E2/M1 Multipole Mixing Ratios of Gamma Transitions
in the "Quasi-Spherical" Nucleus Xe^{132} *

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E2/M1 Multipole Mixing Ratios of Gamma Transitions
in the "Quasi-Spherical" Nucleus Xe^{132} *

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The E2/M1 multipole mixing ratios $\delta(\gamma) = \langle I_f || \vec{J}_{N2}^{\vec{A}}(E) || I_i \rangle / \langle I_f || \vec{J}_{N1}^{\vec{A}}(M) || I_i \rangle$ of 10 gamma transitions in the quasi-spherical nucleus Xe^{132} have been measured by means of gamma-gamma 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):
 $\delta(506) = -1.3 \pm 0.4$; $\delta(523) = -0.25 \pm 0.15$; $\delta(630) = +5.3^{+2.1}_{-1.0}$;
 $\delta(727) = -0.32 \pm 0.04$; $\delta(955) = -0.15 \pm 0.05$; $\delta(1136) = +0.9 \pm 0.3$;
 $\delta(1143) = -(0.04^{+0.09}_{-0.04})$; $\delta(1173) = -0.40 \pm 0.15$; $\delta(1291) = +0.01 \pm 0.08$; $\delta(1399) = +0.07 \pm 0.02$. The results are discussed in terms of the collective vibrational model and in terms of a quasi-rotational 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 gamma transitions in the "quasi-spherical" 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 gamma transitions between these "vibrational" states.^{1,2}

Several attempts have been made to understand the structure of "quasi-spherical" nuclei on the basis of a microscopic description^{3,4} in terms of quasi-particle states plus a quadrupole force. The effect of this force is determined by the quasi-particle 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 quasi-spherical nuclei in terms of quasi-rotational bands has become fashionable.^{5,6} The 2^+ 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 gamma transitions between the quasi-rotational 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

quasi-spherical 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 gamma transitions between "vibrational" states has been made by Korolev⁸, who treated the quasi-spherical 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.

Grechukhin⁹ 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 Greiner¹⁰ 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 quasi-spherical and quasi-deformed

regions has been made by Kumar and Baranger¹¹ 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 $182 \leq A \leq 196$. 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 quasi-particle 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 quasi-spherical 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 $\delta = \langle 2^+ || \vec{j}_N \vec{A}_2^{(E)} || 2^+ \rangle / \langle 2^+ || \vec{j}_N \vec{A}_1^{(M)} || 2^+ \rangle$ of the 2^+ to 2^+ gamma transitions in the even-even ^{44}Ru , ^{46}Pd , ^{48}Cd , ^{52}Te nuclei that have been measured so far (Ru^{104} , $\text{Pd}^{106,108,110}$, $\text{Cd}^{106,108,110,112,114,116}$, $\text{Te}^{122,124,126}$) 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 $\delta \approx 0$.^{18,19} The mixing ratios of the 2^+ to 2^+ transitions in $^{54}\text{Xe}^{126}$ and $^{54}\text{Xe}^{128}$, 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-isotopes to the Xe-isotopes may possibly be related to the fact that in the Te-isotopes the

4^+ states are below the 2^+ state in energy, whereas the 4^+ states are above the 2^+ state 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^+ and the 4^+ states in quasi-spherical 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 gamma-gamma directional correlations from the decay of I^{132} was undertaken in order to measure the E2/M1 mixing ratios of gamma 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 gamma 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 keV and 1440 keV level are members of the 0^+ , 2^+ , 4^+ two-phonon triplet, and some of the levels in the energy range 1804 keV to 2112 keV would be interpreted as members of the 0^+ , 2^+ , 3^+ , 4^+ , 6^+ three-phonon quintuplet. In support of this interpretation, gamma transitions changing the phonon

number by two units are in general observed to be reduced in intensity relative to those 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 fifteen times as intense as that to the ground state. Similar relationships are observed for transitions from the three-phonon levels at 1963 keV, 2110 keV, and 2112 keV, but not for transitions from the 1985 keV level. It thus appears that collective quasi-vibrational effects play a significant part in the structure of the lower excited states. On the other hand, some features of a quasi-rotational band have been observed in the Te^{132} nucleus in $(\alpha, 2n)$ reactions.^{7, 23} A rather long-lived isomeric state with $T_{1/2} = 8.4 \times 10^{-3}$ 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 dotted 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 gamma-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 studied³⁸⁻⁴¹; 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, $\text{Te}^{130} (\alpha, 2n)$ 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 gamma 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 gamma-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 hours. 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 gamma radiations in the energy range of interest in the present work (500 keV 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 2mm in diameter and 5-10mm 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 gamma rays at 724 keV 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 keV 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 gamma rays were observed using two 30cc coaxial Ge(Li) detectors having a resolution of 3 keV for Ni^{60} gamma 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 ($2^+ - 0^+$) and 772 keV ($4^+ - 2^+$) transitions simultaneously. Sample 1 was investigated using an automatic angular correlation apparatus, in which the moveable

detector remained at each angular position for 40 minutes, 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 keV 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 minute counting interval. In the investigations using sample 2, the MCA was divided into two 800-channel subgroups, corresponding to spectra gated in coincidence with the 668 keV and 772 keV transitions. Spectra were accumulated at a given angular position for 10 - 12 hours, 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 minute 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 moveable 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 fit to a function of the form

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

where

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

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 keV 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:

$$B_k(\gamma) = \frac{F_k(11I_1I_f) - 2\delta(\gamma) F_k(12I_1I_f) + \delta^2(\gamma) F_k(22I_1I_f)}{1 + \delta^2(\gamma)} \quad (3)$$

where the $F_k(LLI_1I_f)$ are the F-coefficients and the mixing (amplitude) ratio

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

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

$$U_k(\gamma) = (-1)^{I_1+I_2+k} \left[(2I_1+1)(2I_2+1) \right]^{\frac{1}{2}} \frac{- \left\{ \begin{matrix} I_1 & I_1 & k \\ I_2 & I_2 & 1 \end{matrix} \right\} + \Delta^2 \left\{ \begin{matrix} I_1 & I_1 & k \\ I_2 & I_2 & 2 \end{matrix} \right\}}{1 + \Delta^2} \quad (5)$$

where Δ^2 is the intensity ratio

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

of all the $L = 2$ transitions (gamma 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 appears 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 gamma-ray spectrum obtained with a Ge(Li) detector is shown in Fig. 3, and typical gamma-gamma coincidence spectra are shown in Figs. 4 - 7. The spectra in Figs. 4 and 5 were obtained in coincidence with the 630 keV and 955 keV transitions, respectively. The coincidence relationships observed are in agreement with those of Ref. 37. Typical spectra in coincidence with the 668 keV 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 gamma spectroscopy or more detailed gamma-gamma 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 quoted represent both contributions from the statistical counting uncertainty as well as uncertainties in the corrections applied.

The relatively weak 670 keV 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 keV and 672 keV gamma 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 coefficient, 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 keV and 2112 keV levels, a second iteration was then performed using more exact correction factors.

The results for the 772 keV - 668 keV cascade show good agreement for both gating configurations, and in addition are in agreement with the coefficients expected for a $4^+ - 2^+ - 0^+$ 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 keV and 672 keV transitions.

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

$$A_2(668) = F_2(2202) = -0.598 \quad (7)$$

$$A_4(668) = F_4(2202) = -1.069 \quad ,$$

$$A_2(772) = F_2(2224) = -0.448$$

$$A_4(772) = F_4(2224) = -0.304 \quad . \quad (8)$$

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

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

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

The 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 $2^{+1} - 2^{+1}$ transition

$$\delta(630) = +5.3 \begin{matrix} +2.1 \\ -1.0 \end{matrix}$$

The 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 - 3 correlations 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.

The 523 keV Transition

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

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

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

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:

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

The 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.

The 727 keV Transition

Measurements involving this transition involve the 672 keV transition as an unobserved intermediate radiation, and thus there are four unknowns to be determined: the multipolarities of the 727 keV and 672 keV transitions and the spins of the 2839 keV 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 - 3 and for the 727 - (672) - (772) - 668 keV 1 - 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 $3^+ - 6^+$ 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 $5^+ - 4^+$ 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 $5^+ \rightarrow 4^+$ transition corresponds to a pure E2 multipolarity for the 672 keV gamma 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 ($6^+ \rightarrow 4^+$), 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 data⁴² also favor a high spin for the 2112 keV level.

The 810 keV and 812 keV Transitions

The directional correlation of the combination of these two gamma 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 keV 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 keV 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 for 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 support this spin assignment.

The 955 keV Transition

From the directional correlation coefficients for the 955 - 772 keV and for the 955 - (773) - 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 two 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

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

The 1136 keV 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 $\delta(1143) = -(0.04 \begin{smallmatrix} +0.09 \\ -0.04 \end{smallmatrix})$ for the 5^+ choice. The absence of transitions from this level to any of the 2^+ levels and the non-population of this level in (n,γ) capture reactions⁴² strongly favors the 5^+ choice, for which case one obtains:

$$\delta(1143) = - (0.04 \begin{smallmatrix} +0.09 \\ -0.04 \end{smallmatrix}) .$$

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

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

The 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 reactions⁴² strongly favors the 5^+ choice, for which one obtains:

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

The 1291 keV 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

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

The 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 a 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.

The 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 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

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

The 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 keV - 668 keV

cascade, which are 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} gamma 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 $2^{+1} - 2^+$ transition was deduced to be + 5.3, indicating a substantial collective nature of the 1298 keV state. The corresponding $2^{+1} - 2^+$ 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^{+1} 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^{+1} state increases, it is presumed that the quasi-particle contribution to the state also increases, and thus the $2^{+1} - 2^+$ 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 $2^{+1} - 2^+$ mixing ratios in $\text{Xe}^{126,128,132}$ are in contrast to the negative mixing ratios observed in $\text{Te}^{122,124,126}$.^{2,44} Detailed calculations of quasi-particle 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 due to 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 measurements³⁶ indicate that none of the reasonable 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 gamma transitions between these states make this interpretation

doubtful. On the other hand, some aspects of a quasi-rotational 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-gamma 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 quasi-rotational 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.

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

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

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

Transition Energy (keV)	$\delta(\gamma) = \frac{\langle I_f \vec{j}_N \vec{A}_2^{(E)} I_i \rangle}{\langle I_f \vec{j}_N \vec{A}_1^{(M)} I_i \rangle}$
506	-1.3 ± 0.4
523	-0.25 ± 0.15^a
630	$+5.3 \pm 2.1$ -1.0
727	-0.32 ± 0.04^a
955	-0.15 ± 0.05^a
1136	$+0.9 \pm 0.3$
1143	$-(0.04 \pm 0.09)^a$ -0.04
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 Section IV.	

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FIGURES

1. The "one-phonon" and "two-phonon" states and the E2/M1 mixing amplitude ratios in even-even Te and Xe isotopes.
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 ⁷ are indicated.
3. Gamma-ray spectrum from the decay of I^{132} observed with a 30-cc Ge(Li) detector.
4. 630-keV gated coincidence gamma-ray spectrum observed using two Ge(Li) detectors. The spectrum shown is uncorrected for effects due to chance coincidences and Compton-scattered radiation.
5. 955-keV gated coincidence gamma-ray spectrum observed using two Ge(Li) detectors. (Uncorrected for effects due to chance coincidences and Compton-scattered radiation.)
6. 668-keV gated coincidence gamma-ray spectrum observed using two Ge(Li) detectors. (Uncorrected for effects due to chance coincidences and Compton-scattered radiation.)
7. 772-keV gated coincidence gamma-ray spectrum observed using two Ge(Li) detectors. (Uncorrected for effects due to chance coincidences and Compton-scattered radiation.)
8. Spin assignments to the excited states of Xe^{132} based on the present work.

4+ 238 h
132I
53I

132Xe
54Xe

2.4 h
 β^-
 $53 \rightarrow 79$