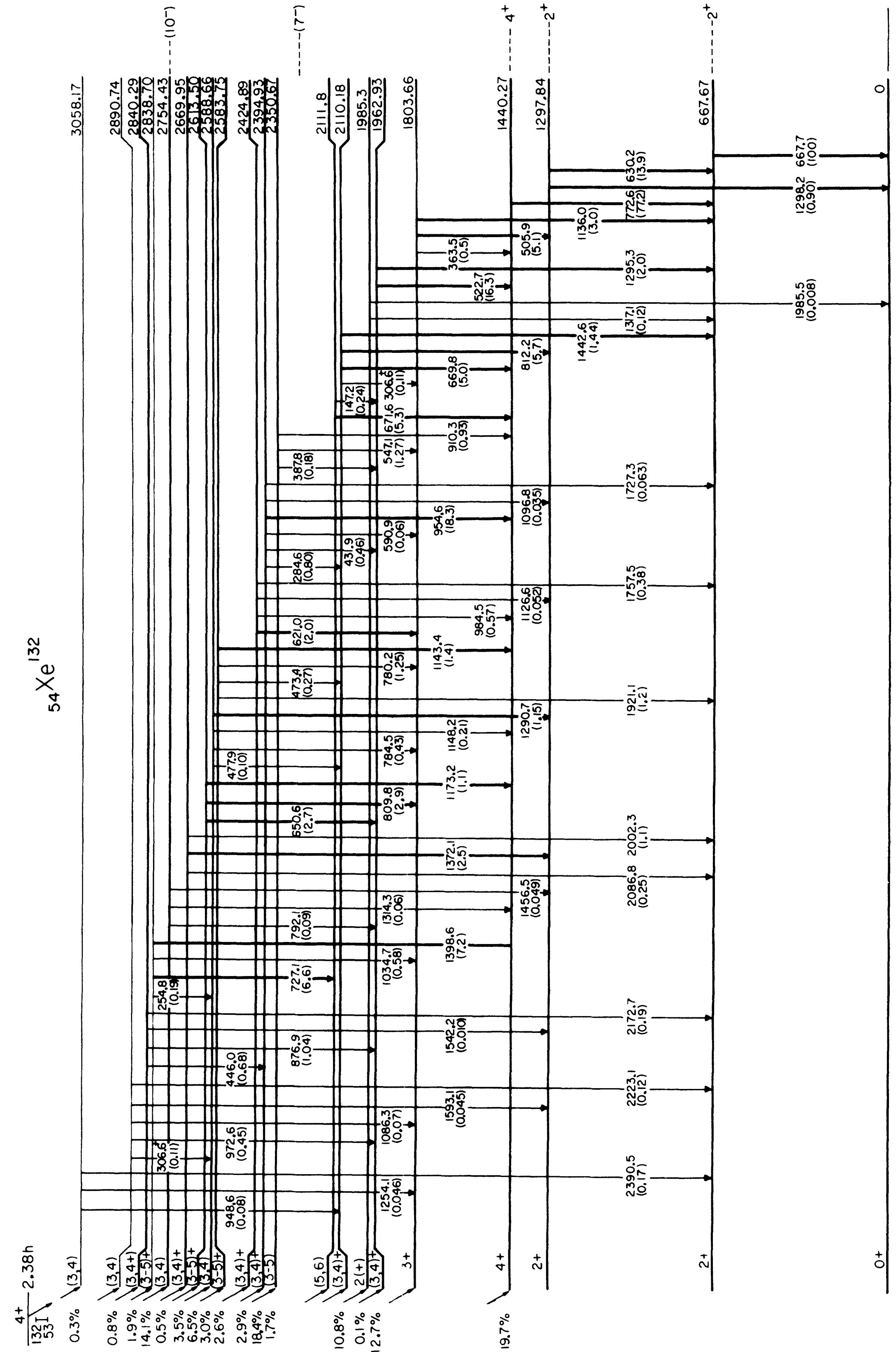

FIG. 2. Level scheme of Xe^{132}. Those levels and transitions that are directly or indirectly involved in the present work are shown as heavy lines. Spin, parity, and energy assignments are taken from Ref. 37. On the right-hand side the states observed in $(\alpha, 2n)$ reactions (Ref. 7) are indicated.

changing the phonon number by one unit; the vibrational model predicts the selection rule that only transitions changing the phonon number by one unit are allowed. For example, the transition from the 1298-keV level to the first excited state is some 15 times as intense as that to the ground state. Similar relationships are observed for transitions from the three-phonon levels at 1963, 2110, and 2112 keV, but not for transitions from the 1985-keV level. It thus appears that collective quasivibrational effects play a significant part in the structure of the lower excited states. On the other hand, some features of a quasirotational band have been observed in the Te^{132} nucleus in $(\alpha, 2n)$ reactions.[7,23] A rather long-lived isomeric state with $T_{1/2} = 8.4\times10^{-3}$ sec at 2.754 MeV has also been observed.[23] A spin and parity of $I^{\pi}=8^{-}$ has been assigned to this state,[23] although this spin assignment is doubtful in view of results obtained in more recent $(\alpha, 2n)$ investigations.[7] The states populated in $(\alpha, 2n)$ reactions are indicated by dashed lines in Fig. 2.

The decay of I^{132} to levels of Xe^{132} has been the subject of numerous investigations.[24–37] The advent of high-resolution γ-ray and internal-conversion-electron spectrometers has resulted in a reasonably complete knowledge of the complex Xe^{132} level scheme,[36,37] with more than 60 transitions depopulating some 20 excited states. The decay of Cs^{132} to Xe^{132} has likewise been extensively studied[38–41]; however, only five of the excited levels of Xe^{132} are populated in the Cs^{132} decay, and thus little information concerning the Xe^{132} level scheme may be obtained. Similarly, $Te^{130}(\alpha, 2n)$ reactions[7,23] populate the one- and two-phonon levels in Xe^{132}, as well as a few high-spin states which are not populated in the I^{132} decay. Thus detailed information concerning the structure of the Xe^{132} excited states must be obtained from the decay of I^{132}.

Recently the γ rays emitted from Xe^{132} after neutron capture in the 14.1-eV resonance in Xe^{131} have been investigated and on the basis of the observed relative γ-ray intensities, spin and parity assignments to many low-spin levels of Xe^{132} of up to about 4-MeV excitation energy have been made.[42] Previous studies[25,26,33] of directional correlations in Xe^{132} have been performed using NaI(Tl) detectors; however, the complexity of the I^{132} decay scheme requires the use of high-resolution Ge(Li) detectors in order to obtain unambiguous results.

III. EXPERIMENTAL DETAILS

A. Source Preparation

Radioactive samples of the fission product Te^{132} were obtained from Oak Ridge National Laboratory; the Te^{132} activity decays to I^{132} with a half-life of 78 h. An equilibrium mixture of Te^{132} and I^{132} would thus serve to eliminate problems associated with the short half-life of the I^{132} decay (2.4 h); the decay of Te^{132} produces no γ radiation in the energy range of interest in the present work (500 to 1500 keV).

Two different samples were obtained for the present investigation. The first was in the form of an I^{132} generator, containing sodium tellurite adsorbed onto an alumina column. The column was washed with NaOH (2–3 M), and the resulting solution was used as a source for the experiment. The second sample was obtained directly in the form of a solution of sodium tellurite in NaOH. The sources employed for the experiment were contained in a thin-walled cylindrical glass ampule 2 mm in diameter and 5–10 mm in length.

Both samples were observed to contain contaminant activities resulting from the fission process. The first sample contained activities identified as I^{131}, Te^{129m}, and Zr^{95}. Because of the high resolution of the Ge(Li) detectors, the I^{131} and Te^{129m} activities did not have any serious effect on the measurement. However, the Zr^{95} activity emits γ rays at 724 and 765 keV; in the later stages of the measurement, when the Te^{132} activity had decayed considerably relative to the longer-lived Zr^{95} activity, a large uncertainty was introduced by the chance-coincidence corrections necessary for investigations of the 727- and 772-keV transitions. Sample 2 contained a Ru^{103} contamination, the 497-keV transition from which caused similar problems in analyzing the Xe^{132} 506-keV transition.

B. Procedure

The γ rays were observed using two 30-cc coaxial Ge(Li) detectors having a resolution of 3 keV for Ni^{60} γ rays. Details of the apparatus have been described in Ref. 1. The directional correlations were measured by accumulating gated coincidence spectra in a 1600-channel analyzer, for various angular separations of the two detectors. Spectra were accumulated at 90, 135, 180, and 210° in coincidence with the 668-keV ($2^{+}\rightarrow0^{+}$) and 772-keV ($4^{+}\rightarrow2^{+}$) transitions simultaneously. Sample 1 was investigated using an automatic angular-correlation apparatus, in which the movable detector remained at each angular position for 40 min, and then automatically proceeded to the next position. The coincidence event was then routed into the appropriate 200-channel subgroup, depending on the angular position and on whether the event was observed in coincidence with the 668- or the 772-keV transition. This method suffered from the disadvantage of compressing the spectrum into 200 channels, and thus seriously degrading the energy resolution; however, changing angular positions frequently tended to minimize systematic effects, particularly half-life corrections. During the course of a measurement (lasting 2–3 days) with a given source, the singles and coincidence (true as well as chance) counting rates were recorded at the end of each 40-min counting interval. In the investigations using sample 2, the multichannel analyzer was divided into two 800-channel subgroups, corresponding to spectra gated in coincidence with the 668- and 772-keV transitions. Spectra were accumulated at a given angular position for 10–12 h, following which the gated coincidence spectra were read out and the detector was moved manually to the next position. In this case also, singles and coincidence counting rates were recorded at 40-min intervals. Following each run of 2–3 days, a new source was prepared of approximately twice the present strength; thus each run was begun with a source of approximately the same strength.

C. Data Analysis

The peak counting rates for the various spectra were extracted by summing the counts above a background assumed to be linear over the range of the peak. Corrections were applied to compensate for the radioactive decay of the source, and for other variations in the singles data (due, for example, to a slight misalignment of the source relative to the center of rotation of the movable detector). The total number of chance-coincidence counts measured by the scalers was used to estimate the contribution of chance coincidences to the peak intensities of the coincidence spectra, and thus the counting rates could be corrected for chance coincidences. Corrections for coincidence counts due to Compton-scattered events accepted in the gating energy window were measured by moving the gating window to the Compton background beside the peak of interest.

After the various corrections were applied, the counting rates were fitted to a function of the form

$$W(\theta)=\sum_k Q_{kk}A_{kk}P_k(\cos\theta)\,, \tag{1}$$

where

$$A_{kk}=B_k(\gamma_1)U_k(\gamma_2)A_k(\gamma_3)\,. \tag{2}$$

The orientation parameters $B_k(\gamma_1)$, deorientation coefficients $U_k(\gamma_2)$, and directional-distribution coefficients $A_k(\gamma_3)$ have been defined in Ref. 1. The geometrical correction factors Q_{kk} correct for the finite angular resolution of the two detectors and have been tabulated for Ge(Li) detectors by Camp and Van Lehn.[43]

In all cases, the last transition of the cascade under investigation was either the 668- or the 772-keV transition, both of which are pure $E2$ radiations and thus have a unique $A_k(\gamma)$ coefficient. Hence, all mixing-ratio information is contained in the $B_k(\gamma_1)$ or $U_k(\gamma_2)$ coefficients.

For mixed $E2+M1$ multipole transitions the orientation coefficients $B_k(\gamma)$ are given by

$$B_k(\gamma)=\frac{F_k(11I_iI_f)-2\delta(\gamma)F_k(12I_iI_f)+\delta^2(\gamma)F_k(22I_iI_f)}{1+\delta^2(\gamma)}\,. \tag{3}$$

The $F_k(LL'I_iI_f)$ are the F coefficients and the mixing (amplitude) ratio

$$\delta(\gamma)=\frac{\langle I_f\|\vec{j}_N\vec{A}_2^{(E)}\|I_i\rangle}{\langle I_f\|\vec{j}_N\vec{A}_1^{(M)}\|I_i\rangle}\,,\quad E_i>E_f \tag{4}$$

is exactly defined in Ref. 1 in terms of explicitly given multipole operators $\vec{A}_{LM}^{(\pi)}$.

The deorientation coefficients $U_k(\gamma)$ for mixed $E2+M1$ transitions between two states I_1 and I_2 are given by

$$U_k(\gamma)=(-1)^{I_1+I_2+k}[(2I_1+1)(2I_2+1)]^{1/2}\times\frac{\begin{Bmatrix}I_1&I_1&k\\I_2&I_2&1\end{Bmatrix}+\Delta^2\begin{Bmatrix}I_1&I_1&k\\I_2&I_2&2\end{Bmatrix}}{1+\Delta^2}\,, \tag{5}$$

where Δ^2 is the *intensity* ratio

$$\Delta^2=\frac{|\langle I_2\|L=2\|I_1\rangle|^2}{|\langle I_2\|L=1\|I_1\rangle|^2} \tag{6}$$

of *all* the $L=2$ transitions (γ radiation *and* conversion electrons) and of all the $L=1$ transitions between I_1 and I_2. We will note here that all mixing ratios are defined in terms of emission matrix elements, and that the orientation parameters are written such that the $M1$-$E2$ interference term ap-

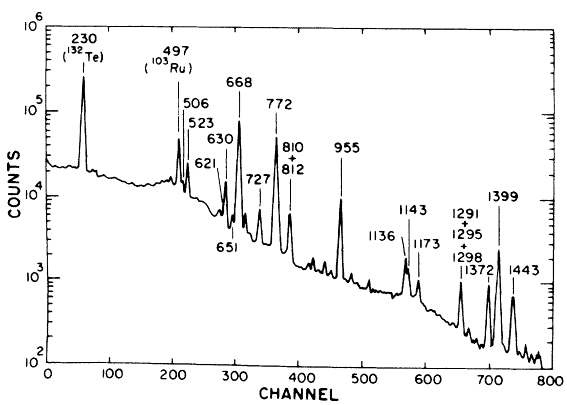

FIG. 3. γ-ray spectrum from the decay of I^{132} observed with a 30-cc Ge(Li) detector.

pears in the equation with a negative sign.

The effect of extranuclear perturbations on the directional correlations has been neglected. While the lifetimes of most of the Xe^{132} excited states are not known, lifetimes of excited states of other nuclei in this mass region are sufficiently short to justify this assumption.

IV. RESULTS

A sample γ-ray spectrum obtained with a Ge(Li) detector is shown in Fig. 3, and typical γ-γ coincidence spectra are shown in Figs. 4–7. The spectra in Figs. 4 and 5 were obtained in coincidence with the 630- and 955-keV transitions, respectively. The coincidence relationships observed are in agreement with those of Ref. 37. Typical spectra in coincidence with the 668- and 772-keV transitions, respectively, that were employed in the directional-correlation analysis are illustrated in Figs. 6 and 7. Results were again in agreement with those of Ref. 37, with one exception – a transition at 630 keV was observed in coincidence with the 772-keV transition. Such a relationship was observed in Ref. 37, but was ascribed to the influence of the wide windows set on the NaI(Tl) detectors used for gating. The observed coincidences could be caused by an unresolved transition accepted in the 772-keV window, or by an additional transition in the neighborhood of 630 keV. Detailed analysis of the singles spectrum failed to corroborate either possibility; it is possible that higher-resolution γ spectroscopy or more detailed γ-γ coincidence studies could help to explain this apparent coincidence relationship.

The results for the directional-correlation coefficients A_{22} and A_{44} extracted from the present measurement are given in Table I; all corrections discussed above have been applied. Results presented represent the average between measurements using sample 1 and sample 2; error limits

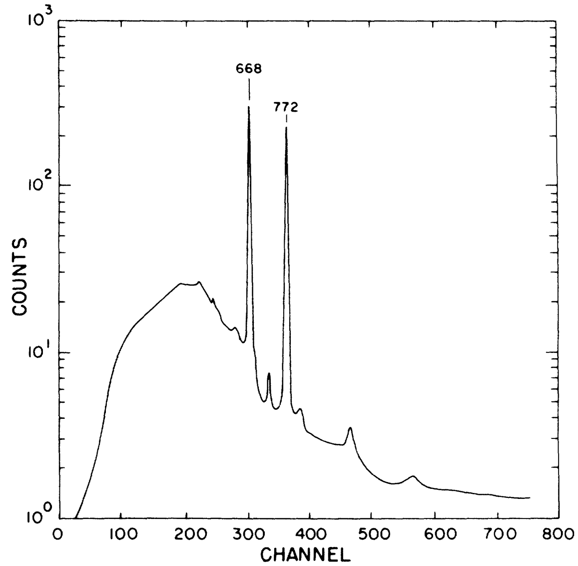

FIG. 5. 955-keV gated coincidence γ-ray spectrum observed using two Ge(Li) detectors. (Uncorrected for effects due to chance coincidences and Compton-scattered radiation.)

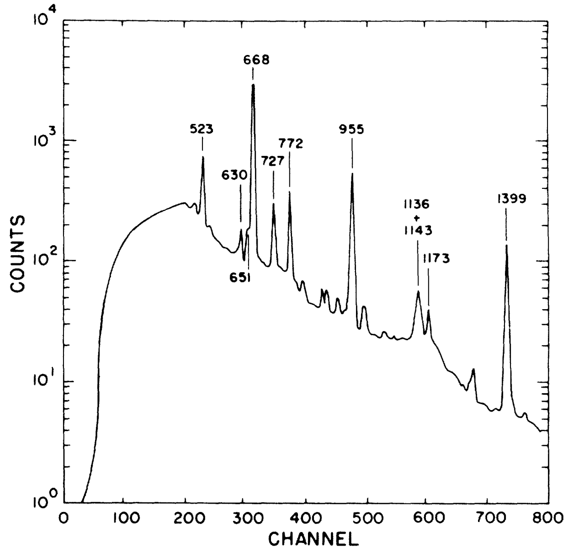

FIG. 4. 630-keV gated coincidence γ-ray spectrum observed using two Ge(Li) detectors. The spectrum shown is uncorrected for effects due to chance coincidences and Compton-scattered radiation.

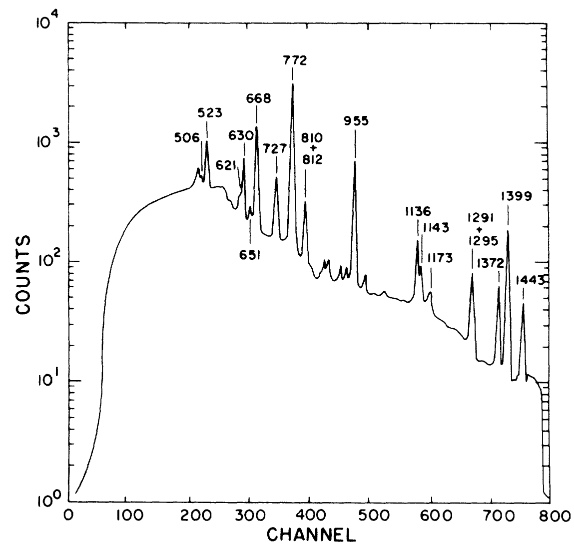

FIG. 6. 668-keV gated coincidence γ-ray spectrum observed using two Ge(Li) detectors. (Uncorrected for effects due to chance coincidences and Compton-scattered radiation.)

quoted represent both contributions from the statistical counting uncertainty as well as uncertainties in the corrections applied.

The relatively weak 670- and 672-keV transitions could not be resolved from the 668-keV transition. Since the spins of the nuclear states and the multipolarities of the 670- and 672-keV γ rays are not known, exact corrections could not be computed for effects due to these transitions on measurements gated on the 668-keV transition; the effect was rather taken into account by an increase in the error limits of the appropriate directional-correlation coefficients. The amount of the increase was determined by the directional-correlation coefficients computed for these two transitions based on all possible spins and multipolarities. When subsequent analysis revealed more definite spin assignments for the 2110- and 2112-keV levels, a second iteration was then performed using more exact correction factors.

The results for the 772-668-keV cascade show good agreement for both gating configurations, and in addition are in agreement with the coefficients expected for a $4^+ \to 2^+ \to 0^+$ cascade ($A_{22} = 0.102$, $A_{44} = 0.009$); such good agreement lends confidence to the values of the correction factors used. The small discrepancy between the measured values and the theoretical ones may be due to the influence of the unresolved 670- and 672-keV transitions.

The directional-distribution coefficients $A_k(\gamma)$ for the $2^+ \to 0^+$ 668-keV $E2$ and for the $4^+ \to 2^+$ 772-keV $E2$ transitions can therefore be assumed to be well established:

$$A_2(668) = F_2(2202) = -0.598\,, \quad A_4(668) = F_4(2202) = -1.069\,, \tag{7}$$

$$A_2(772) = F_2(2224) = -0.448\,, \quad A_4(772) = F_4(2224) = -0.304\,. \tag{8}$$

Also, the values of the de-orientation coefficients $U_k(772)$ are known with certainty:

$$U_2(772) = \sqrt{5}\sqrt{9}\begin{Bmatrix} 4 & 4 & 2 \\ 2 & 2 & 2 \end{Bmatrix} = 0.749\,, \quad U_4(772) = \sqrt{5}\sqrt{9}\begin{Bmatrix} 4 & 4 & 4 \\ 2 & 2 & 2 \end{Bmatrix} = 0.285\,. \tag{9}$$

The results presented in Table I show good overlap between directional-correlation coefficients obtained by gating on the 668- *and* 772-keV transitions, for cases of transitions in coincidence with both. In addition, fair agreement is obtained with previous directional-correlation measure-

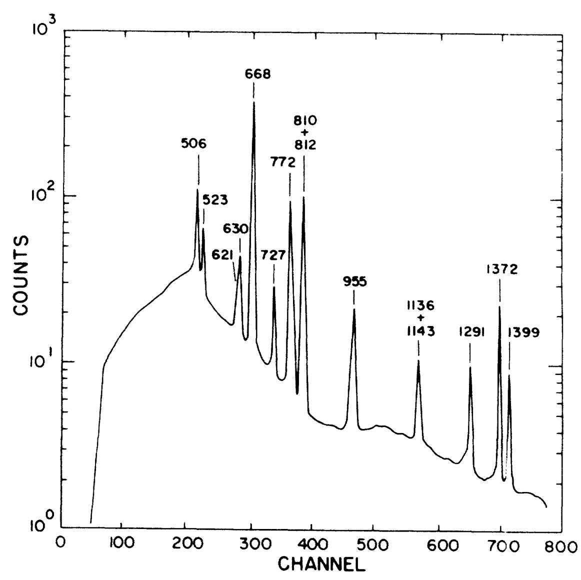

FIG. 7. 772-keV gated coincidence γ-ray spectrum observed using two Ge(Li) detectors. (Uncorrected for effects due to chance coincidences and Compton-scattered radiation.)

TABLE I. Directional-correlation coefficients of the Xe^{132} γ cascades.

Transition energy (keV)	Gating transition 668 keV	772 keV
506	A_{22} = 0.129 ± 0.030	
	A_{44} = 0.038 ± 0.043	
523	A_{22} = 0.248 ± 0.030	A_{22} = 0.249 ± 0.025
	A_{44} = −0.035 ± 0.040	A_{44} = −0.026 ± 0.035
630	A_{22} = −0.191 ± 0.027	
	A_{44} = 0.310 ± 0.039	
668		A_{22} = 0.096 ± 0.009
		A_{44} = 0.001 ± 0.011
727	A_{22} = 0.105 ± 0.033	A_{22} = 0.112 ± 0.035
	A_{44} = 0.040 ± 0.050	A_{44} = 0.003 ± 0.045
772	A_{22} = 0.093 ± 0.009	
	A_{44} = 0.004 ± 0.011	
810 } 812	A_{22} = 0.003 ± 0.030	
	A_{44} = −0.050 ± 0.048	
955	A_{22} = 0.225 ± 0.014	A_{22} = 0.237 ± 0.013
	A_{44} = −0.002 ± 0.017	A_{44} = −0.004 ± 0.016
1136 } 1143	A_{22} = 0.213 ± 0.037	A_{22} = −0.101 ± 0.052
	A_{44} = −0.001 ± 0.057	A_{44} = −0.031 ± 0.080
1173	A_{22} = −0.31 ± 0.11	A_{22} = −0.31 ± 0.08
	A_{44} = 0.05 ± 0.13	A_{44} = −0.04 ± 0.10
1291 } 1295	A_{22} = 0.105 ± 0.044	
	A_{44} = −0.027 ± 0.070	
1372	A_{22} = −0.072 ± 0.050	
	A_{44} = 0.005 ± 0.068	
1399	A_{22} = −0.035 ± 0.016	A_{22} = −0.020 ± 0.014
	A_{44} = −0.005 ± 0.028	A_{44} = 0.006 ± 0.025
1443	A_{22} = 0.130 ± 0.054	
	A_{44} = 0.005 ± 0.085	

ments[25, 26, 33] although the poor energy resolution of the latter due to the use of NaI(Tl) detectors may introduce considerable uncertainties because of the complexity of the Xe^{132} level scheme.

Due to the uncertainties in the spins of the Xe^{132} levels, in many cases definite conclusions could not be drawn regarding mixing ratios of the Xe^{132} γ rays, but based on the measured possible range of values of the directional-correlation coefficients, certain values of the spins could be excluded from the suggested spin assignments of Ref. 37. Results for specific transitions are discussed below.

630-keV Transition

Based on the A_{22} and A_{44} coefficients for the 630-668-keV directional correlation given in Table I and Eq. (7) we compute from Eq. (3) for the $E2/M1$ mixing ratio of the $2^{+\prime} \rightarrow 2^{+}$ transition

$$\delta(630) = +5.3^{+2.1}_{-1.0}.$$

506-keV Transition

Using this value for $\delta(630)$ to compute the U_2 for the 630-keV transition, the orientation parameters $B_k(506)$ for the 506-keV transition may be computed from the measured A_{kk} coefficients of the 506-(630)-668-keV $1 \rightarrow 3$ correlation and from Eqs. (5) and (7):

$$B_2(506) = 1.14 \pm 0.27,$$

$$B_4(506) = -0.14 \pm 0.16.$$

Assuming spin 3 for the 1804-keV level, we compute for the $E2/M1$ mixing ratio of the 506-keV transition

$$\delta(506) = -1.3 \pm 0.4.$$

The measured value of $B_2(506)$ is not consistent with a spin of 2 or 4 for the 1804-keV level; thus the spin of this level is directly verified to be 3, as was assumed earlier from the spins of the states which populate and depopulate this level.[37] In addition the existence of such a large quadrupole content in the radiation field may be taken as confirmation for the positive-parity assignment.

523-keV Transition

From the directional-correlation coefficients A_{kk} of the 523-772-keV cascade we calculate using Eq. (8)

$$B_2(523) = -0.553 \pm 0.056,$$

$$B_4(523) = 0.086 \pm 0.115,$$

whereas the correlation coefficients of the 523-(727)-668-keV $1 \rightarrow 3$ directional correlation gives using Eqs. (7) and (9)

$$B_2(523) = -0.550 \pm 0.067,$$

$$B_4(523) = 0.115 \pm 0.130.$$

The weighted average of these two independent measurements is

$$\overline{B}_2(523) = -0.552 \pm 0.042,$$

$$\overline{B}_4(523) = 0.095 \pm 0.095.$$

The spin of the 1963-keV level is believed to be 3 or 4, with positive parity.[37, 42] For either spin assignment, two values of $\delta(523)$ may be computed from the B_2 coefficient, and associated with each δ there is a value of B_4. The following values were computed:

$$I = 3: \quad \delta(523) = -0.55 \pm 0.05 \Rightarrow B_4(\delta) = 0.14 \pm 0.02$$

$$\text{or } \delta(523) = -3.1 \pm 0.4 \Rightarrow B_4(\delta) = 0.55 \pm 0.02,$$

$$I = 4: \quad \delta(523) = -0.25 \pm 0.15 \Rightarrow B_4(\delta) = -0.03 \pm 0.03$$

$$\text{or } \delta(523) = -0.6 \pm 0.2 \Rightarrow B_4(\delta) = -0.13 \pm 0.03.$$

For both spin assignments, the larger value of δ can be excluded on the basis of the observed B_4 value, but based on the directional-correlation data alone, neither spin value may be excluded. However, the lack of feeding of this level from the 2^- state of Cs^{132} favors the 4^+ choice, which results in

$$\delta(523) = -0.25 \pm 0.15.$$

621-keV Transition

In the present measurements, the 621-keV transition could not be resolved from the 630-keV transition; however, a detailed analysis of the low-energy side of the 630-keV peak (in coincidence with the 668-keV transition) indicated the presence of a large, positive anisotropy corresponding to the 621-keV transition. Considering the effects of the unobserved intermediate radiations, this corresponds to a large, negative B_2 coefficient for the 621-keV radiation; on this basis either spin 3 or 4 for the 2425-keV level would be consistent with the data.

727-keV Transition

Measurements involving this transition have the 672-keV transition as an unobserved intermediate radiation, and thus there are four unknowns to be determined: the multipolarities of the 727- and 672-keV transitions and the spins of the 2839- and 2112-keV levels. (Internal-conversion measurements[36] indicate a probable $E2/M1$ multipole assignment for both transitions, implying positive parity for both levels.) Based on the coefficients

A_{kk} for the 727-(672)-772-keV $1 \to 3$ and for the 727-(672)-(772)-668-keV $1 \to 4$ directional correlations given in Table I, one obtains

$$B_2(727)U_2(672) = -0.241 \pm 0.054\,,$$

$$B_4(727)U_4(672) = -0.076 \pm 0.115\,.$$

The 4^+ choice for the 2839-keV level (see Fig. 2) may be eliminated based on the analysis of the 1399-keV transition given below. For a 3^+ choice for the 2839-keV state, the 2112-keV level must be 5^+, since a $3^+ \to 6^+$ transition ($M3$ or $E4$) is unlikely to exist with an intensity as large as that observed for the 672-keV transition. Thus, for a 3^+ assignment to the 2839-keV state, the 727-keV transition must be pure $E2$. The B_k's are then uniquely determined, and we obtain $U_2(672) = 0.57 \pm 0.13$ and $U_4(672) = 0.31 \pm 0.47$. The minimum value of U_2 for a $5^+ \to 4^+$ transition is $U_2(672)_{min} = 0.705$. The measured $U_2(672)$ value is somewhat smaller than the minimum value. Also, the minimum value of $U_2(672)$ for a $5^+ \to 4^+$ transition corresponds to a pure $E2$ multipolarity for the 672-keV γ radiation. Such a strong collective transition existing at this high an excitation energy is inconsistent with systematics of other transitions in this isotope and in this mass region; hence the 3^+ assignment to the 2839-keV state is very unlikely, leaving 5^+ as the most likely choice for the spin of the 2839-keV level. This spin assignment also agrees with the fact that the 2839-keV excited state is not populated in (n, γ) reactions.[42]

If the 2112-keV level has $I^\pi = 6^+$, the 672-keV transition would be pure $E2$ ($6^+ \to 4^+$), for which $U_2(672) \approx 0.90$; if the level were 5^+, we would again expect $U_2(672) > 0.80$. Thus for either choice, drawing similar conclusions regarding U_4, we obtain

$$B_2(727) = -0.27 \pm 0.06\,,$$

$$B_4(727) = -0.10 \pm 0.15\,.$$

For a 6^+ 2112-keV level, $\delta(727) = -0.32 \pm 0.04$ which gives $B_4(727) = +0.04$ (the other possible value of δ requires $B_4 = 0.52$ and thus it can be eliminated). For a 5^+ 2112-keV level, possible values of the mixing ratio of the 727-keV transition would be $\delta(727) = -1.3 \pm 0.2$ ($B_4 = -0.31$) or $\delta(727) = +0.25 \pm 0.08$ ($B_4 = -0.02$). The latter value is more acceptable because of the B_4 value deduced from the measurement. However, based solely on the directional-correlation data, there is no reason for eliminating either the 5^+ or 6^+ assignments for the 2112-keV level; the fact that the level decays to the 4^+ 1963-keV level but not to the 3^+ 1804-keV level indicates a preference for the 6^+ assignment, for which

$$\delta(727) = -0.32 \pm 0.04\,.$$

Again, the neutron-capture data[42] also favor a high spin for the 2112-keV level.

810- and 812-keV Transitions

The directional correlation of the combination of these two γ rays with the 668-keV radiations shows a vanishing anisotropy. Internal-conversion measurements[36] indicate a substantial $E2$ character for the 812-keV transition, which favors a 4^+ choice for the 2110-keV level. For such a transition, $B_2(812) = -0.17$; based on the relative intensities of the 810- and 812-keV transitions, the isotropy of the observed correlation implies that $B_2(810) \approx -0.25$, for which the spin of the 2614-keV level is permitted to be 3, 4, or 5, with the appropriate choice of $\delta(810)$. However, the analysis of the 1173-772- and of the 1173-(772)-668-keV directional correlations, which is presented below, favors a $I^\pi = 5^+$ assignment to the 2614-keV state. For such a choice, the orientation parameter of a pure $E2$ transition leading from the 5^+ state to the 3^+ state at 1804 keV would be $B_2(810) = -0.21$ in agreement with the experimental value extracted above. The neutron-capture data[42] support this spin assignment.

955-keV Transition

From the directional-correlation coefficients for the 955-772- and for the 955-(772)-668-keV cascades we compute

$$B_2(955) = -0.515 \pm 0.020\,,$$

$$B_4(955) = 0.010 \pm 0.046\,.$$

The spin of the 2395-keV level is likely to be 3^+ or 4^+.[37,42] Values of $\delta(955)$ may be computed from the B_2 coefficients for either spin assignment, and B_4 values may be computed from the so-obtained values of $\delta(955)$, with the following results:

$$I = 3: \quad \delta(955) = -0.50 \pm 0.03 \Rightarrow B_4(\delta) = 0.12$$
$$\text{or } \delta(955) = -3.6 \pm 0.2 \Rightarrow B_4(\delta) = 0.59\,,$$
$$I = 4: \quad \delta(955) = -0.15 \pm 0.05 \Rightarrow B_4(\delta) = -0.01$$
$$\text{or } \delta(955) = -0.71 \pm 0.06 \Rightarrow B_4(\delta) = -0.16\,.$$

For both spin assignments, the larger values of δ may be excluded on the basis of the comparison of the computed B_4 values with the measured one. In addition, the smaller value of δ for the $I = 3$ assignment requires a B_4 value that lies more than 2 standard deviations from the measured value, making that an unlikely choice. Thus we favor a 4^+

choice for the 2395-keV level, for which one obtains

$$\delta(955) = -0.15 \pm 0.05 .$$

1136- and 1143-keV Transitions

While it was not possible to completely resolve these two transitions, only the 1143-keV transition is in coincidence with the 772-keV transition. From the directional-correlation coefficients A_{kk} of the 1143-772-keV cascade in Table I we thus obtain

$$B_2(1143) = 0.23 \pm 0.12 ,$$

$$B_4(1143) = 0.10 \pm 0.26 .$$

The 2584-keV level may have spin 3^+, 4^+, or 5^+.[37] The two possible values of δ for a 4^+ choice require large, negative $B_4(1143)$ values which would not be consistent with the measured value of B_4. In a similar way one of the two possible choices of δ for both the 3^+ and 5^+ spin assignments may be excluded. The two remaining possibilities are $\delta(1143) = -0.05 \pm 0.05$ for the 3^+ choice, and $\delta(1143) = -(0.04^{+0.09}_{-0.04})$ for the 5^+ choice. The absence of transitions from this level to any of the 2^+ levels and the nonpopulation of this level in (n, γ) capture reactions[42] strongly favors the 5^+ choice, for which case one obtains

$$\delta(1143) = -(0.04^{+0.09}_{-0.04}) .$$

After correcting the directional-correlation coefficients that were obtained in the (1143 + 1136)-668-keV cascade measurement gated on the 668-keV transition, for the effect of the 1143-keV transition, we obtain (knowing the spin of the 1804-keV level to be 3^+)

$$B_2(1136) = -0.56 \pm 0.15 ,$$

$$B_4(1136) = -0.01 \pm 0.10 ,$$

which yields

$$\delta(1136) = +0.9 \pm 0.3 .$$

1173-keV Transition

From the directional-correlation coefficients of the 1173-772-keV cascade and of the 1173-(772)-668-keV cascade, we calculate

$$B_2(1173) = 0.69 \pm 0.15 ,$$

$$B_4(1173) = 0.04 \pm 0.33 .$$

The possible spins of the 2614-keV level are 3^+, 4^+, or 5^+.[37] For a 4^+ choice, the maximum value of B_2 permitted is 0.4, making this choice unlikely. Both the 3^+ and 5^+ choices provide reasonable values of δ; again, the lack of transitions to any 2^+ levels and the lack of excitation of this level in neutron-capture reactions[42] strongly favors the 5^+ choice, for which one obtains

$$\delta(1173) = -0.40 \pm 0.15 .$$

1291- and 1295-keV Transitions

Both of these transitions are in coincidence with the 668-keV transition; the 1295-keV transition is greater in intensity by a factor of 2, and the contribution of the 1291-keV transition to the A_{22} coefficient is further reduced by a factor of 0.2 due to the de-orientation effect of the unobserved 630-keV transition. Thus the 1295-keV transition dominates the A_{22} coefficient by approximately a factor of 10, and as a first approximation, the angular distribution of the 1291-keV transition will be assumed to be isotropic. Within this approximation, the data are consistent with a 4^+ assignment for the 1963-keV level, in agreement with the conclusion drawn above on the basis of the analysis of the 523-keV transition. However, because of the large error limits of the correlation coefficients, a 3^+ assignment cannot be ruled out purely on the basis of an analysis of the 1295-keV transition; such an assignment would require $\delta(1295) \approx 0.4$.

On the basis of the 4^+ assignment for the 1963-keV level, the contribution of the 1291-keV transition to the angular distribution is computed to be

$$B_2(1291) = 0.1 \pm 0.1 ,$$

which is not consistent with a spin assignment $I = 4$ for the 2589-keV level [$B_2(1291) = -0.17$]. If the spin 3 is assigned to the 2589-keV level, the 1291-keV transition must be predominantly dipole, with

$$\delta(1291) = +0.01 \pm 0.08 .$$

1372-keV Transition

The spin assignment of the 2670-keV level is assumed[37] to be 3^+ or 4^+; the present data are consistent with either assignment. A 4^+ assignment would necessitate $A_{22} = -0.019$, which lies just outside the large error limits of the correlation coefficients given in Table I; a 3^+ assignment would be consistent with the data if $0.3 \leq \delta(1372) \leq 2.0$. Internal-conversion data[36] indicate a slight preference for an $M1$ multipolarity, but the preference is not strong enough from either the internal-conversion data or the present angular-correlation data to make a definite spin assignment.

1399-keV Transition

The 2839-keV level is assigned[37] either 3^+, 4^+, or 5^+. Based on the 4^+ assignment, two values of δ may be computed from the experimental A_{22} coefficient; these two values require A_{44} values of

TABLE II. $E2/M1$ mixing ratios of the Xe^{132} γ rays.

Transition energy (keV)	$\delta(\gamma) = \frac{\langle I_f \Vert j_N A_2^{(E)} \Vert I_i \rangle}{\langle I_f \Vert j_N A_1^{(M)} \Vert I_i \rangle}$
506	-1.3 ± 0.4
523	-0.25 ± 0.15 [a]
630	$+5.3^{+2.1}_{-1.0}$
727	-0.32 ± 0.04 [a]
955	-0.15 ± 0.05 [a]
1136	$+0.9 \pm 0.3$
1143	$-(0.04^{+0.09}_{-0.04})$ [a]
1173	-0.40 ± 0.15 [a]
1291	$+0.01 \pm 0.08$ [a]
1399	$+0.07 \pm 0.02$ [a]

[a] Based on the spin assignments derived in Sec. IV.

0.14 or 0.043, both of which are unlikely, in comparison with the observed A_{44} value. In addition, the lack of transitions to any of the 2^+ levels and the lack of excitation in (n, γ) reactions[42] strongly supports the assumption that the spin of this level is neither 3^+ nor 4^+.

The analysis of the 727-keV transition given above indicates a 5^+ assignment for the 2839-keV level; on that basis, the two possible values of $\delta(1399)$ are +0.07 ($A_{44} = 0.00$) and 6.8 ($A_{44} = -0.06$). On the basis of systematics and the observed A_{44} values, we choose

$$\delta(1399) = +0.07 \pm 0.02 .$$

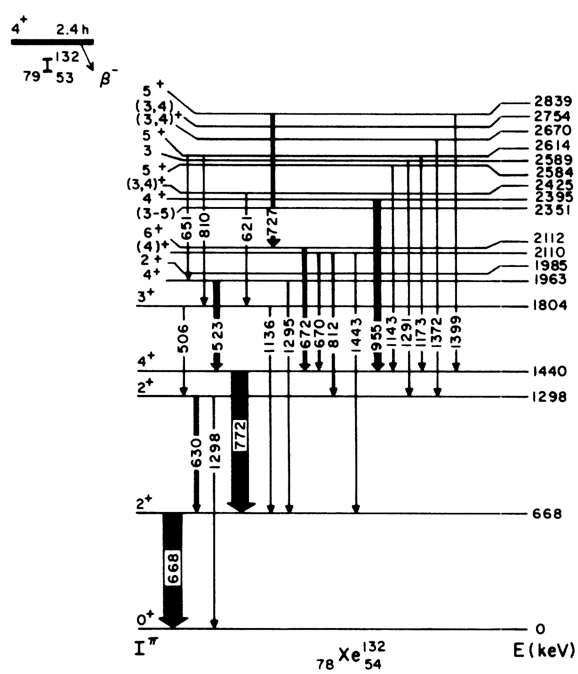

FIG. 8. Spin assignments to the excited states of Xe^{132} based on the present work.

1443-keV Transition

Based on the analysis given above for the 812-keV transition, the data are consistent with a 4^+ assignment for the 2110-keV level. Such an assignment would require $A_{22} = 0.102$ and $A_{44} = 0.009$, for the 1440-668-keV cascade, which is in agreement with the measured values. The 4^+ assignment also agrees well with the neutron data.[42]

V. DISCUSSION

The present investigation has yielded the $E2/M1$ multipole mixing ratios for a number of Xe^{132} γ rays (Table II) and has resolved some ambiguities in the spin assignments of the Xe^{132} excited states as shown in Fig. 8.

The mixing ratio of the 630-keV $2^{+\prime} \to 2^+$ transition was deduced to be +5.3, indicating a substantial collective nature of the 1298-keV state. The corresponding $2^{+\prime} \to 2^+$ transitions in Xe^{126} ($\delta = +9.1$)[2,20] and Xe^{128} ($\delta = +6.4$)[21] show somewhat larger quadrupole contents. It is noteworthy that the $2^{+\prime}$ state in the even-even Xe isotopes rises from 880 keV in Xe^{126} to 1298 keV in Xe^{132}. As the energy of the $2^{+\prime}$ state increases, it is presumed that the quasiparticle contribution to the state also increases, and thus the $2^{+\prime}$-2^+ transition would be expected to be less collective as A increases. This is consistent with the systematics observed in the even-even Xe isotopes.

The positive values observed for the $2^{+\prime}$-2^+ mixing ratios in $Xe^{126, 128, 132}$ are in contrast to the negative mixing ratios observed in $Te^{122, 124, 126}$.[2,44] Detailed calculations of quasiparticle effects on collective transitions in this mass region would be desirable in helping to account for this contrast.

The "three-phonon" states have been more conclusively identified as a result of the present investigation. The 6^+ identification for the 2112-keV state is consistent with the expected location of the 6^+ state of the three-phonon quintuplet. Two 4^+ states have been identified as possible candidates for the 4^+ "three-phonon" level. The 4^+ state at 1963 keV and the 4^+ state at 2110 keV both decay to the two-phonon 4^+ state of 1441-keV energy. The $E2/M1$ mixing ratio of the former decay indicates a small $E2$ content, and thus this is an unlikely candidate for a three-phonon state. The $E2/M1$ mixing ratio of the 670-keV transition from the higher-energy 4^+ state could not be measured in the present work because of the presence of the strong 668-keV transition. Thus, more definite conclusions regarding the 4^+ three-phonon level cannot be drawn at the present time.

The two $E2/M1$ mixing ratios deduced from the present work for transitions from the 3^+ 1804-keV state both show approximately equal quadrupole and dipole contents, indicating a strong basis for interpreting the 1804-keV state as the 3^+ member of the three-phonon quintuplet.

The transitions from the states above 2300 keV exhibit no regularities which can be interpreted in terms of vibrational levels or rotational bands. It is interesting to note that internal-conversion measurements[36] indicate that none of the reasonably intense transitions in Xe^{132} appear to be $E1$ in character. Thus no definite identification has been proposed for the 3^- state, corresponding to a one-octupole phonon. One possible candidate might be the 2589-keV level; the 1291-keV transition from this level is strongly dipole in nature. However, since the directional-correlation results are not sensitive to the electric or magnetic character of the radiation, the present data provide no conclusive assignment for the octupole-phonon state.

Although some properties (energy, spin, parity) of some of the excited states of Xe^{132} show vibrational aspects, the significant $M1$ admixtures observed in the γ transitions between these states make this interpretation doubtful. On the other hand, some aspects of a quasirotational nature can be found in some of the Xe^{132} states. The excited states at 1298, 1804, and 2395 keV with spins and parities 2^+, 3^+, and 4^+, respectively, can be interpreted as members of the quasi-γ band. However, only the 2^+ and 4^+ members of the ground-state band have been observed in $(\alpha, 2n)$ reactions, whereas in the more neutron-deficient even-even Xe isotopes ground-state bands up to $I^\pi = 10^+$ have been identified.[7]

Hence, it is clear that an interpretation of the excited states of Xe^{132} in terms of vibrational or quasirotational models is of limited value. More refined models that take into account the interactions between the collective modes and the individual quasiparticle modes are required to explain the structure of this nucleus.

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Decay of ^{136}Pr and the Level Structure of ^{136}Ce†

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A new isotope with a 13.1 ± 0.1-min half-life has been assigned to ^{136}Pr. It has been produced by the reactions ^{136}Ce$(p,n)^{136}$Pr and ^{136}Ce$(d,2n)^{136}$Pr. It decays by electron capture and positron emission to excited states in ^{136}Ce. It has a capture-to-positron ratio of 0.65 ± 0.01 and a total decay energy of 5120 ± 70 keV. The energies and intensities of 63 γ rays have been measured. Conversion coefficients of the 540- and the 552-keV transitions have been found to be 6.5×10^{-3} and 6.8×10^{-3}, respectively. γ-γ coincidences have been measured using two 40-cm^3 Ge(Li) detectors from which an energy-level diagram for ^{136}Ce has been deduced. Spin and parity assignments have been made to many of the levels. The low-lying energy levels have been separated into quasi-ground and quasi-γ bands.

I. INTRODUCTION

An isotope with a 70-min half-life which emitted positrons and γ rays was assigned by two different groups[1,2] to ^{136}Pr. Most of the properties of this isotope including the maximum β^+ energy, the K/β^+ ratio, and γ-ray energy (170 keV) were the same as those now known[3] to be associated with the decay of ^{137}Pr. Our attempts to produce a ^{136}Pr isotope with a 70-min half-life have been unsuccessful. In addition, we have produced a new isotope with a 13.1-min half-life which we have assigned[4] to ^{136}Pr. The details of the mass assignment, the decay energy, and the measurements of the radiations emitted in the decay of the new isotope are reported below. The energy level structure of ^{136}Ce populated by the decay of ^{136}Pr is also discussed.

Zhelev *et al.* and Gromov *et al.*[5,6] have also studied ^{136}Pr. It was present as the daughter of ^{136}Nd which they produced in a gadolinium target exposed to a 660-MeV proton beam. Their measurements and ours tend to supplement one another and lead to the same spin assignments for the low-energy excited states in ^{136}Ce.

II. EXPERIMENTAL

A. Source Preparation

The sources used to study the new isotope were prepared by cyclotron irradiation of thin targets of ceric oxide enriched in ^{136}Ce. Most of the work was done with ^{136}Ce enrichments of 30 to 35% and with targets which were less than 2 mg/cm^2 thick. In preliminary work targets were irradiated with 11-MeV protons in either the Oak Ridge 86-in. cyclotron or the Oak Ridge isochronous cyclotron (ORIC). In later work it was found more convenient to make measurements on ^{136}Pr as the daughter of the longer-lived ^{136}Nd[6,7] which was produced by ^{3}He irradiation of ^{136}Ce in the ORIC.

In all cases targets were purified after cyclotron irradiation by dissolving the ceric oxide in sulfuric acid and reprecipitating with ammonium hydroxide. Among the radioactive impurities removed in this process were ^{13}N, ^{18}F, and ^{24}Na. When element identification or a genetic relationship was to be established, neodymium-praseodymium separations were achieved on ion-exchange chromatographic columns.