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# New results on the decay spectroscopy of $^{254}$No with GABRIELA@SHELS

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**Abstract.** The structure of the $^{254}_{102}$No$_{152}$ nucleus has been studied for more than 20 years: the last publications on its decay spectroscopy are from LBNL [1], GSI [2], JYFL [3] and ANL [4]. Four decay schemes featuring two isomers have been published and are interpreted differently in terms of excitation energy and decay scheme of the $2^{nd}$ isomer and configuration assignments of both K-isomers. These discrepancies have triggered new experiments including this one, performed with the GABRIELA [5, 6] array, at the focal plane of the SHELS [7] separator at the FLNR, Dubna. The first part of this proceeding will present the experimental setup and the analysis techniques used to reveal the electromagnetic decay of the known isomers in $^{254}$No. The second part will focus on the new results obtained with more than 1 million $^{254}$No nuclei implanted in the focal plane detector. In particular, the internal conversion electron spectrum observed in the decay of the $8^-$ K-isomer has revealed the presence of a strong transition, most likely E0, suggesting low-lying shape coexistence in this nucleus as predicted in [8, 9]. The $\gamma$-ray spectrum obtained from the decay of the short-lived 170 $\mu$s isomer has revealed new $\gamma$-ray lines putting in doubt the previous interpretations about this isomer decay.

## 1. Scientific context

Nuclear shell effects play a crucial role in the existence of extreme mass nuclei since they can counterbalance the strong Coulomb repulsion between the numerous protons [10]. Theories aim to predict the properties of these elements, including the identification of spherical magic shell closures. Experimentally, more detailed spectroscopic information can be obtained in lighter deformed nuclei, which are produced in greater quantities. In particular, the $^{254}_{102}$No$_{152}$ nucleus offers a unique laboratory for studying the underlying single-particle structures since the reaction $^{48}$Ca($^{208}$Pb, 2n)$^{254}$No has the largest cross section in the region.

Four spectroscopic experiments were conducted on the $^{254}$No nucleus within a span of four years, yielding disparate interpretations of the data [1, 2, 3, 4]. Each experiment observed the presence of two high-K isomers : a long-lived isomer with a half-life of 263.7(7) ms, characterized by a spin-parity of $K^\pi = 8^-$, and a short-lived K-isomer lasting for 170(2) $\mu$s, with possible

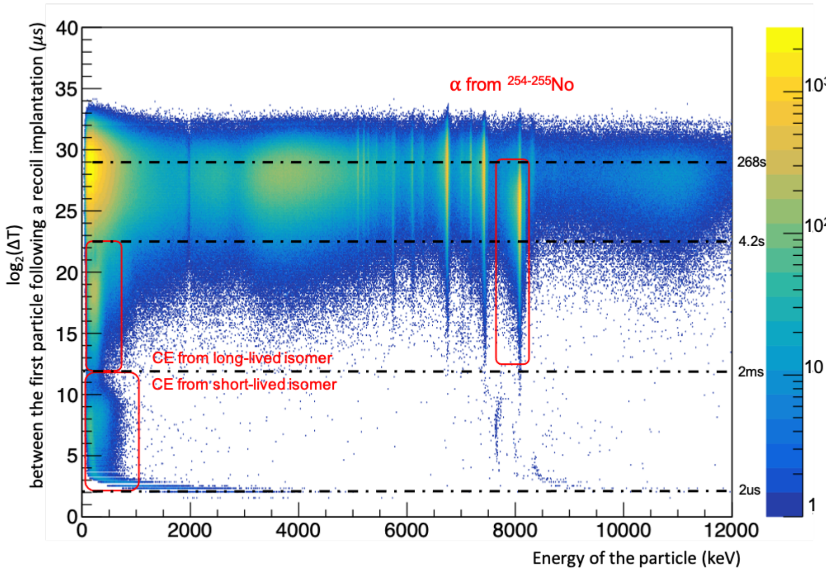


**Figure 1.** Energy-lifetime correlation spectrum for $^{254}$No analysis. The conditions applied for the data analysis are shown in this figure and detailed in the text.

spin-parities of $K^{\pi} = 16^{-}$ or $16^{+}$ or $14^{+}$ depending on the specific study. The authors disagree regarding the interpretation of the excitation energy and decay scheme for the short-lived K-isomer, as well as the configuration assignment for both K-isomers. Hence, the primary objective of this new investigation on $^{254}$No is to offer a fresh perspective and propose an interpretation of its nuclear structure.

## 2. Experimental Set Up

The investigation of $^{254}$No was performed using the Super-Heavy ELements Separator (SHELS) [7]. After passing through the time-of-flight detectors, the recoils of interest are implanted in the DSSD of the GABRIELA focal plane setup [5, 6] composed of eight tunnel Si detectors for the detection of Internal Conversion Electrons (ICE) surrounded by eight HPGe $\gamma$-ray crystals for $\gamma$-ray detection. Additionally, the DSSD can Capture low-Energy signals (CE) caused by the summation of ICEs and atomic relaxation emissions. These consist mainly of the ejection of other electrons and/or the emission of characteristic X rays [11]. Finally, space-time genetic correlations are applied to identify the implanted nucleus by its $\alpha$ decay chain. A triggerless analog electronics was used. All events were timestamped with a 1 $\mu$s precision and the dead time was $\sim$4 $\mu$s.

## 3. $^{48}$Ca($^{208}$Pb, 2n)$^{254}$No reaction

The experiment was conducted over 3 weeks in October 2019 with a beam intensity from 300 to 400 pnA (from 1.8 to 2.5$\times 10^{12}$ pps) and a mid-target energy ranging from 218 to 226 MeV. To establish correlated events, a specific sequence was selected : first, the implantation of a recoil followed by a CE and finally the characteristic $\alpha$ decay of $^{254}$No. These correlations are called R-CE-$\alpha$ correlations. Then, we analyzed $\gamma$ rays and ICEs in coincidence with the CE coming from either the long or short-lived isomer. More precisely, the energy of the $\alpha$ particle was confined within the range of 7780 to 8150 keV and a recoil-$\alpha$ time-window of 268 s corresponding to 97% decay events. The CE events require a time difference greater than 2 ms (2 $\mu$s) and less than 4.2 s (2 ms) for the long (short)-lived isomer. In total, $\sim 10^{6}$ full-energy $\alpha$ particles from $^{254-255}$No were identified.

Fig.1 shows the recoil-decay correlations, displaying the logarithmic time difference (base 2) between the implantation of a recoil and its subsequent decay as a function of the decay energy. Various types of events can be observed : the full-$\alpha$ energy decay events of $^{254-255}$No and CE signals from the decay of the long-lived and the short-lived isomers. A pile-up effect is noticeable below 8 $\mu$s resulting in an overestimated energy. Around 20% of the short-lived isomeric decays correspond to isomeric decays of the other synthesized $^{255}$No isotope [12].

Regarding the short-lived isomer decay, all the $\gamma$-ray transitions from previous studies such as 111, 133, 144, 157, 168, 179, 254, 279, 300, 312, 325, 248, 482 and 605 keV peaks could be identified, as well as new and weaker peaks at 319 and 808 keV. To take into account these transitions into the $^{254}$No level scheme, it was necessary to account for the internal-conversion-electrons intensities, the $\gamma$-$\gamma$ coincidences and the measured electromagnetic transitions. Despite different attempts to add new transitions and rotational structures, we were unable to find a satisfactory decay scheme that fulfills all the observables. Nevertheless, some information has been confirmed. The total excited energy of the short-lived isomer decay obtained by a calorimetric measurement is 2927 keV $\pm$ 30 keV (reproduced by Geant 4 simulations of the published decay scheme [1]). Then, the conversion coefficient of the strongest 605 keV transition could be measured and is found to be more consistent with an E2 transition. In this scenario, the $10^+$ band-head in [1] would rather be a $11^-$ band-head state.

Let us concentrate on the $8^-$ isomer state, for which we have substantially more statistics. The previous transitions such as 53, 58, 70, 82, 102, 135, 152, 159, 214, 778, 787, 842, 856, 887, 890, 939, 943 keV were well identified. New transitions were observed : 173, 205, 216, 226, 725, 946, 990 and 1016 keV. All these transitions were incorporated into the new decay scheme, as shown in Fig.2. We retrieved also the two other transitions in parallel with the 53 keV transition leaving the $8^-$ state. To accommodate for the remaining transitions at 173, 216 and 226 keV, we used $\gamma$-$\gamma$ and $\gamma$-ICE coincidences. They revealed coincidences between the 943 and 216 keV as well as the 842 and 216 keV transitions. Also, the measured conversion coefficient revealed that the 216 keV is a M1 transition. Thus, we introduced another structure built on a $4^+$ state, which is interpreted as the unfavoured-coupling partner of the $3^+$ 2qp-state based on the $[521]\frac{1}{2}^- \downarrow \pi$ and $[514]\frac{7}{2}^- \uparrow \pi$ proton orbitals. Consequently, this provides the first measurement of the Gallagher-Moszkowski [13] energy splitting at 216 keV in such very heavy nuclei. These results were cross-checked by GEANT 4 simulations.

## 4. Shape-coexistence or super-deformed state ?

An unexpected result has emerged, indicating the presence of potential shape-coexistence. Fig.3 displays the high-energy part of the spectrum of ICEs detected in the tunnel detectors during the decay of the long-lived isomer, along with the corresponding high-energy $\gamma$-ray spectrum. Notably, the conversion of the weak 887 kev transition stands out as the most dominant. The extracted K-conversion coefficient ($\sim$0.6) suggests an M4 transition, although this possibility is ruled out due to the resulting half-life being on the order of a few seconds. Consequently, the only alternative remaining is an E0 contribution at 737 keV in the ICE spectrum. There are 2 scenarii:

- The 887 keV $4^+ \rightarrow 4^+$ transition is a mixed E0-M1-E2 transition,
- There is another $\sim$887 keV transition connecting a second $0^+$ state to the ground state.

The presence of such an E0 contribution may be related to shape coexistence, and in particular it could be due to the coexistence of a "normally" deformed or super-deformed states at low energy, which have been predicted by Egido and Robledo [8] as well as Delaroche [9]. It may also be due to the coexistence of prolate and triaxial shapes, as was recently observed in $^{282}$Cn [14].

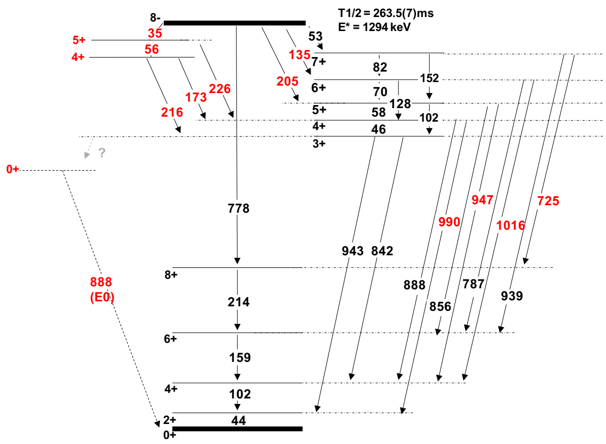


**Figure 2.** Decay scheme of the long-lived isomer of $^{254}$No. Transition energies are given in keV. All the new transitions found in this work (compared to [1]) are displayed in red.

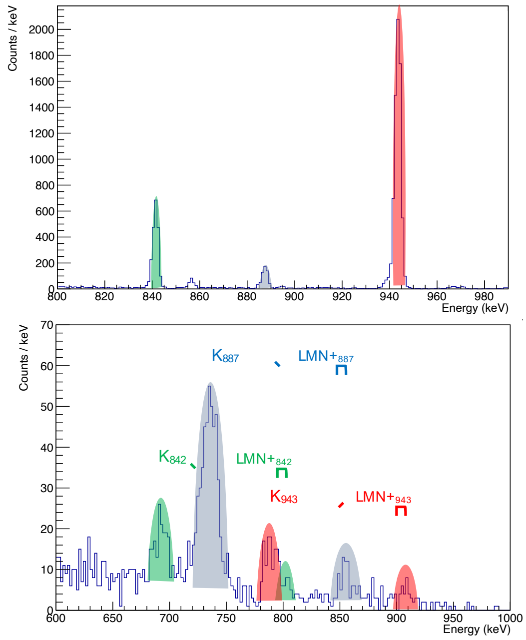


**Figure 3.** Bottom : ICE detected in tunnel detectors in coincidence with a CE implanted in DSSD detector in the following correlation : Recoil - Long-lived isomer CE signal - $\alpha$ from $^{254}$No. Top : $\gamma$-ray spectrum in coincidence with the long-lived isomer at high energy.

## 5. Conclusion

The study of the long-lived isomer decay has revealed new states below the $8^-$ isomer state. These have been interpreted as members of the rotational band built on top of the Gallagher-Moszkowski partner of the 2qp $3^+$ state. The decay of the $8^-$ isomeric state has also revealed a possible E0 decay, which is generally associated with a shape coexistence. These decays could be related to the presence of a low-energy super-deformed state, as predicted by a couple of theoretical models. There is still much to uncover regarding how this state can be reached and whether the E0 decay might simply be a result of accidental mixing. The data analysis for the short-lived isomer needs higher data statistics and a better efficiency in the $\gamma$-$\gamma$ coincidences matrix to establish its decay scheme and reveal its nature.

## References

[1] R.M. Clark et al. 2010 *Phys. Lett.* B **690**, 19
[2] F.P. Hessberger et al. 2010 *Eur. Phys.* J A **43**, 55
[3] R.-D. Herzberg et al. 2006 *Nature* **442**, 896
[4] S.K. Tandel et al. 2006 *Phys. Rev. Lett.* **97**, 082502
[5] K. Hauschild et al. 2006 *Nucl. Instr. Methods* A **560**, 388-394
[6] R. Chakma et al. 2020 *Eur. Phys.* J A **56**, 245
[7] A.G. Popeko et al. 2016 *NIM* B **376**, 140-146
[8] J.L. Egido and L.M. Robledo 2000 *Phys. Rev. Lett.* V **85**, 6
[9] J.-P. Delaroche et al. 2006 *Nucl. Phys.* A **771**, 103-168
[10] S. Hofmann 2019 *Radiochimica Acta* **107** (9-11), 879-915
[11] G.D. Jones 2002, *Nucl. Instr. Meth. Phys. Res.* A **488**, 471-472
[12] K. Kessaci 2022 *Doctoral dissertation, Université de strasbourg*
[13] C. J. Gallagher and S. A. Moszkowski 1958, *Phys. Rev.* **111**, 1282
[14] A. Samark-Roth et al. 2021 *Phys. Rev. Lett.* **126**, 032503