Variation with mass of $B(E3; 0^+_1 \rightarrow 3^-_1)$ transition rates in $A = 124 – 134$ even-mass xenon nuclei

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(Dated: September 14, 2018)

$B(E3; 0^+_1 \rightarrow 3^-_1)$ transition matrix elements have been measured for even-mass $^{124-134}$Xe nuclei using sub-barrier Coulomb excitation in inverse kinematics. The trends in energy $E(3^-)$ and $B(E3; 0^+_1 \rightarrow 3^-_1)$ excitation strengths are well reproduced using phenomenological models based on a strong coupling picture with a soft quadrupole mode and an increasing occupation of the intruder $h_{11/2}$ orbital.

PACS numbers: 21.10.Ky, 21.10.Re, 21.60.Ev, 21.60.Jz, 23.20.Lv, 27.60.+j, 29.40.Gx

Xenon isotopes with mass numbers from $A = 124$ to 134 are located in a transitional region of nuclei where their low-spin structure indicates an evolution from a weakly-deformed, $\gamma$-soft rotor to a vibrator. The positive-parity states of xenon nuclei in this region have been described within the framework of algebraic models of triaxial rotor-vibrator models, and using a pair-truncated shell-model description. However, the low-spin, negative-parity structures have not been extensively investigated.

The properties of such negative-parity states can provide important information on the octupole degree of freedom. General features of collective octupole motion are still not well understood. Specifically, the excitation energy and, more importantly, the $B(E3; 0^+_1 \rightarrow 3^-_1)$ transition probabilities for $3^-_1$ states are signatures of either octupole vibrational strength or static octupole deformation.

While some information is available on the $B(E3; 0^+_1 \rightarrow 3^-_1)$ strength of nuclei in this mass region such as for $^{124}$Te, $^{126}$Te, and $^{130}$Ba, the only data on octupole collectivity in xenon isotopes stems from an inelastic proton-scattering measurement on $^{136}$Xe. The combination of soft quadrupole and octupole modes can make such nuclei as $^{128}$Xe good candidates for the search of enhancement of the nuclear Schiff moment and atomic electric dipole moment. Here, we present the first determination of the $B(E3; 0^+_1 \rightarrow 3^-_1)$ rates in the chain of even-mass $^{124-134}$Xe isotopes. These results are obtained under identical experimental conditions and compared to a global model reproducing the trends of the $B(E3; 0^+_1 \rightarrow 3^-_1)$ strengths across the nuclear chart.

The xenon beams were delivered by the ATLAS accelerator at Argonne National Laboratory. The beam energies for the $A = 124 – 134$ even xenon isotopes were 555, 556, 553, 563, 571, and 579 MeV, respectively. These beams were directed to the experimental setup (see Fig. 1) where they impinged on a $^{58}$Ni target with 1.1 mg/cm$^2$ thickness and an enrichment of $\geq 95\%$. Scattered xenon nuclei were detected in a large area, four quadrant, parallel-plate avalanche counter (PPAC). The entrance window was located 21.5 cm downstream from the target. The PPAC size was such that it covered laboratory scattering angles between 9° and 40°. The maximum laboratory scattering angle for the xenon nuclei was about 27°. Hence, it was possible to cover the most relevant scattering angular ranges.
The \( \gamma \) rays from the reaction were observed with a setup of six germanium detectors from the MSU SeGA array. These detectors were arranged in a barrel of 9.5 cm radius from the middle of the target to the center of the germanium crystals. In this arrangement, the array had an absolute photopeak efficiency of 6.0% at 1.3 MeV. The germanium detectors of SeGA are 32-fold segmented and allow for a precise Doppler reconstruction of \( \gamma \) rays emitted by nuclei in flight. The total energy and timing information from each germanium detector were obtained from the central contact. The efficiency of the entire germanium array was determined with standard \( \gamma \)-ray calibration sources covering an energy range from 88 to 1836 keV. Corrections to this efficiency due to the summing of coincident events in individual detectors were estimated with the use of GEANT simulations of the setup.

For each event, the arrival of a scattered particle in the PPAC was measured with respect to the ATLAS resonators frequency (rf). This allows for a clear separation of the small-angle (<90°) and large-angle (>90°) scattering in the center-of-mass due to the significant difference in the momentum (and consequently in time of flight) of the xenon nuclei in the two cases. Representative \( \gamma \)-ray spectra, gated on a partial angle range of forward (in the center-of-mass) scattered \(^{128}\text{Xe}\) nuclei, are shown in Fig. 2.

For the analysis of data on \(^{124}\text{Xe}\) and \(^{126}\text{Xe}\), the \( \gamma \) events were sorted into spectra corresponding to five equal divisions of scattering angles between 10.6° and 16.0° in the laboratory frame. For the heavier Xe isotopes, the five angle cuts were between 12.7° and 19.0°. It should be noted that in all cases the condition \( \tau_{\text{min}} > (1.25(A_1^{1/3} + A_2^{1/3}) + 3) \) [fm] was satisfied, excluding nuclear contributions to the excitation process.

The \( \gamma \)-ray intensities corrected for the efficiency were determined for each scattering angle. From these, level schemes were constructed by comparing the measured energies to previously known data with verification that the relative intensities were consistent with Coulomb excitation. In cases where new \( \gamma \) rays were identified, placements are proposed based on \( \gamma-\gamma \) coincidences.

Excited states with confirmed spins of 3\( \hbar \) have been clearly identified in \(^{124}\text{Xe}\), \(^{126}\text{Xe}\), and \(^{128}\text{Xe}\) at 1898.0, 2004.8, and 2138.7 keV, respectively. While the negative parity for these states is suggested, there is circumstantial evidence to support such an assignment in each case.

The observation of a 3\( ^- \) state in \(^{130}\text{Xe}\) has not been reported previously. In the present experiment, several candidate \( \gamma \)-ray transitions were observed. Five transitions were found to feed the 2\(^+ \) state in \(^{130}\text{Xe}\) and can be viewed as candidates for decays from a 3\( ^- \) state. Two of these \( \gamma \) rays at 1687 and 1707 keV have been previously observed to feed the first 2\(^+ \) level following \(^{130}\text{Cs}\) electron capture decay. However, the reported log\( f \) values are not consistent with the forbidden decay that would be expected between the 1\(^+ \) ground state of \(^{130}\text{Cs}\) and a 3\( ^- \) state. Of the three remaining \( \gamma \) rays with respective energies of 1742, 1896, and 2033 keV, the most intense—after efficiency corrections—is the 1742 keV transition. For \(^{124,126,128}\text{Xe}\), the 3\(^- \) → 2\(^+ \) transition was the dominant \( \gamma \) ray in the spectrum above 1400 keV (see e.g. Fig. 2). Consequently, the 1742 keV transition is identified as a candidate for the decay of the 3\(^- \) state. Based on sum-energy and intensity-balance considerations, an observed 1073 keV \( \gamma \) ray is placed feeding the 4\(^+ \) state from this same level. It should be noted that, if this assignment is in error, the \( B(E3; 0^+_1 \rightarrow 3^-_1) \) strength would be less than the value presented below.

A candidate 3\(^- \) state in \(^{132}\text{Xe}\) was proposed at an excitation energy of 2469 keV by Gelletly et al. from the decay by a 1801 keV \( \gamma \) ray that is also observed in the present experiment. Unlike the lighter Xe nuclei, where the strongest decay branch from the 3\(^- \) level occurs to the 2\(^+_1 \) state, the 2469 keV level in \(^{132}\text{Xe}\) has rather significant de-excitation branches to the 4\(^+_1 \), 2\(^+_2 \), and 2\(^+_3 \) states.

In \(^{134}\text{Xe}\), a candidate for the 3\(^- \) level has not yet been identified. In addition, none of the \( \gamma \) rays identified in the present experiment are consistent with expectations for a 3\(^- \) state (i.e., a \( \gamma \) ray feeding the 2\(^+_1 \) state with an energy between 1500 to 2000 keV). Consequently, an energy for

![FIG. 2: Representative \( \gamma \)-ray spectra for the \(^{128}\text{Xe} + ^{58}\text{Ni}\) reaction in coincidence with scattered \(^{128}\text{Xe}\). The spectra are gated on forward scattering angles from 17.8° to 19.0° in the laboratory frame. Panel (a) represents the energy range of interest. Panel (b) shows peaks corresponding to the 2\(^+\) → 0\(^+_1 \), 2\(^+_2 \) → 2\(^+_1 \), and 4\(^+_1 \) → 2\(^+_1 \) \( \gamma \)-ray transitions. Panel (c) highlights the 3\(^-\) → 2\(^+_1 \) transition of interest in the present work.](image-url)
the $3^-$ state is not proposed for $^{134}$Xe. An upper limit on the $B(E3; 0_1^+ \rightarrow 3_1^-)$ strength was determined assuming that the excitation energy for the $3^-$ state is between 2400 and 3000 keV.

For the determination of the electromagnetic transition matrix elements, the angle-dependent γ-ray yields were analyzed using the Coulomb excitation code GOSIA [30, 31]. This code combines the semi-classical theory of multiple Coulomb excitation [32] and the measured γ-ray de-excitation patterns with a numerical least-squares analysis to determine the electromagnetic matrix elements from the experimental γ-ray yields. In addition to the γ-ray yields determined in the present experiments, the previously observed γ-ray branching ratios and multipole mixing ratios for relevant transitions were used when possible as additional information to constrain the determination of the matrix elements further. For those cases where a branching ratio is not known (e.g. the $3^-$ state in $^{130}$Xe), the ratio is fit based solely on the presently measured data.

All observed γ-ray yields were used in the calculation of the transition matrix elements in each of the Xe nuclei. This includes transitions not presented in Fig. 3 γ-ray branching ratios for transitions from the $3^-$ states are listed in Table III. The determination of the $M(E3)$ transition matrix elements was carried out using the method described in Ref. [14]. Specifically, the $M(E1)$ transition matrix elements (e.g. $M(E1; 2_1^+ \rightarrow 3^-)$ and $M(E1; 4_1^+ \rightarrow 3^-)$) were set equal to a total strength of $10^{-4}$ W.u., with relative strengths adjusted to reproduce the branching ratios (if known). $E1$ strengths of $10^{-4}$ W.u. are typical for this mass region (see e.g. Ref. [35]). The static quadrupole moments for the $3^-$ states for different Xe isotopes.

| Table I: γ-ray branching ratios for transitions from the $3^-$ states for different Xe isotopes. |
|---|---|---|---|---|
| $E(3^-)$ (keV) | $E_f$ (keV) | $E_γ$ (keV) | Branching ratio |
| $^{124}$Xe | 1898$^*$ | 354 | 1544 | 100(13) |
| $^{126}$Xe | 2005 | 389 | 1616 | 100(17) |
| $^{128}$Xe | 2139 | 443 | 1696 | 100(3) |
| $^{130}$Xe | 2278 | 536 | 1742$^*$ | 54(10) |
| $^{132}$Xe | 2469 | 668 | 1801 | 56(11) |

$^*$ Negative parity proposed by the present work.
$^1$ γ-ray not previously reported.

![FIG. 3: Partial decay schemes for even $^{124-134}$Xe isotopes. Shown for each isotope are the experimental (Exp.) $0^+, 2^+$, and $4^+$ levels, as well as the proposed $3^-$ state with corresponding γ-ray transitions (dashed transitions correspond to known γ rays that are not observed in the present measurements).](image)
The data presented here represent the first determination of the $B(E3; 0^+_1 \rightarrow 3^-_1)$ values in a chain of even-\textsuperscript{124}–\textsuperscript{134}Xe nuclei. The trends in energy $E(3^-)$ and $B(E3; 0^+_1 \rightarrow 3^-_1)$ excitation strengths are well reproduced using phenomenological models with the universal $A$- and $Z$-dependence. The smoothly increasing excitation energy of the $3^-_1$ states from \textsuperscript{124}Xe to \textsuperscript{134}Xe and the decreasing $B(E3 \uparrow)$ strength can be understood, at least qualitatively, as being associated with the presence of the soft quadrupole mode of the mean field and the decreased availability of the $\nu h_{11/2}$ orbital for the generation of octupole correlations.

The authors thank the staff of \textsc{atlas} for providing high-quality xenon beams. W.F. Mueller thanks D. Cline and C. Y. Wu for significant assistance in using high-quality xenon beams.
ing the GOSIA code and acknowledges fruitful discussions with P.D. Cottle and R.M. Ronningen. A.G. acknowledges support from Professor P. von Brentano and the University of Cologne. This work was supported by the National Science Foundation under grant numbers PHY-0110253, PHY-9875122, PHY-0244453, and by the United States Department of Energy, Office of Nuclear Physics, under contract numbers W-31-109-ENG-38 and DE-FG02ER41220.

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