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Evidence for non-yrast states in ^{254}No

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Abstract. Evidence for the decay of non-yrast states in ^{254}No has been observed for the first time in an experiment performed at the University of Jyväskylä. The experiment employed the JUROGAM array of germanium detectors coupled to the gas-filled recoil separator RITU and the focal-plane spectrometer GREAT. The ground-state rotational band has been tentatively extended up to a spin of $24\hbar$ and has a smoothly behaving dynamical moment of inertia. It is speculated that the observation of high-energy γ-rays is due to the decay of a $K = 3$ band-head state.

PACS. 23.20.Lv γ transitions and level energies – 27.90.+b $220 \leq A$ – 29.30.-h Spectrometers and spectroscopic techniques

1 Introduction

One of the long-standing challenges of nuclear physics has been the exploration of nuclei at the limits of existence. The relative stability of the heaviest nuclei against fission ($Z \geq 104$) is generated entirely by microscopic shell corrections to the liquid-drop energy. A great deal of effort, both experimental and theoretical, has been invested in the heaviest elements and the predicted island of stability. This island is expected to be located in the vicinity of the next closed proton and neutron shells above ^{208}Pb. The exact location of the island is still unknown, and has been the subject of much theoretical debate. According to most non-relativistic mean-field models, the new closed shells are expected to be $Z = 124, 126$ and $N = 184$ and predicted to be situated around $Z = 120$, $N = 172$ by relativistic mean-field models. Microscopic-macroscopic approaches seem to favour $Z = 114$, $N = 184$. For overviews of the theoretical progress in this field, see, *e.g.*, refs. [1–4] and references therein. Although unambiguous identification of nuclei up to proton number $Z = 112$ (see, *e.g.,* [5]) has been made, extremely low production cross-sections mean that only ground states and occasionally very low-lying excited states of nuclei of the heaviest elements have been studied. The transfermium nuclei, situated just below the superheavy region, are the heaviest systems which are accessible using present-day in-beam spectroscopic techniques. The transfermium nuclei in the region of ^{254}No ($N = 152$) are deformed, and the Nilsson orbitals active at the Fermi surface are derived from single-particle levels situated close to the predicted spherical superheavy systems. Experimental studies of the rotational properties of even-even transfermium nuclei provide information concerning their deformation and the maximum spin and

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excitation energy that they can sustain. The variation of the moments of inertia with transition energy along a rotational band can be studied systematically. The comparison with theoretical predictions tests the predictive power of current nuclear models and the reliability of extrapolation to the heaviest elements. Small production cross-sections and large fission probabilities make spectroscopic studies of heavy systems very difficult. However, cold fusion-evaporation reactions of ^{48}Ca beams with various targets around ^{208}Pb have anomalously high cross-sections. In particular, the use of a doubly magic ^{208}Pb target yields a cross-section of around 2 μb for the production of ^{254}No through the 2n channel [6]. Although still too low for standard gamma-ray spectroscopic techniques, it is well within reach of the Recoil-Decay Tagging (RDT) and recoil-gating methods [7,8]. A number of studies of transfermium nuclei centred around ^{254}No have already been carried out in different laboratories (for overviews, see [9–11]). The following section briefly reviews the current experimental knowledge of ^{254}No.

In this paper a new experimental study of ^{254}No, carried out at the Accelerator Laboratory of the University of Jyväskylä (JYFL) under significantly improved experimental conditions, is discussed.

2 Previous studies of ^{254}No

The ground-state rotational band of ^{254}No was first observed in an experiment carried out at the Argonne National Laboratory (ANL) employing the GAMMASPHERE array of germanium detectors coupled to the Fragment Mass Analyser (FMA) [12]. In this initial experiment the ground-state band was observed up to a spin of $14\hbar$. A follow-up experiment carried out using the SARI germanium detector array coupled to the gas-filled recoil separator RITU at the Department of Physics of the University of Jyväskylä (JYFL) confirmed this observation and extended the band to a spin of $16\hbar$ [13]. These experiments allowed a value for the quadrupole deformation parameter, β_2, of 0.28(2) to be derived from the extrapolated energy of the lowest 2^+ state, in good agreement with theoretical predictions. The ground-state band was again extended to a spin of $20\hbar$ in a further experiment carried out at ANL to study the entry distribution, fission barrier and formation mechanism of ^{254}No [14].

An experiment carried out in the 1970s [15] revealed evidence for an isomeric decay with a half-life of 280±40 ms. The existence of this isomer in ^{254}No has recently been confirmed in experiments using recoil separators at JYFL and subsequently at ANL [16,17]. It is believed that this isomer is due to a high-K ($K = 7$ or 8) two-quasiparticle state. Further indirect evidence for the presence of high-K bands was obtained in in-beam conversion-electron studies carried out at JYFL. The experiments employed the SACRED conversion-electron spectrometer [18,19] coupled to RITU and inferred that the observed high-multiplicity electron distribution was due to strongly converted low-energy intraband transitions [20]. This series of experiments also allowed the energy of the 4^+ to 2^+ transition to be determined for the first time and confirmed the $E2$ multipolarity of the lowest observed transitions [21].

3 Experimental details

The experiment employed the ^{208}Pb(^{48}Ca, 2n)^{254}No reaction, the ^{48}Ca beam being produced in the 14.6 GHz ECR ion-source and accelerated with the JYFL $K = 130$ MeV cyclotron. Two different cyclotron beam energies, 219 MeV and 221 MeV, were used with 115 and 40 hours of beam on target, respectively. The isotopically enriched ^{208}Pb targets (> 98%) had a thickness of 500 μg/cm^2. The stationary targets were situated in the He filling gas of RITU and could withstand the beam intensities of up to 30 pnA used in the experiment. The maximum beam intensity was limited by the maximum counting rate of the individual Ge detectors ($\sim$ 10 kHz). The average beam intensity during the experiment was approximately 19 pnA. Prompt γ-rays were detected at the target position with the JUROGAM array comprising 31 EUROGAM Phase-1 and 12 GASP-type Compton-suppressed germanium detectors with a total photopeak efficiency of 4.2% at 1332 keV. Fusion-evaporation residues were separated in flight with the gas-filled recoil separator RITU [22]. The separator was operated at a He pressure of 0.6 mbar and a differential pumping system was used to separate the filling gas from the beam line vacuum. The RITU transmission efficiency is estimated to be approximately 40% for reactions of this type. After separation from primary beam and fission products, the fusion-evaporation residues were implanted into the Double-Sided Silicon-Strip Detectors (DSSSDs) of the GREAT spectrometer [23]. The two adjacent 300 μm thick DSSSDs each consist of 60×40 strips with a 1 mm strip pitch. In addition, the GREAT detector system has a position-sensitive Multi-Wire Proportional Counter (MWPC) placed upstream of the DSSSDs, allowing discrimination between recoils and decay products on the basis of coincidence or anticoincidence with the DSSSDs. The MWPC also affords Time-of-Flight (ToF) and energy loss (ΔE) information which can be used to provide further discrimination of fusion-evaporation products from scattered beam and target-like events. The GREAT spectrometer was completed with 28 Si PIN-diodes and a segmented germanium Clover detector, the data from which have not been used in the present analysis. Signals from all detectors were handled by the new Total Data Readout (TDR) data acquisition system [24]. TDR is a triggerless acquisition system, the data from each channel being treated individually and time-stamped with a resolution of 10 ns. All data are then merged into a time-ordered stream and filtered in software before being stored. The system reduces the dead time to a minimum and allows for greater flexibility in performing temporal and spatial correlations between the various detector groups. Event building is performed in software and for both online and offline analysis the software package Grain [25] was used.

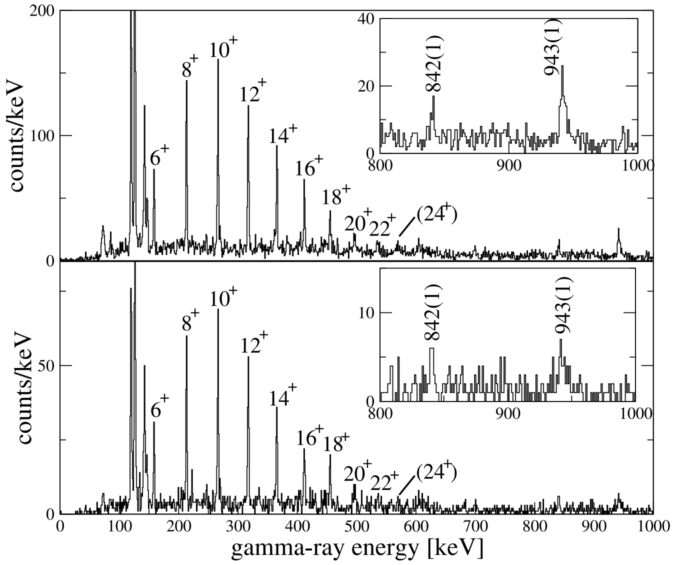

Fig. 1. Upper panel: recoil-gated γ-ray singles spectrum of ^{254}No. The rotational ground-state band transitions are labelled with the spin assignment of the depopulated level. The inset displays an expansion of the spectrum showing the two prominent high-energy γ-ray peaks. Lower panel: recoil-decay tagged γ-ray singles spectrum of ^{254}No. The search time was 180 seconds. Again, the inset shows the high-energy peaks.

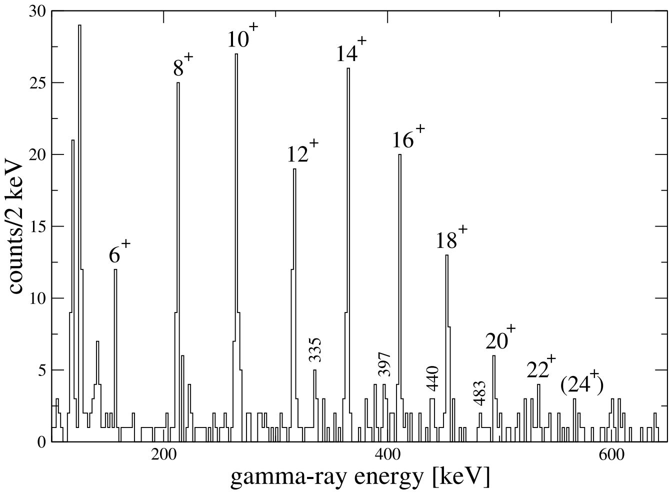

Fig. 2. A sum of γ-ray spectra projected from the recoil-gated γ-γ coincidence matrix. The spectrum is a sum of spectra gated on ground-state band transitions from the 6^+ state up to the 18^+ state.

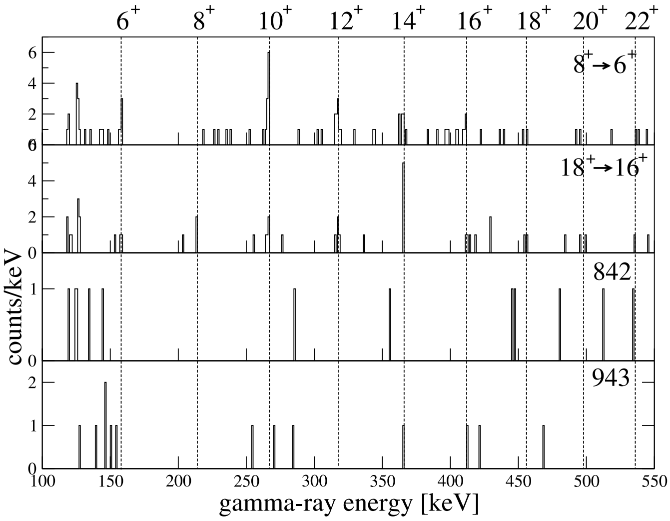

Fig. 3. Example spectra projected from the recoil-gated γ-γ coincidence matrix. The labels in the upper right-hand corner indicate the transition or transition energy used as a gate. The upper two panels show spectra gated on ground-state band transitions; the lower two panels show spectra gated on the high-energy transitions. The dotted lines indicate the positions of the ground-state band transitions.

4 Results and discussion

The competing reaction channels producing ^{253}No and ^{255}No through 3n and 1n evaporation, respectively, amount to only 1% of the total fusion-evaporation cross-section [26,27]. Therefore, for the majority of the analysis, the technique of recoil-gating was employed to extract the γ-rays of interest. As discussed above, fusion-evaporation events at the focal plane are discriminated from scattered beam and other implant events by setting conditions on ToF between the MWPC and DSSSDs and the ΔE signal in the MWPC. Approximately 55000 events were selected and the associated prompt γ-rays are displayed in the recoil-gated γ-ray singles spectrum shown in the upper panel of fig. 1, which is discussed below. The data taken at the higher beam energy (221 MeV) did not show significant enhancement in population of the higher-spin states and contained relatively low statistics, thus the data displayed here are for both beam energies combined. Also shown for completeness (in the lower panel of fig. 1) is the γ-ray singles spectrum obtained through use of the RDT technique. The spectrum was obtained by selecting only those recoils which were followed by an 8.09 MeV ^{254}No α decay in the same pixel of the DSSSD within a search time of 180 seconds. A total of approximately 12000 correlated recoil-α pairs were found.

4.1 Ground-state band

The regular sequence of peaks seen in fig. 1 are assumed to form an yrast rotational band of stretched $E2$ transitions built upon the ground state. The earlier assignment of these transitions to the ground-state band of ^{254}No (up to a spin $20\hbar$) [12–14] could be confirmed. The energy of the 20^+-to-18^+ transition was determined to be 498(1) keV, in agreement with the tentative value given in ref. [14]. A clear peak is observed at an energy of 536(1) keV, which is assumed to be the 22^+-to-20^+ transition. This assignment is supported by the recoil-gated γ-γ coincidence data. Example spectra from the recoil-gated γ-γ coincidence data for the ground-state band transitions are shown in fig. 2 and in the upper two panels of fig. 3.

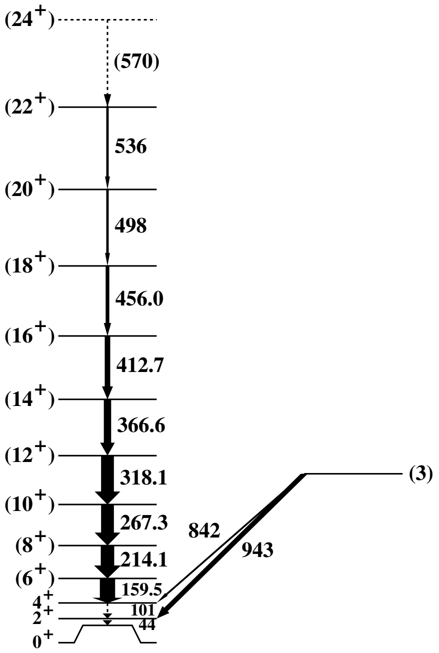

Fig. 4. Proposed partial level scheme of ^{254}No (see sects. 4.1 and 4.2).

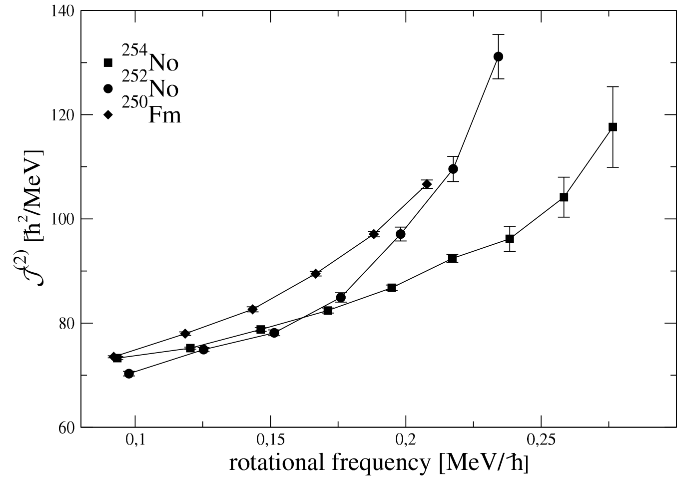

Fig. 5. Dynamical moment of inertia $\mathcal{J}^{(2)}$ against rotational frequency of the ground-state band of ^{254}No, compared with that of the $N = 150$ isotones ^{252}No [29] and ^{250}Fm [30].

Figure 2 shows a sum of spectra projected from the recoil-gated γ-γ coincidence matrix. The spectrum is a sum of gated spectra with gates on ground-state band transitions from the 6^+ state up to the 18^+ state. The spectrum clearly shows all transitions up the 22^+ state, and the peak at an energy of 570(1) keV is tentatively assigned as the 24^+-to-22^+ transition. If the moment of inertia continues to behave smoothly (see fig. 5), the next transition is expected to have an energy of 600 keV. A cluster of counts is observed at this energy in fig. 2, though the inspection of the recoil-gated singles spectrum (fig. 1) suggests that there is a contribution from some other structure at this energy. Also of note in this spectrum is the sequence of peaks at 335, 397, 440 and 483 keV, which could not be placed in the level scheme due to the lack of statistics.

As in the earlier γ-ray spectroscopic studies, the lowest two transitions of the ground-state band were not observed due to strong internal conversion. However, their energies have been extrapolated from a Harris fit to the known members of the band [28,12]. This has proven to be a valid method as the energy of the 4^+-to-2^+ transition was recently confirmed to be 101.1(6) keV in an in-beam conversion-electron spectroscopy measurement, as discussed in sect. 2 [21]. The ground-state rotational band is shown as part of the proposed level scheme in fig. 4.

Figure 5 shows a plot of the dynamical moment of inertia, $\mathcal{J}^{(2)}$, against rotational frequency for the extended ground-state band of ^{254}No, and compared with the $N = 150$ isotones ^{252}No and ^{250}Fm. The data for ^{252}No and ^{250}Fm are taken from refs. [29,30], respectively. At low rotational frequencies the moments of inertia for all three nuclei are similar, whilst at higher frequencies the $\mathcal{J}^{(2)}$ values for the $N = 150$ isotones increase more rapidly than for ^{254}No. This contrasting behaviour in the alignment has been discussed previously and is well described theoretically using various approaches (see refs. [31,3]). In the work of Afanasjev *et al.*, a sharp upbend in the moment of inertia is predicted at a rotational frequency of approximately 0.3 MeV, due to the simultaneous alignment of proton $1i_{13/2}$ and neutron $1j_{15/2}$ pairs. As yet, no evidence for the this upbend is observed, though it should be noted that the maximum rotational frequencies observed are still somewhat below the region where the upbend is expected to occur.

4.2 Non-yrast states

An interesting feature of the recoil-gated γ-ray singles spectrum is the observation at high energies of two intense transitions at 842(1) keV and 943(1) keV, as shown in fig. 1. An expansion of the high-energy part of the spectrum is shown in the inset. The intensities of these transitions are 31(8)% and 86(14)% of the 8^+-to-6^+ ground-state band transition, respectively (where all intensities are corrected only for γ-ray efficiency, not for internal conversion). The energy difference of these two γ-rays (101(1) keV) corresponds exactly to the energy of the 4^+-to-2^+ transition (101.1(6) keV) measured in the recent conversion-electron spectroscopic study [21]. The γ-rays are therefore assumed to originate from a high-lying low-spin state which decays into the 4^+ and 2^+ yrast states as shown in the partial level scheme of fig. 4 and schematically in fig. 6. This assumption is supported by the absence of clear γ-γ coincidences with ground-state band transitions above the 4^+ state. This is illustrated in fig. 3 where coincidence spectra gated on both the high-energy lines and sample ground-state band transitions are shown. Although the 18^+-to-16^+ ground-state band transition and the 943 keV transition have comparable intensities in the recoil-gated γ-ray

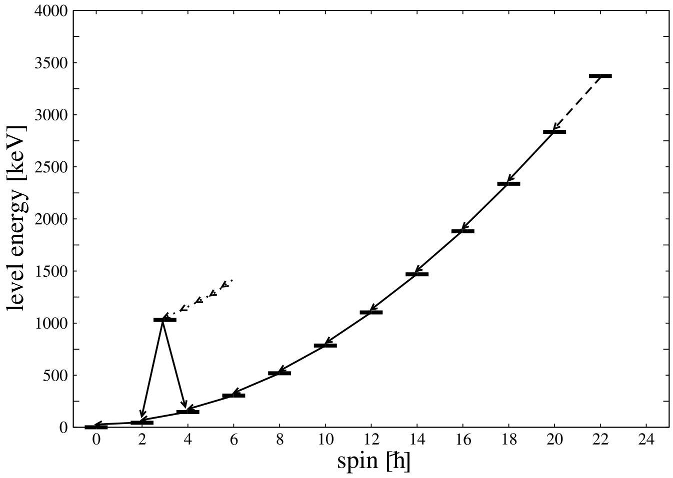

Fig. 6. Yrast plot of ground-state band with suggested positioning of high-energy lines. The assumed feeding pattern of the high-lying low-spin state is indicated with dashed lines.

singles spectrum of fig. 1, they show a large difference in the number of coincidences with the ground-state band transitions above a spin of 4^+. The positions of the ground-state band transition energies are marked with vertical dotted lines in fig. 3. The second panel from the top of fig. 3 shows the coincidence spectrum obtained by gating on the 18^+-to-16^+ transition, where coincidences with the ground-state transitions can be clearly seen. The coincidence spectra gated on the 842 keV and 943 keV transitions (shown in the lower two panels of fig. 3) do not show such a clear correlation. Having placed the two high-energy γ-rays feeding the 4^+ and 2^+ states, it then remains to speculate as to the spin and parity of the decaying state. Due to the low level of statistics obtained, it has not been possible to perform an angular distribution analysis to aid in the determination of the γ-ray multipolaries. However, as the γ-rays are observed prompt in the germanium detectors surrounding the target, the multipolarity of the transitions can immediately be constrained to $E1$, $M1$ or $E2$. The likely spins and parities of the decaying state are then $I^\pi = 2^\pm$ or $3^\pm$. The $I^\pi = 4^+$ possibility can be ruled out, as for $K = 4$ the transition is too slow to be observed in the target array, and for lower K values it is expected that further transitions from the band-head state should be observed.

Very little systematic data exist in this region of the Segré chart, though in lighter isotopes of Fm, Cf and Cm, a number of octupole $K = 2^-$ bands (*e.g.* ^{250}Cf [32], ^{246}Cm [33,34]) and $K = 2^+$ or $K = 3^+$ bands (*e.g.* ^{256}Fm [35], ^{252}Cf [36]) have been observed. The $I^\pi = 2^\pm$ possibilities can be quickly ruled out on the basis of the observed decay pattern. For a $K = 2^+$ band-head state, the Alaga rules suggest that for $E2$ transitions decaying to the 4^+, 2^+ and 0^+ states, the intensities should approximately have the relationship 3 : 100 : 85, respectively [37]. This is clearly not what is observed, as there is no strong transition to the ground state. The case of $K = 2^-$ can be ruled out by comparing the decay patterns observed from the known $K = 2^-$ octupole bands in ^{250}Cf and ^{246}Cm. In both cases, the 2^- state decays by a dominating $E1$ transition to the 2^+ state (see, for example, refs. [32,34]). Again, this is clearly not what is observed in the present case. The most plausible spin assignment is then $I = 3$. Assignment of the parity of this state is difficult from the present data. There is no clear evidence for decays of the band members above this state, which may have allowed for a determination of the multipolarity on the basis of intensity balance arguments. The feeding of this high-lying low-spin state is expected to proceed via highly converted low-energy $M1$ transitions. Recently, a broad distribution comprising high-multiplicity electron cascades was observed in an in-beam conversion-electron spectroscopic study of ^{254}No [20]. The cascades are expected to arise from $M1$ transitions in bands built on high-K states. It was not possible to observe these low-energy, highly converted transitions in the present experiment. It could be speculated that the decay pattern of interband transitions from the $K = 3$ band members to the ground-state band would give an indication as to the parity of the $K = 3$ band. As can be seen from fig. 1, no evidence for further interband transitions can be gleaned from the spectra. It could be argued that this non-observation of interband transitions suggests that such transitions are K-hindered, and are not observed as the decay is dominated by unhindered in-band low-energy $M1$ transitions. In the octupole case the interband transitions may be expected to carry more intensity. However, the inspection of the level schemes and decay intensities observed in the $K = 2$ octupole bands in ^{250}Cf and ^{246}Cm shows that the intensities of interband transitions from the band members are at most only around 8% [32,34] of the decay intensity of the band-head state. Such transitions would have an intensity of less than 10 counts in the spectra obtained here and it is therefore again not possible to draw any conclusion. The limited data available in the region also suggest that the $K = 2$ octupole bands lie lowest in energy, which may be an argument against the $K^\pi = 3^-$ scenario. Calculations of Neergård and Vogel performed in the 1970s also predict that the $K = 2$ octupole states lie lowest, at least up to Fm, the highest-Z element considered [38]. It should be noted, however, that the systematic behaviour is such that the energies of the $K = 2$ and $K = 3$ bands converge when going to heavier systems.

This then leaves the $K^\pi = 3^+$ scenario. An excellent candidate for a two-quasiparticle $K^\pi = 3^+$ state can be formed by coupling the proton $7/2^-[514]$ and $1/2^-[521]$ orbitals which are close to the Fermi surface in ^{254}No. On the basis of Weisskopf estimates and the systematics of K-hindrance factors of Löbner *et al.*, the lifetime of such a $K^\pi = 3^+$ band-head state is expected to be less than 1 ns [39]. A lifetime at this level means that the state decays well within the focus of the detectors surrounding the target.

5 Summary

An in-beam spectroscopic study of ^{254}No employing the efficient spectrometer systems at JYFL allowed confirmation and extension of the ground-state band of ^{254}No to a spin of $24\hbar$. The dynamical moment of inertia, $\mathcal{J}^{(2)}$, of the ground-state band shows a smooth behaviour up to the highest spin observed. Two high-energy γ-ray transitions were observed and determined to represent the decay from a non-yrast $K = 3$ band-head state to the ground-state band. The present data did not allow the parity of the state to be determined directly. Whilst the octupole case cannot be ruled out, it is considered more likely that the state is a $K^\pi = 3^+$ two-quasiparticle state formed by the coupling of the proton $7/2^-[514]$ and $1/2^-[521]$ orbitals.

The occurrence of highly converted transitions renders it very difficult to study non-yrast transitions via in-beam gamma-ray spectroscopy. Simultaneous γ- and electron spectroscopy at the target position would be the best way to further investigate the region around ^{254}No. It is hoped that such studies will be possible within a few years at JYFL with the development of the new SAGE spectrometer. SAGE will be designed and built in a collaboration led by the University of Liverpool and Daresbury Laboratory in the UK.

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