Identification of Excited States in the $T_z = 1$ Nucleus ^{110}Xe: Evidence for Enhanced Collectivity near the $N = Z = 50$ Double Shell Closure

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Gamma-ray transitions have been identified for the first time in the extremely neutron-deficient ($N = Z + 2$) nucleus ^{110}Xe, and the energies of the three lowest excited states in the ground-state band have been deduced. The results establish a breaking of the normal trend of increasing first excited 2^+ and 4^+ level energies as a function of the decreasing neutron number as the $N = 50$ major shell gap is approached for the neutron-deficient Xe isotopes. This unusual feature is suggested to be an effect of enhanced collectivity, possibly arising from isoscalar *n*-*p* interactions becoming increasingly important close to the $N = Z$ line.

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With the recent refinements in experimental techniques, it is becoming possible to delineate the structure of heavy nuclei over long isotopic chains, across the entire span of major shells and beyond. This is of fundamental importance for testing the validity of nuclear structure models, which are generally derived from the properties of nuclei at or near stability. It is expected that important features of current model descriptions may not be extrapolated to nuclei far from stability, providing a strong experimental and theoretical impetus for studies of such rare systems. As the neutron and proton drip lines are approached, new phenomena are likely to appear due to the effects of coupling to the unbound "continuum" of states, the changing density distributions of neutrons and protons, and the interactions between neutrons and protons in new combinations of single-particle states near the Fermi level [1,2]. The latter can be expected to result in new regimes and modes of nuclear deformation, since it is well known that residual neutron-proton interactions are important for the development of nuclear deformation and low-lying collective phenomena such as rotations and vibrations [3]. Such effects, which are due to the interaction of unlike particles, are unique to atomic nuclei and are therefore not found, for example, in other mesoscopic systems such as atomic clusters. This class of phenomena may be especially pronounced in the vicinity of the $N = Z$ line due to strong dynamical coupling between the neutrons and protons occupying identical orbitals [4]. This Letter presents the first γ-ray spectroscopic study of the $T_z = 1$ nucleus ^{110}Xe, at the limit of what is currently achievable with state-of-the-art detector systems for nuclear spectroscopy.

An important aspect for understanding the structure of nuclei far from stability is the evolution of collectivity with proton and neutron number. The mechanisms behind the emergence of collective phenomena are favorably studied in medium-mass and heavy nuclear systems with a limited number of valence nucleons outside closed shells. The region around the presumed doubly magic self-conjugate $^{100}_{50}$Sn$_{50}$ nucleus is, in this respect, a unique regime, since it is the only place on the Segrè chart where the nuclei contain a sufficient number of particles (the level density is high enough) for pronounced collective excitations to appear, and, at the same time, the $N = Z$ line coincides with an expected double shell closure. When the valence neutrons and protons occupy identical orbits neutron-proton correlations are expected to be particularly important, with theoretical predictions of isoscalar ($T = 0$) neutron-proton pairing to appear [5–9]. Such dynamical coupling of neutrons and protons has, however, to our knowledge not been taken into account in any current mean field calculations. Further theoretical work as well as experimental data that may elucidate the structural evolution of nuclei approaching ^{100}Sn are therefore of major importance in order to develop a better understanding of neutron-proton correlations and their implications for nuclear shell structure far from stability.

For the most neutron-deficient xenon nuclides, the single-particle orbitals closest to the Fermi surface for both protons and neutrons are derived from the $2d_{5/2}$, $1g_{7/2}$, and $1h_{11/2}$ subshells. The nucleus ^{110}Xe, which has four valence protons and six valence neutrons outside the ^{100}Sn core, is at the current lower mass limit of the xenon isotopic chain. It is predicted to lie at the proton drip line and to be bound only by about 0.2 MeV [10]. The lightest Xe isotopes belong to the "island" of alpha radioactivity that also includes the very neutron-deficient Te, I, and Cs isotopes. The characteristic alpha (or proton) decays can be used as a signature, "tag," for identifying excited states in these exotic nuclei using the highly selective recoil-decay tagging (RDT) technique [11,12].

The experiment was performed at the K130 Cyclotron accelerator facility at the University of Jyväskylä, Finland. ^{54}Fe ions were accelerated to an energy of 195 MeV and used to bombard a target consisting of a 1.0 mg/cm^2 self-supporting foil of isotopically enriched (99.8%) ^{58}Ni. The average beam intensity was 5 pnA during 5 days of irradiation time. Prompt γ rays were detected at the target position by the Jurogam γ-ray spectrometer consisting of 43 Eurogam [13] type escape-suppressed high-purity germanium detectors. The fusion-evaporation products were separated in-flight from the beam particles using the gas-filled recoil separator RITU ("recoil ion transport unit") [14] and implanted into the double-sided silicon strip detectors (DSSDs) of the Gamma Recoil Electron Alpha Tagging (GREAT) spectrometer [15]. Spatial and temporal correlations of recoil implants and their subsequent radioactive decays were performed and in-beam RDT γ-ray spectra were constructed.

A serious complication in the selection of the extremely weakly populated ($\sigma \approx 50$ nb) ^{110}Xe nuclei was contamination emanating from the strong population of reaction channels which are subject to β-delayed proton emission, with energy distributions overlapping that of the ground-state α decay of ^{110}Xe. This is illustrated in Fig. 1(a), which shows the correlated energy spectrum for particles emitted following the implantation of a recoiling fusion-evaporation residue. This spectrum has no distinct peak that can be attributed to the decay of ^{110}Xe. Fortunately, the daughter of ^{110}Xe, ^{106}Te, is an α emitter with a 100% branching ratio and a short ($\simeq$70 μs) half-life [16,17]. This enabled around 1200 ^{110}Xe ions to be cleanly selected by means of "mother-daughter" correlations in which the recoil implantation and subsequent α decays of ^{110}Xe and ^{106}Te are required to occur in the same DSSD pixel within the specified time intervals [Figs. 1(b) and 1(c)]. The half-life of ^{110}Xe as extracted from the recoil-α-decay time correlations was measured to be 93(3) ms while the α-particle energy was determined to be 3717(19) keV, corresponding to a Q_α value of 3856(20) keV. Our results are in agreement with previous decay studies of ^{110}Xe which have obtained a half-life of 105^{+35}_{-25} ms [16], an α-decay branching of 64 ± 35% [18], and a Q_α value of 3885(14) keV [19].

Figure 2(a) shows the prompt γ-ray energy spectrum extracted by requiring delayed coincidence with implantation of a recoiling fusion-evaporation residue, whereas the spectrum in Fig. 2(b) was created from clean ^{110}Xe events by requiring recoil-mother-daughter-decay correlations. The three most intense γ-ray transitions assigned to ^{110}Xe (470, 643, and 777 keV) have been ordered into a ground-state band based on their relative intensities (caption, Fig. 2). Because of the low production cross section of approximately 50 nb, the statistics were too limited for a full γ-γ coincidence analysis. However, it was found that

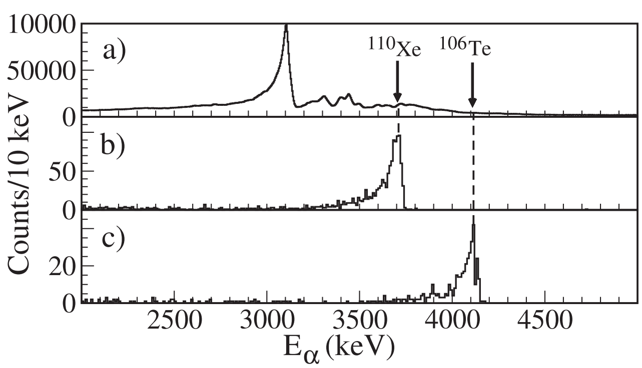

FIG. 1. (a) Correlated decay energy spectrum obtained by requiring the implantation of a recoiling fusion product and a subsequent decay event in the same pixel of the DSSD, within a correlation time of 330 ms (corresponding to approximately three half-lives of ^{110}Xe). The largest peak is due to decays of the most strongly populated α emitter ^{109}Te [28]. (b) As in (a) with the additional requirement of proper spatial and temporal correlations (220 μs) with the subsequent α decay of the daughter nucleus ^{106}Te. (c) As in (b), showing the energy spectrum corresponding to the daughter (^{106}Te) α decays.

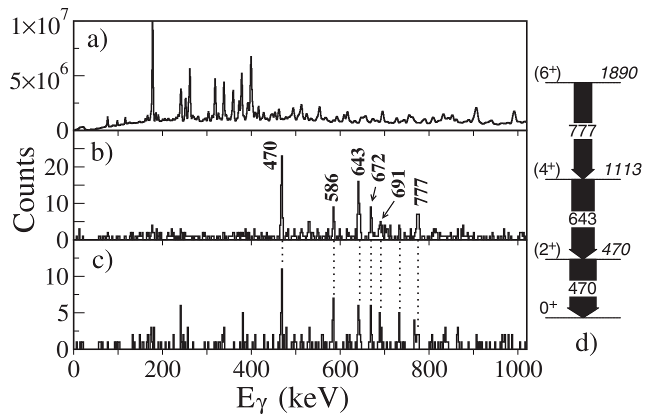

FIG. 2. (a) Recoil-correlated prompt γ-ray energy spectrum, dominated by transitions in the strongest fusion 3-proton evaporation channel, ^{109}Sb [29]. (b) As in (a), with the additional selection of events tagged by the subsequent α decays of ^{110}Xe and ^{106}Te. The energies (given in keV) and relative intensities (%) of the γ-ray transitions assigned to ^{110}Xe are as follows: 469.7(2),100(9); 531.5(5),13(3); 586.3(4),39(5); 643.4(3),81(7); 671.7(5),36(5); 691.1(5),38(5); 735.4(5),13(3); 776.6(6),66(7); 816.8(3),19(3). (c) Recoil-decay-tagged prompt γ-γ-coincidence spectrum extracted from a sum of gates on the 470, 643, and 777 keV transitions. (d) Level scheme showing the lowest levels assigned to ^{110}Xe.

these γ rays form a mutually coincident decay sequence, as indicated by the sum of coincidence gates shown in Fig. 2(c). Although the limited statistics precludes an accurate angular distribution analysis and, hence, firm spin assignments, it is likely that the 470, 643, and 777 keV γ-ray transitions form a cascade of stretched $E2$ transitions depopulating the first excited 2^+, 4^+, and 6^+ states, respectively.

In order to elucidate the structural evolution in the xenon isotopic chain, our results for ^{110}Xe are compared with the energy systematics of the first excited 2^+ and 4^+ states of heavier even-even xenon isotopes in Fig. 3. Such energies are valuable indicators of nuclear deformation and collectivity as demonstrated, for example, by the well-known existence of a general systematic relationship between the transition strengths [$B(E2)$ values] and the 2_1^+ energies of even-even nuclei [20,21]. For a high degree of collectivity (deformation), the 2_1^+ energy will be low, whereas it is expected to take on a maximum value at a shell closure for spherical nuclei exhibiting purely single-particle degrees of freedom. Let us follow the evolution of the xenon isotopes, starting at the top of the $N = 50$–82 neutron shell, towards the $N = 50$ shell closure, and, in particular, focus on the behavior for the lightest nuclides as N approaches Z. The closed neutron shell nucleus ^{136}Xe exhibits the characteristic features of a rigid spherical system with a high 2_1^+ energy and a small $E(4_1^+)/E(2_1^+)$ ratio. As expected, the signatures of collectivity develop and become stronger with decreasing N towards midshell ($N = 66$), where the 2_1^+ energy assumes a minimum value and the $E(4_1^+)/E(2_1^+)$ ratio is near its maximum. As the neutron number is decreased further, below midshell, this trend is (as expected and discussed, e.g., in Refs. [22,23]) initially reversed, i.e., with increasing 2_1^+ and 4_1^+ energies. However, for $N \leq 58$ a different pattern starts to emerge [23] and for $N = 56$ (^{110}Xe), it is clear that there has been no further decrease in collectivity as a function of decreasing neutron number. Features similar to this remarkable observation have recently been found in the extremely neutron-deficient tellurium isotopes [17]. Our new results on $^{110}_{54}$Xe$_{56}$ are even more striking as the excitation energy of the lowest excited 2^+ state differs only by 4 keV (less than 1%) from that of ^{112}Xe, while the excitation energy of the 4_1^+ state in ^{110}Xe is *lower* than that of its ^{112}Xe counterpart. The collective nature of the yrast spectrum in ^{110}Xe therefore seems significantly stronger than expected, given the proximity to the $Z = N = 50$ double shell closure.

In their work on the systematics of $B(E2)$ values for light Xe isotopes, Raman, Sheikh, and Bhatt [22] compare experimental data with results from calculations using several state-of-the-art nuclear models. All of them predict similar decreasing trends for the $B(E2; 2_1^+ \rightarrow 0_1^+)$ values as a function of decreasing neutron number N below the $N = 66$ midshell. We exemplify the theoretical model predictions with total Routhian surface (TRS) calculations based on the cranked Strutinsky formalism [24]. The TRS calculations reveal energy minima as a function of the deformation parameters β_2, β_4, and γ at moderately deformed prolate shapes with the elongation parameter β_2 gradually decreasing as a function of decreasing neutron number, from $\beta_2 \approx 0.23$ for ^{116}Xe to $\beta_2 \approx 0.17$ for ^{110}Xe. Since experimental $B(E2)$ values are lacking for the lightest (^{110,112}Xe) nuclides, a comparison between the theoretical predictions and the available experimental data is made (see Fig. 4) based on the empirical relationship $B(E2; 2_1^+ \rightarrow 0_1^+) \approx 0.66E(2_1^+)^{-1}Z^2A^{-0.69}$ [21] between 2_1^+ energies in even-even nuclides and the corresponding reduced transition probabilities, which are a measure of the nuclear collectivity. The comparison is more relevant for

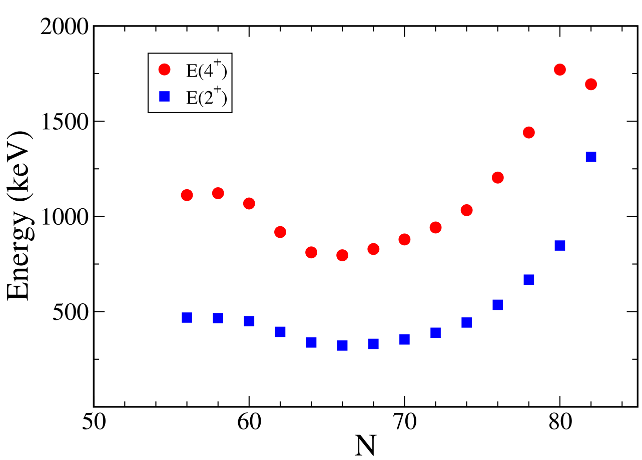

FIG. 3 (color online). Energies of 2_1^+ (squares) and 4_1^+ (circles) states plotted versus neutron number N for even-even Xe isotopes in the mass region $110 \leq A \leq 136$. Data are from the present work and Refs. [23,30].

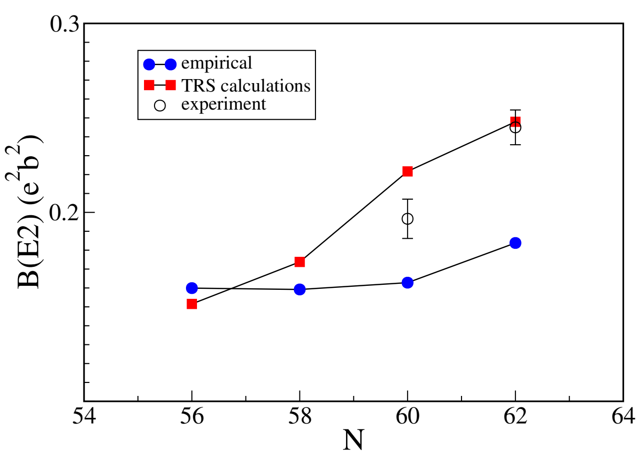

FIG. 4 (color online). Systematics of theoretical $B(E2; 2_1^+ \rightarrow 0_1^+)$ values compared with empirical data derived from experimental 2_1^+ energies according to the formula proposed by Raman, Sheikh, and Bhatt [22]. Data points with error bars are directly measured $B(E2)$ values for ^{114,116}Xe [25].

trends rather than absolute $B(E2)$ values, although the directly measured values available for ^{114,116}Xe [25] show a fair agreement with the theoretical predictions. Whereas the TRS calculations, as well as the wide spectrum of theoretical model calculations presented in Ref. [22], predict a continuous *decrease* in $B(E2)$ as a function of decreasing neutron number N, the experimentally deduced values instead reveal a leveling off, with even a small *increase* in the empirically deduced $B(E2)$ value for ^{110}Xe. Hence, it appears that the energies of the low-lying yrast states of the xenon nuclei close to $N = 50$ deviate clearly from a large variety of theoretical model predictions.

It is noteworthy that, although important effects on fundamental nuclear properties, such as a weakening of the nuclear shell structure [26,27], have been predicted far from stability, they are expected for highly neutron-rich nuclei and not on the extremely proton-rich side of the valley of stability, as in the present case. While the rigidity of nuclear shell structure as extrapolated from nuclei near stability is questionable for highly neutron-rich nuclei, a well-developed double shell closure at $N = Z = 50$ has been generally expected. The observed breaking of the trend of increasing first excited 2^+ and 4^+ energies for the highly neutron-deficient Te and Xe isotopes as a function of decreasing neutron number therefore points to unexpected features of these extremely neutron-deficient, isospin-symmetric nuclei.

Seeking a physical mechanism behind the observed effect, we note that, in Ref. [23], increased octupole correlations were suggested as a possible cause of increased quadrupole deformation based on results from Hartree-Fock–BCS calculations. The observed effect might also be related to neutrons and protons occupying similar orbitals, the enhancement of collectivity observed in the lightest Xe isotopes then possibly arising from enhanced vibrational correlations, due to the increased influence from isoscalar neutron-proton interactions as N approaches Z. Such features have previously not been considered in the long-standing search for neutron-proton pair correlations in $N \approx Z$ nuclei and are beyond the framework of current nuclear structure models.

In summary, γ-ray transitions in the highly neutron-deficient nuclide ^{110}Xe have been identified for the first time, and the three lowest energy levels in the ground-state band are proposed. The observed 2_1^+ and 4_1^+ energies in ^{110}Xe reveal a breaking of the normal trend of decreasing collectivity as the neutron number approaches the $N = 50$ shell closure. This is a pattern that significantly deviates from the expected increased influence from single-particle, seniority coupling near the shell closure. These findings constitute possible evidence for the importance of isoscalar neutron-proton interactions for the development of nuclear collectivity.

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