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High-K, $t_{1/2} = 1.4(1)$ ms, isomeric state in ^{255}Lr

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An isomeric state in ^{255}Lr with a half-life of $t_{1/2} = 1.4(1)$ ms and $E_x > 720$-keV has been observed for the first time using the GABRIELA setup at the focal plane of the VASSILISSA separator. Based on its K-forbiddeness, the configuration of the state is most probably formed by coupling the valence proton to a two quasiparticle neutron excitation. Possible three quasiparticle configurations are discussed.

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The position of the spherical "doubly magic" nucleus beyond $^{208}_{82}$Pb$_{126}$ still remains controversial. The macroscopic-microscopic model, based on the Strutinsky shell-correction method and the Woods-Saxon potential predicts spherical gaps at $Z = 114$ for protons and $N = 184$ for neutrons [1]. In contrast, most self-consistent Skyrme-Hartree-Fock mean field calculations predict $Z = 124$ or $Z = 126$, depending on the parametrization, and $N = 184$. For relativistic approaches, and some Skyrme interactions, the gaps are predicted to be at $Z = 120$ and $N = 172$ (for more details see Refs. [2–4] and references therein). The main cause of these differences is probably the treatment of the spin-orbit term: the spherical gap at $Z = 114$ depends strongly on the splitting between $2f_{7/2}$ and $2f_{5/2}$ proton levels. While the extraction of single-particle energies in the region of the predicted spherical gaps is beyond current experimental observations, important orbitals can be probed in the deformed nuclei around $^{254}_{102}$No.

The recent surge in experimental studies in nuclei around ^{254}No is driven by this need to compare experimental and theoretical single-particle energies with the goal of improving the accuracy and predictive powers of nuclear structure models. The methodology can be split into three categories: prompt spectroscopy of rotational bands, fine-structure α-decay studies and delayed spectroscopy from isomeric states. The advantages of studying isomeric states are (i) high beam intensities can be used, (ii) delayed decays provide a clean signal, and (iii) otherwise inaccessible levels may be populated following the decay of the isomer. Furthermore, the measurement of the excitation energy E_x and the spin and parity J^π of these states also provides stringent tests of nuclear structure models. Contemporary results [5,6] on the known isomer in ^{254}No [7] are excellent examples of what can be achieved with modern methods [8] and setups.

In this Rapid Communication we report on the first observation of the decay of an isomeric state in ^{255}Lr.

Excited states in ^{255}Lr were populated via the fusion-evaporation reaction ^{209}Bi(^{48}Ca,2n) at a nominal midtarget energy of 219 MeV. The 700 pnA ^{48}Ca beam was provided by the U400 cyclotron of the FLNR, JINR, Dubna. The 330 μg/cm^2 Bi_2O_3 targets were mounted on a 1.5 μm Ti backing and placed on a rotating target frame. The fusion-evaporation residues [mainly the one-neutron- (1n) and two-neutron-evaporation (2n) channels into ^{255,256}Lr] were transported by the VASSILISSA separator [9,10] and implanted into a 16-strip position sensitive Si detector of the GABRIELA setup [11]. A combined time-of-flight and energy measurement allowed the evaporation residues (ERs) to be distinguished from the background of scattered beam and transfer products. The subsequent time- and position-correlated α decays of the implanted ERs were also measured in the implantation detector in anticoincidence with the time-of-flight detectors. Known activities from the ^{174}Yb(^{48}Ca,xn)$^{222-x}$Th reaction were used to perform the in-beam energy calibration.

Four 4-strip Si detectors, placed upstream of the implantation detector in a tunnel configuration, were used to detect conversion electrons emitted in the backward direction by the implanted nuclei and their daughter products. The energy calibration of these electron detectors was performed by producing and implanting ^{207}Rn recoils in an isomeric state which is known to decay via internal-conversion-electron emission [12]. In this way, the energy loss of the electrons in the implantation detector could be corrected for. Seven germanium detectors from the French-UK loan pool were used to detect γ-rays emitted from the ERs and their daughters. The signals from all detectors were processed individually and time-stamped with a 1 μs precision when written to hard

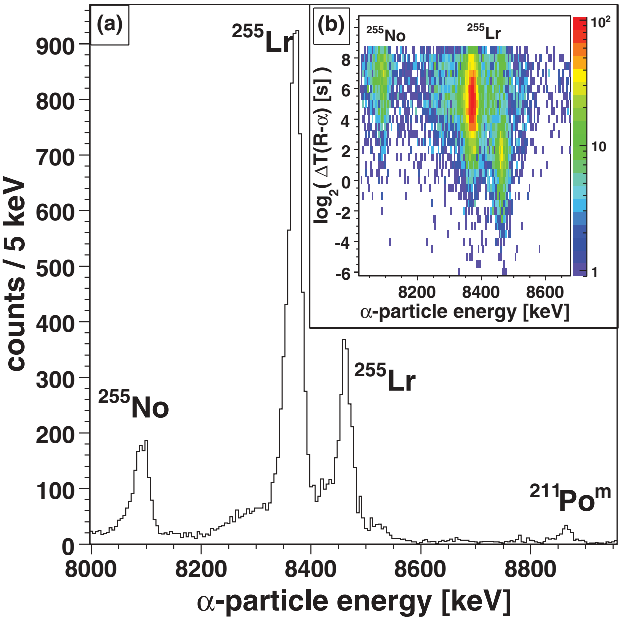

FIG. 1. (Color online) (a) Total α-particle energy spectrum measured at the focal plane. (b) A logarithmic plot of the time difference between position-correlated α-particles and recoils as a function of α-particle energy.

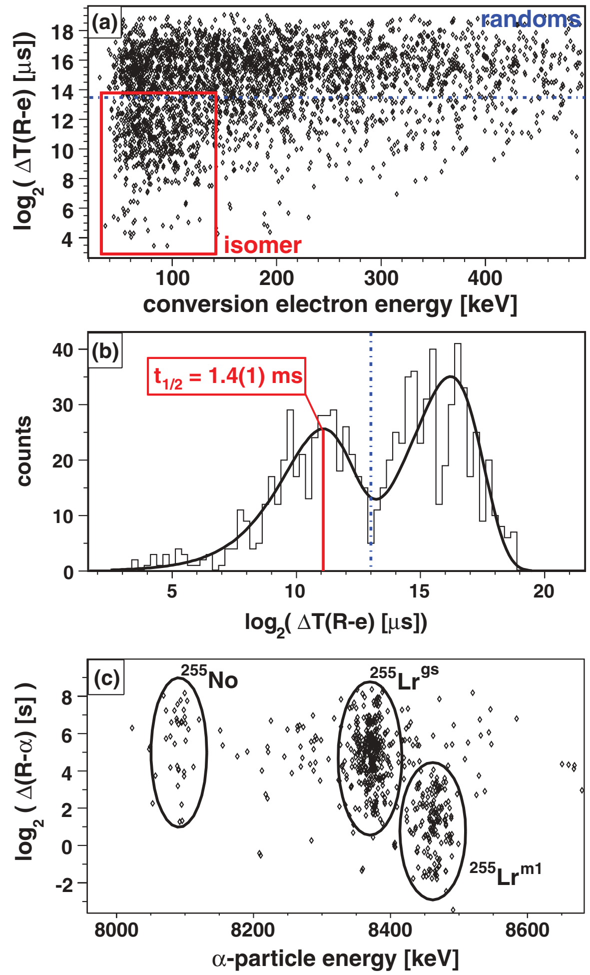

FIG. 2. (Color online) (a) A logarithmic plot of the time difference between recoil and conversion electron detection ($\log_2(\Delta T\,(R-e))$ as a function of conversion electron energy. (b) Time differences for conversion electrons with energies less than 140-keV [projection of (a) onto the y-axis]. (c) Decay time as a function of energy for position correlated α particles in coincidence with the isomeric conversion electron decay.

disk. Events were subsequently constructed during the off-line analysis.

The total alpha spectrum measured is shown in Fig. 1(a). It is dominated by the α-decay lines of ^{255}Lr and ^{255}No, the latter being populated via electron capture or β-decay of ^{255}Lr. The inset, (b), presents a plot of the time difference measured between the implantation of an evaporation residue and its subsequent position-correlated α decay as a function of the correlated α particle energy. A maximum search time of 350 s was used, which is visible as the cutoff in Fig. 1(b). For the ^{255}Lr favored ground-state decay we obtained $E_\alpha =$ 8371(10)-keV and a half-life of 31(2) s. An α decay energy of 8463(10)-keV and half-life of 2.6(1) s was measured for the favoured decay out of the known spin isomer at an excitation energy of 37-keV (henceforth denoted ^{255}Lr^{m1}). These results are in good agreement with those published in Ref. [13]. Note that some of the ^{255}No α-decays have been correlated with the implanted recoils since the emitted X-rays and/or Auger electrons associated with the electron capture (EC) decay mode of ^{255}Lr deposits too little energy to be registered in the implantation detector. Indeed, an estimate of the EC branch can be made with these data: $B_{\mathrm{EC}}(^{255}\mathrm{Lr}) = [N_\alpha(^{255}\mathrm{No}{:}\ 8095)/B_\alpha(^{255}\mathrm{No}{:}\ 8095)] \times [B_\alpha(^{255}\mathrm{Lr})/N_\alpha(^{255}\mathrm{Lr})]$. Using the relevant branching ratios given in Refs. [14,15] we obtain $B_{\mathrm{EC}}(^{255}\mathrm{Lr}) = 0.26(5)$ which is consistent with the accepted value of $< 30\%$ [14].

Decay from isomeric states in ^{255}Lr with half-lives shorter than that of the ^{255}Lr^{m1} decay were searched for in the upstream Si detectors. In Fig. 2(a) the time difference between recoil and conversion electron detection is plotted as a function of the electron energy on an event-by-event basis (recoils preceding electrons). A distinct cluster is visible for energies less than 140-keV and $\log_2(\Delta T) < 13$ (8192 μs). In order to extract a half-life for this isomer the time differences for conversion electrons with energies of less than 140-keV were projected out; see Fig. 2(b). A half-life of $t_{1/2} = 1.4(1)$ ms was obtained from a fit of this projection assuming a single decay component for both the isomer and the random background. The longer lived component reflects the random coincidence rate. Shown in Fig. 2(c) are the position correlated α-particles observed in coincidence with delayed conversion electrons delimited by the "isomer" box in Fig. 2(a). Since no α energy condition has been applied, Fig. 2(c) clearly indicates that the delayed conversion electrons can be attributed to an isomeric decay in ^{255}Lr. The relative intensities of the alpha decays from the ground and first-excited states are, within errors, as those in the total projection of Fig. 1(a). Therefore no additional information on the decay path from the isomer can be obtained.

Delayed γ-ray emission was also searched for. However, beyond about 1 ms it becomes increasingly difficult to isolate weak lines from the background (mainly from the naturally

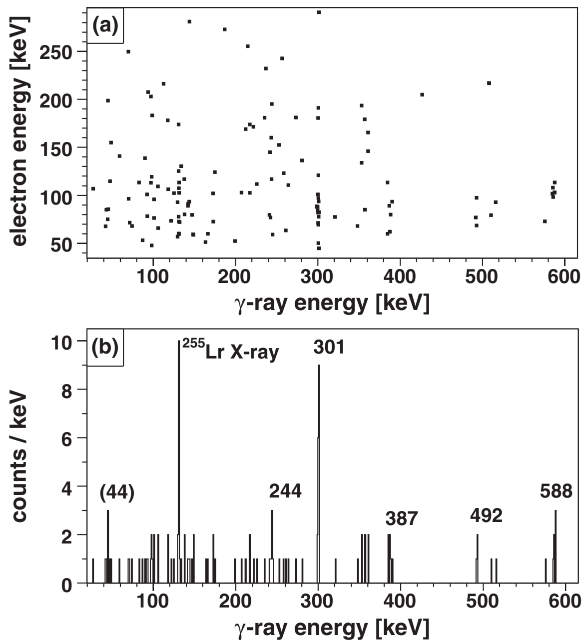

FIG. 3. (a) A conversion electron-γ-ray prompt coincidence matrix. (b) Projection onto the γ-ray energy axis. Transition energies are labeled in keV.

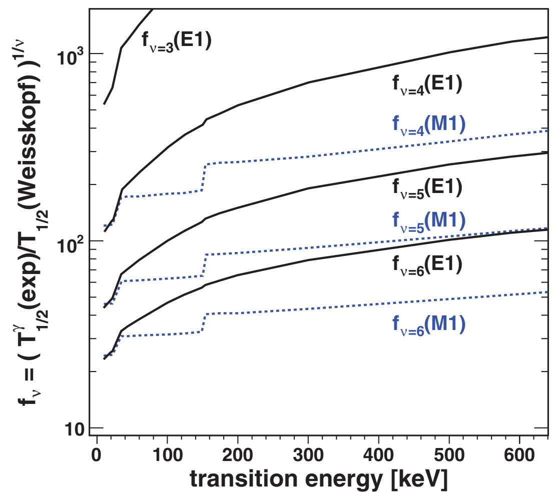

FIG. 4. (Color online) Reduced hindrance factors f_ν as a function of transition energy for both $E1$ (solid line) and $M1$ (dashed line) decays from a state with $t_{1/2} = 1.4$ ms in ^{255}Lr for various values of $\nu = \Delta K - \lambda$.

occurring K, Th, and U decay chains and from the 511-keV annihilation quanta). To isolate γ-rays associated with the decay of the newly observed isomer it was necessary to demand the additional condition of a prompt coincidence (ΔT$< 2\,\mu$s) between conversion electrons and γ-rays, i.e., the conversion electrons shown in Fig. 2 are used to tag the isomeric decay. The resulting E(electron) $- E(\gamma)$ matrix is shown in Fig. 3 and shows distinct coincidences. Figure 3(b) is the projection onto the γ-ray energy axis and clearly shows a number of transitions, including Lr K X-rays.

In the trans-fermium region one expects the occurrence of both spin- and K-isomers. The former is due to the coexistence of both high- and low-j orbitals close to the Fermi surface, and, an example is the α emitting $7/2^-[514]$ state at 37-keV above the $1/2^-[521]$ ground state in ^{255}Lr. The latter is due to the combination of nuclear deformation and the presence of orbitals with a large spin projection K on the symmetry axis of the nucleus. Transitions between states are governed by K selection rules since in prolate deformed nuclei K is an approximately conserved quantum number. For an allowed transition $\Delta K \leqslant \lambda$, where ΔK is the change in K between initial and final states and λ is the multipolarity of the transition. The degree of K forbiddeness ν is defined as $\nu = \Delta K - \lambda$. Empirically, in the mass 180 region each degree of ν results in an increase of the partial gamma lifetime of the state with respect to the Weisskopf estimate by a factor of $f_\nu \sim 100$ [16,17], where $f_\nu = [t^\gamma_{1/2}/t^W_{1/2}]^{1/\nu} = F_W^{1/\nu}$ with W representing the Weisskopf estimate. In the mass 250 region K-isomers have been observed in ^{250,256}Fm [7,18,19] and ^{252,253,254}No [5–7,20,21].

Although the rather meager γ-ray statistics do not allow a detailed study of the $t_{1/2} = 1.4$ ms isomer some remarks can be made. The observation of a γ-ray transition of 588-keV in coincidence with a 100-keV conversion electron means that the isomeric state must have an excitation energy of at least 720-keV assuming LM-conversion, or, $E_x > 850$-keV assuming K-conversion. In this heavy, highly fissile, deformed nucleus the only plausible explanation for the observation of a metastable state at such an excitation energy is K-isomerism. In both ^{250}Fm and ^{252}No a low energy ($\sim$25-keV) $M1$ transition, which decays into a low-lying rotational band, competes with a high energy ($\sim$700-keV) $E1$ transition to the ground state rotational band. The reduced hindrance factors f_ν are of the order of 200 in ^{250}Fm and 100 in ^{252}No. However, in ^{254}No a particularly high value of $f_\nu \sim 800$ was observed for the 53-keV $E1$ transition out of the $K^\pi = 8^-$ isomer.

In order to estimate the degree of K-forbiddeness of the isomeric decay in ^{255}Lr, reduced hindrance factors f_ν as function of transition energy for both $E1$ and $M1$ decays with different assumptions of $\Delta K = \nu + \lambda$ are shown in Fig. 4. Making the assumption that the decay observed in ^{255}Lr is similar to that of ^{250}Fm and ^{252}No then one can estimate that for a low energy $M1$ branch $\Delta K \gtrsim 5$ and for the higher energy $E1$ transition $\Delta K \gtrsim 6$. Another scenario could be a decay similar to that observed in ^{254}No. In this case an estimate of $\Delta K \gtrsim 4$ can be made.

To determine which configurations can lead to such K-forbiddeness at an excitation energy close to 1 MeV, it is useful to recall the ground state configuration in ^{255}Lr as well as the low lying proton and neutron states available near the Fermi surface. These are shown in Fig. 5. Considering only proton states it is possible to construct the excitations labeled '1 q-p' and '3 q-p' with K values of 9/2 and 17/2, respectively. A transition between these two configurations would have $\Delta K = 4$, and, assuming a retardation in half-life of a factor of 100 per degree of K-forbiddeness, one would expect an M1 transition to be 1×10^6 slower than the Weisskopf estimate. As indication, the Weisskopf estimate for the half-life of a state decaying by a 588 keV M1 transition is $t_W^{1/2}(588; M1) =$

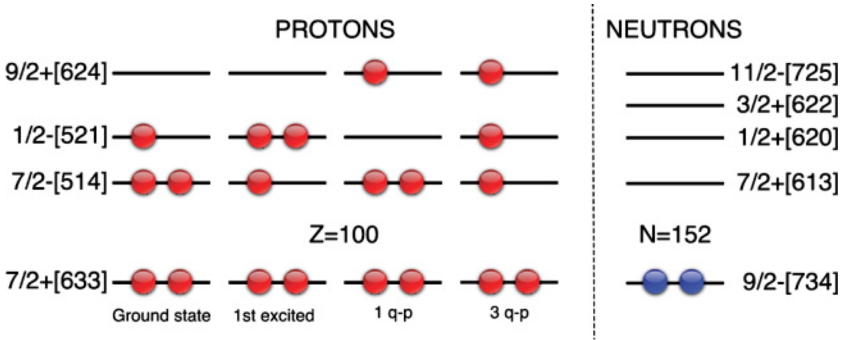

FIG. 5. (Color online) Schematic representation of the available proton (left) and neutron (right) configurations based on the single-particle levels calculated in Ref. [22].

$t_W^{\gamma,1/2}/(1+\alpha_{TOT}) \sim 80 \times 10^{-6}$ ns. The expected half-life of the '3 q-p' $17/2^+$ band head would therefore be of the order of 80 ns. To obtain a half-life in the ms range would require an anomalous f_ν of $\sim$2500 or an improbably low energy difference. Therefore, in ^{255}Lr long-lived, low-lying, high-K isomers can only be formed by coupling the valence proton to a two quasiparticle neutron excitation. Calculations performed by Tandel *et al.* [5] for the isotone ^{254}No indicate that possible two-qp neutron configurations could involve the coupling of the $9/2^-[734]$ to either of the following: $7/2^+[613]$, $3/2^+[622]$ or $1/2^+[620]$. For the odd proton the available orbitals are the $1/2^-[521]$ (ground state), $7/2^-[514]$, $7/2^+[633]$, $5/2^+[512]$ and $9/2^+[624]$. These can combine to make numerous high-K three-qp states.

A new isomeric state has been observed in ^{255}Lr with a half-life $t_{1/2} = 1.4(1)$ ms. A lower limit of 720-keV is estimated for the excitation energy of this state from coincidences between γ-rays and conversion electrons. Based on its K-forbiddeness, the configuration of the state is most probably formed by coupling the valence proton to a two quasiparticle neutron excitation. To obtain spectroscopic information concerning the decay properties of this state would require the tagging of the isomeric decay in the implantation detector, as proposed in Ref. [8]. The electronics of GABRIELA have recently been upgraded to enable this.

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