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Enhanced math

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Enhanced $B(E3)$ strength observed in ^{137}La

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The ^{137}La nucleus was populated by the reaction $^{130}\text{Te}(^{11}\text{B}, 4n)$ at 40 MeV beam energy and the lifetime of the $11/2^-$ state at 1004.6 keV was measured using a hybrid array of HPGe clover and $\text{LaBr}_3(\text{Ce})$ detectors by electronic fast-timing technique, providing the value $T_{1/2} = 263 \pm 12$ ps. The reduced transition probability $B(E3) = 23.3 \pm 2.4$ W.u. is found to be significantly larger compared to the values observed in lighter odd-A La isotopes. The experimentally determined $B(E3)$ value is compared with theoretical calculations of Random Phase Approximation (RPA) which explains the enhanced transition probability to be arising from higher contribution of the $g_{9/2}$ orbital to the proton transition density.

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One of the prominent themes of nuclear structure physics is the investigation of the effects of octupole correlations on the low lying excitations in nuclei [1, 2]. The coupling of single-particle and octupole degrees of freedom enriches the complexity in the level structure and remains a subject of contemporary interest [3, 4]. A recent theoretical investigation has predicted several regions of ground-state octupole deformation across the nuclear landscape [5]. The region of Ba, Ce, Nd, and Sm isotopes around ^{146}Ba is reported to constitute the second-largest concentration of octupole unstable nuclei predicted theoretically that are within the experimental range. Ba isotopes are preferred for studying octupole correlations due to the gap in proton single-particle levels at $Z = 56$ for $\beta_3 = 0.1$ [6]. The presence of strong octupole correlations in this region has been confirmed by studies of even-even isotopes, in which negative-parity bands have been observed at lower excitation energy and connected to the positive-parity ground-state bands by strong electric dipole transitions. Interestingly, more distinctive signatures of octupole deformation are expected in odd-A isotopes. Therefore, the predicted gap in proton levels for octupole deformed $Z = 56$ nuclei should make Cs and La isotopes good candidates for observing parity doublets. While neutron-rich Cs isotopes didn't show any enhanced octupole correlation, ^{145}La isotope showed similar enhancement compared to ^{144}Ba [7]. In addition, the $B(E3)$ transition strengths are a good measure for the octupole collectivity, and the systematics of experimental $B(E3; 3^- \rightarrow 0^+)$ strengths for even-even nu-

clei across the landscape have been described in Ref. [8]. $B(E3)$ strengths for transition other than $3^- \rightarrow 0^+$ have also been studied recently in mass 50, and 210 regions [9, 10]. In particular, the $B(E3; 3^- \rightarrow 0^+)$ values of the chain of even-even Ba isotopes starting from ^{132}Ba to ^{138}Ba [11] and ^{144}Ba to ^{146}Ba [12, 13] indicate substantial octupole collectivity in these nuclei. Recently, the neighboring odd-mass ^{143}Ba has been studied to investigate the interplay between single-particle and collective octupole degrees of freedom [14]. An upper limit on lowest $E3$ matrix element was reported for ^{143}Ba from this Coulomb excitation experiment which suggests that the static octupole deformation may not provide the right description for ^{143}Ba , and implies instead a dynamic nature. Therefore, it is interesting to see the similar evolution in odd-A La isotopes and how it compares to the even-even Ba isotopes. For some of the lighter La isotopes, the $B(E3)$ from $11/2^-$ to $5/2^+$ state are reported to have smaller values compared to the neighbouring even-even Ba isotopes [15]. The present study aims to extract the $B(E3)$ in ^{137}La from lifetime measurement for understanding the evolution of octupole collectivity in the La isotopes.

The excited states of ^{137}La were populated through the fusion evaporation reaction $^{130}\text{Te}(^{11}\text{B}, 4n)$ at a beam energy of 40 MeV. The ^{11}B projectile, obtained from the Pelletron Linac Facility at the Tata Institute of Fundamental Research (TIFR), Mumbai, was incident on the 1.6 mg/cm² thick ^{130}Te target, evaporated on 5.5 mg/cm² ^{197}Au . A hybrid array consisting of

11 Compton-suppressed high purity germanium (HPGe) clover detectors arranged in spherical geometry and 14 LaBr₃(Ce) detectors coupled with digital data acquisition (DDAQ) system [16] was used for the experiment. Four HPGe clover detectors were arranged in 90°, three in 140°, three in 157°, and one at 115°, with respect to the beam direction. To reduce the Compton continuum, each HPGe clover detector is shielded by BGO scintillation detector. The crystal of LaBr₃(Ce) detectors were in cylindrical shape of $\varnothing 2'' \times 2''$. The full width at half maximum (FWHM) of γ -rays at 1.33 MeV energy for the HPGe clover and LaBr₃(Ce) detectors were ~ 2.4 keV and 30 keV, respectively. A mixed source consisting of ¹⁵²Eu and ¹³³Ba isotopes, placed at the target position, was used for the energy calibrations of the HPGe clover and LaBr₃(Ce) detectors. The time-stamped data were collected with two- and higher-fold coincidence condition using an XIA-based digital data-acquisition system [16]. Two crate synchronization method was used, with one crate for 6 digitizer modules with 100 MHz sampling frequency for HPGe clover and other for 1 module with 250 MHz sampling frequency for LaBr₃(Ce) detectors. The details of the method will be communicated through a different paper [17]. The data were sorted using an offline analysis code “MultipARAMeter time-stamp-based COincidence Search program (MARCOS)” [18] and the RADWARE [19] to generate an NTuple containing coincident γ -rays and the time differences between different detectors. The partial level scheme of ¹³⁷La relevant for present discussion is shown in Fig 1. The lifetime of 11/2⁻ state in ¹³⁷La was previously reported as an upper limit of $T_{1/2} \leq 410(70)$ ps [20]. The γ -rays decaying from the 11/2⁻ state are marked as red in the level scheme and consistent with the Ref. [21], which reported a weak transition of 87.2 keV in addition to 169.4, 993.7 and 1004.6 keV transitions mentioned in the other earlier works on ¹³⁷La [20, 22, 23]. We have remeasured the lifetime of this state in the present work using the hybrid array. Figure 2 shows a gated γ -ray spectrum observed in the LaBr₃(Ce) detectors which was used to obtain the time differences across the 11/2⁻ state in ¹³⁷La at excitation energy of 1004.6 keV. The energy gate from the HPGe clover detectors has been used to select the cascade of γ -rays across the 1004.6 keV state in LaBr₃(Ce) to get the time spectrum. The decay half-lives for the states were extracted using time difference spectrum between any two transitions $E_{\gamma 1}$ and $E_{\gamma 2}$ in a cascade. The time difference spectrum can be obtained from the list mode data using the following procedure. Four conditional time spectra ($T_{p1,p2}$, $T_{p1,bg2}$, $T_{bg1,p2}$ and $T_{bg1,bg2}$) were generated from the time-stamped data. Here, $T_{p1,p2}$ represents the time difference spectrum obtained with energy gate around the $E_{\gamma 1}$ and $E_{\gamma 2}$ peaks, while $T_{p1,bg2}$ represents the same for energy gate around the $E_{\gamma 1}$ peak and background near $E_{\gamma 2}$ peak. Similarly, the third and fourth spectra are for background-peak and background-

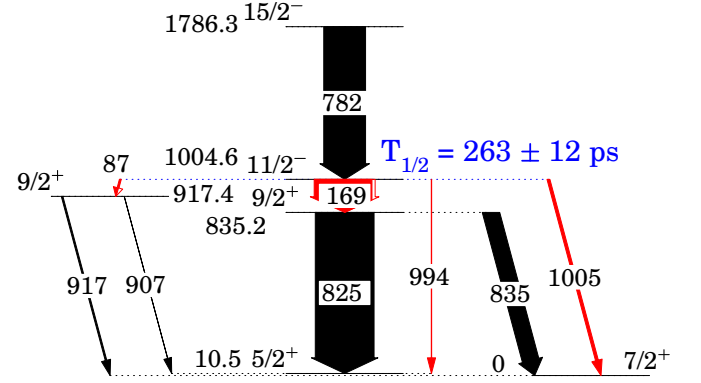


FIG. 1: (Colour online) Partial level scheme of ¹³⁷La relevant for this work. Numbers on the left of each level show the excitation energy in keV. Numbers in each arrow are the transition energy in keV and the thickness of the arrows are proportional to intensities. The transition energies shown in the level scheme have been rounded to the nearest whole numbers. Red line 87.2-, 169.4-, 993.7, and 1004.6- keV γ -rays have been used for evaluating Branching Ratio of 993.7 keV transition.

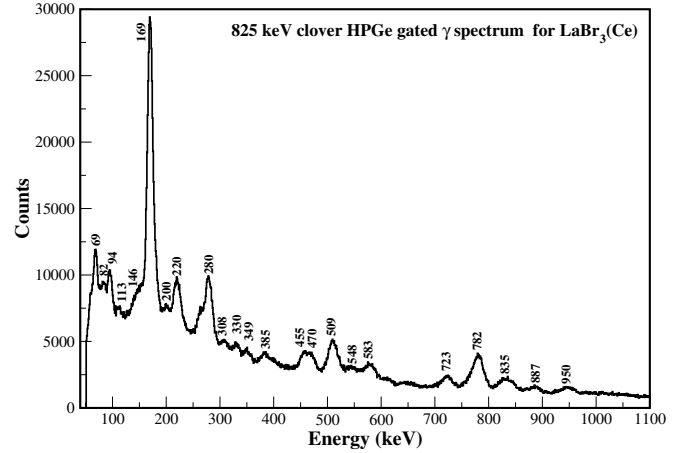


FIG. 2: LaBr₃(Ce) energy spectra obtained by gating on the 825 keV transition in the HPGe clover detectors.

background spectra, respectively. Then the final time difference spectrum was generated by the following formula [16]:

$$T(i) = T_{p1,p2}(i) - T_{p1,bg2}(i) - T_{bg1,p2}(i) + T_{bg1,bg2}(i) \quad (1)$$

The fitting method incorporated the full response function of the time spectra which was assumed to be a convolution of a Gaussian prompt-response function (PRF) and a single component exponential decay associated with the state lifetime [24, 25]. The convolution function associated with a single exponential decay, defined by a mean-lifetime of the decaying state, $\tau = \frac{t_{1/2}}{\ln 2}$ and a Gaussian Prompt Response Function (PRF) defined by a

standard deviation from the mean σ , where the full-width half-maximum (FWHM) for the Gaussian distribution is given by 2.35σ , can be written as,

$$I(t) = A \exp\left(\frac{\sigma^2}{2\tau^2} - \frac{1}{\tau}\right) \left[1 - \operatorname{erf}\left(\frac{\sigma^2 - \tau t}{\sqrt{2}\sigma\tau}\right)\right] \quad (2)$$

where $\operatorname{erf}()$ corresponds to the error function, A is an intensity normalisation constant and t is the time difference since the defined time zero. The time spectrum was fitted with exponential convoluted by gaussian function. The method has been utilized recently in Ref. [26]. All the data fitting has been carried out using the ROOT software packages [27]. The half-life, on fitting the time spectrum with the function of Eq. 2 has been found to be 263 ± 12 ps for the $11/2^-$ state at an excitation energy of 1004.6 keV as shown in Fig 3. The nature of γ -ray transition between $11/2^-$ to $5/2^+$ is $E3$ type. For $E3$ transition, the reduced transition probability is given by [28, 29]

$$B(E3) = \frac{1.75 \times 10^{-3} \times 0.693}{t_{1/2\text{partial}} \times E_\gamma^7} e^2 fm^6 \quad (3)$$

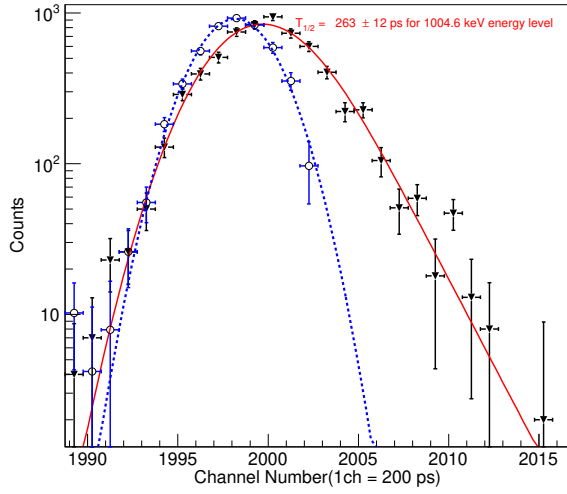


FIG. 3: (Colour online) Time difference spectrum (fitted with exponential convoluted by gaussian function as represented by red colour solid line) was depicted between $\text{LaBr}_3(\text{Ce})$ detectors with γ gated on HPGe , while 169.4 keV at start, and 782 keV at stop in $\text{LaBr}_3(\text{Ce})$, showing $T_{1/2} = 263 \pm 12$ ps for 1004.6 keV energy level. The prompt curve (fitted with gaussian function as represented by blue colour dashed line) having FWHM = 985 ± 23 ps was generated with start at 94 keV and stop at 455 keV (not shown in Fig. 1) from ^{137}La nucleus.

For an isomeric state with N branches, predominantly γ -rays and internal conversion in the present cases, the partial γ -ray mean life of an individual transition i , $\tau_\gamma^i = \tau_{\text{partial}}$ is given by [29]

TABLE I: Summary of intensities for different γ -rays decaying from $11/2^-$ state with 1004.6-keV. These values are used to calculate B.R of 993.7 keV transition

$E_\gamma(\text{keV})$	Relative Intensity	α_{tot}
87.2	1.65 ± 0.17	0.034
169.4	93.44 ± 0.48	0.055
993.7	0.57 ± 0.05	0.004
1004.6	4.82 ± 0.05	0.006

$$\tau_{\text{partial}} = \tau_\gamma^i = \tau^{\text{exp}} \times \frac{\sum_{k=1}^N I_\gamma^k \times (1 + \alpha^k)}{I_\gamma^i} = \tau^{\text{exp}} / B.R \quad (4)$$

where τ^{exp} is the experimental level mean life, I_γ^k ($k = 1, 2, 3, \dots, N$) are the γ -ray intensities of the depopulating transitions, α^k are the total conversion coefficients, and the Branching Ratio is given by the following equation.

$$B.R = \frac{I_\gamma^i}{\sum_{k=1}^N I_\gamma^k \times (1 + \alpha^k)} \quad (5)$$

Consequently, the partial half life becomes

$$t_{1/2\text{partial}} = 0.693 \times \tau_{\text{partial}} = T_{1/2}^{\text{exp}} / B.R \quad (6)$$

where $T_{1/2}^{\text{exp}} = T_{1/2}$ is the measured half life of the particular state.

The corresponding single particle Weisskopf estimate for $E3$ transition is [28],

$$B^W(E3) = 5.940 \times 10^{-2} \times A^2 e^2 fm^6 \quad (7)$$

Using equation 5, and Table I, branching ratio of 993.7 keV transition has been evaluated as $((5.4 \pm 0.5) \times 10^{-3})$ to get the partial half-life of the $11/2^-$ state. 782.1 keV gated spectrum was used for finding the branching ratios of all the transitions decaying from the $11/2^-$ state at 1004.6 keV excitation energy. While extracting the intensity of the 993.7 keV transition, the summing effect for the parallel cascade consisting of 169.4 and 824.8 keV transitions has been taken into account. The count in the peak of the 993.7 keV transition due to the summing of 169.4 and 824.8 keV transitions is estimated to be 0.11% of the yield of 169.4 keV transition based on the GEANT4 simulation results [30]. The GEANT4 estimate of the summing effect of the cascade of γ -rays has been confirmed from the comparison of the area of the sum-peak of 169.4 and 782.1 keV transitions at 951.5 keV and the area of the 169.4 keV transitions in the 455.8 keV gated spectrum (see the level scheme given in Ref. [22]). The reduced transition probability using equation 3, and equation 6 for the 993.7 keV transition is found to be $B(E3) = ((26.0 \pm 2.7) \times 10^3) e^2 fm^6$, which corresponds 23.3 ± 2.4 W.u. in Weisskopf single-particle estimate.

The measured $B(E3; 11/2^- \rightarrow 5/2^+)$ value in ^{137}La has been compared with that of the same transitions in lighter odd-A La isotopes wherever data is available in Fig. 4 [15]. In the same figure, the experimental $B(E3; 3^- \rightarrow 0^+)$ values for even-even Ba isotopes were also plotted. The comparison of $B(E3)$ values between even-even Ba and odd-A La isotopes provides the systematics to understand the coupling between the particle and phonon states in this region. Reference [3] provides an overview of the recent experiments and theoretical attempts to understand low-energy spectra of odd-A nuclei close to magic and semi-magic cores, where particle-phonon coupling phenomena play a significant role. The nuclei around ^{48}Ca , ^{132}Sn , ^{208}Pb and neutron-rich Ni isotopes were discussed. The behaviour of $B(E3)$ strengths for transition $9/2^+ \rightarrow 3/2^-$ have been described in particle phonon coupling model in a chain of odd mass Cu (having one proton only outside the Ni closed shell) isotopes [3]. The significantly large E3 strength for $9/2^+$ states (≈ 20 W.u.) in ^{63}Cu and ^{65}Cu , was attributed to the coupling with the 3^- phonons of ^{62}Ni ($B(E3) = 13(2)$ W.u.) and ^{64}Ni ($B(E3) = 10(2)$ W.u.) [8], respectively. It will be an interesting case to see whether similar kind of behaviour exists for the case of odd-mass La ($B(E3; 11/2^- \rightarrow 5/2^+)$) and even-mass Ba ($B(E3; 3^- \rightarrow 0^+)$) isotopes. Figure 4 shows that our measured $B(E3)$ value in ^{137}La is larger compared to $B(E3)$ values for the same transition in the lighter odd-A La isotopes [15]. It is important to notice that the $B(E3; 11/2^- \rightarrow 5/2^+)$ value measured for ^{137}La isotope with $N=80$ is comparable with the $B(E3; 3^- \rightarrow 0^+)$ in ^{136}Ba , an isotone of ^{137}La , while that of ^{133}La is much smaller compared to the $B(E3; 3^- \rightarrow 0^+)$ of ^{132}Ba .

To understand the experimental value of $B(E3)$ strength, we have performed the Random Phase Approximation (RPA) calculation [31]. The static properties were obtained by a Hartree-Fock calculation. For describing the excited $5/2^+$ state in ^{137}La , we assume spherical symmetry and employ the filling approximation. Namely, 8 (6) protons with occupation probability $6/8$ ($1/6$) occupy $g_{7/2}$ ($d_{5/2}$) orbit, respectively, and 12 neutrons with occupation probability $10/12$ occupy $h_{11/2}$ orbit. The RPA calculations with Skyrme SLy4 interaction [32] was applied to the $5/2^+$ state in a self-consistent manner to calculate the properties of the excited $11/2^-$ state. Figure 4 depicts the comparison of the measured $B(E3; 3^- \rightarrow 0^+)$ of Ba isotopes and $B(E3; 11/2^- \rightarrow 5/2^+)$ of La isotopes with the RPA results. The RPA calculations provide a good description of the variation of measured $B(E3)$ values for even-even Ba isotopes and odd-A La isotopes. Note that the calculation indicates a sudden increase of the $B(E3)$ value at $N=80$ La isotope, which is even more than the $B(E3; 3^- \rightarrow 0^+)$ in ^{136}Ba , while those of $N<80$ stay much smaller values compared to the respective even-even Ba isotopes. Remarkably, the model explains the sudden

rise of $B(E3)$ value for ^{137}La compared to the lighter La isotopes. It will be important to measure the $B(E3)$ strengths in ^{135}La and ^{139}La isotopes to firmly establish the sudden rise of the $B(E3)$ in La isotopes. The proton and neutron transition densities of different states are calculated in the RPA to understand the variation of $B(E3)$ values in La isotopes. Fig. 5 depicts the proton and neutron transition densities of excitations from $5/2^+$ state to $11/2^-$ state, decomposed to the hole orbitals in $5/2^+$ states. It indicates that $g_{9/2}$, $g_{7/2}$, and $d_{5/2}$ proton orbits in $5/2^+$ state are important for exciting to $11/2^-$ state. As shown in Fig. 5, all decomposed transition densities have the same sign (positive), implying large coherency. This indicates that all $11/2^-$ states have strong isoscalar nature. It is clearly seen that as moving from ^{135}La to ^{137}La , both proton and neutron transition densities are enhanced coherently. The calculated transition densities contribution of proton $g_{9/2}$ (blue line) seems to be responsible for the sudden increase of $B(E3)$ value for ^{137}La isotope. In ^{139}La , the proton transition densities are similar to those in ^{137}La , while the neutron transition densities are furthermore enhanced. The sudden rise of $B(E3)$ in ^{137}La is explained by the activation of proton $g_{9/2}$ orbit, which is induced by increasing of neutron number occupying $h_{11/2}$ orbit. On the other hand, such enhancement is not seen in Ba isotopes. This study indicates the possibility of the role of unknown contribution of proton-neutron correlation on the evolution of $B(E3; 11/2^- \rightarrow 5/2^+)$ strength in La isotopes which needs further exploration in future.

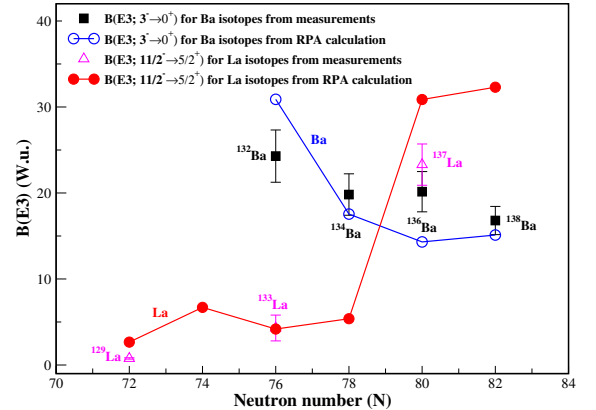


FIG. 4: (Colour online) Variation of experimental $B(E3)$ strengths in Ba and La isotopes. The Random Phase Approximation (RPA) results have been compared with the experimental data. The experimental $B(E3; 11/2^- \rightarrow 5/2^+)$ of $^{129,133}\text{La}$ isotopes from Ref. [15] and $B(E3; 3^- \rightarrow 0^+)$ of $^{132,134,136,138}\text{Ba}$ isotopes have been adopted from Ref. [11]. The $B(E3; 11/2^- \rightarrow 5/2^+)$ of ^{137}La is from present work. The experimental and theoretical values are overlapping for the ^{133}La isotope.

In summary, the lifetime of $11/2^-$ state in ^{137}La

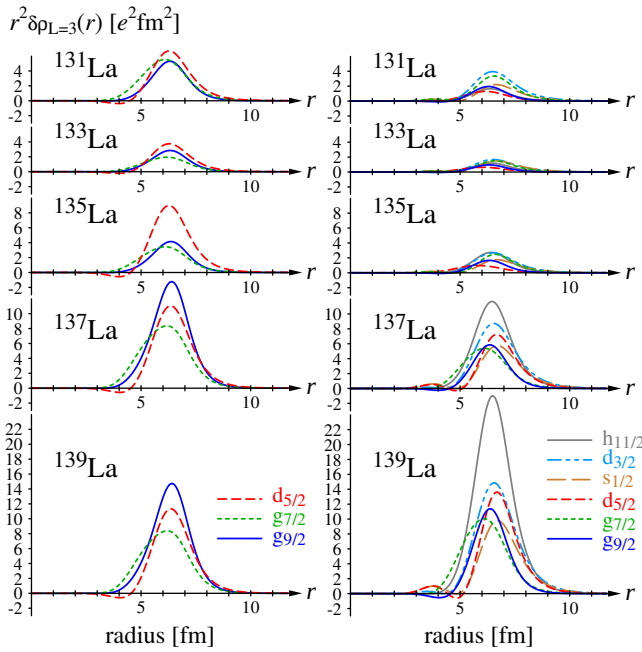


FIG. 5: (Colour online) Proton and neutron transition densities ($r^2\delta\rho_{L=3}$) decomposed to hole states. The gray solid line, cyan dashed double-dotted line, amber long-dashed line, red dashed line, green dotted line, and blue solid line are for $h_{11/2}$, $d_{3/2}$, $s_{1/2}$, $d_{5/2}$, $g_{7/2}$, and $g_{9/2}$, respectively.

has been found to be 263 ± 12 ps, which provides $B(E3; 11/2^- \rightarrow 5/2^+)$ strength as 23.3 ± 2.4 W.u.. The present $B(E3; 11/2^- \rightarrow 5/2^+)$ value of ^{137}La , when compared with that of the lighter La isotopes, confirms for the first time a sudden increase of $B(E3)$ strength at $N=80$. The nature of evolution of $B(E3; 11/2^- \rightarrow 5/2^+)$ strength, which is a measure of octupole collectivity, in odd-A La isotopes seems to be different from the $B(E3; 3^- \rightarrow 0^+)$ of even-even Ba isotopes. These observed variations of $B(E3)$ strengths for La and Ba isotopes have been well explained by RPA calculations. With the addition of an odd proton in $d_{5/2}$ to the even-even Ba core, the evolution of octupole collectivity in La isotopes changes significantly with respect to that of the Ba isotopes. Experimentally it will be important to investigate the $B(E3)$ strength for $11/2^-$ to $5/2^+$ transition in ^{135}La and ^{139}La isotopes to test the predictions of the present RPA calculations. These measurements are required to understand the dynamics of the interaction which causes the sudden rise of the proton $g_{9/2}$ contribution in the transition densities near $N=82$. This work suggests that the possible role of several delta $L = 3$ couplings involving the various orbitals which are reinforcing each other needs to be explored.

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