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Structure of rotational bands in ^{253}No

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Abstract. In-beam gamma-ray and conversion electron spectroscopic studies have been performed on the ^{253}No nucleus. A strongly coupled rotational band has been identified and the improved statistics allows an assignment of the band's structure as built on the $9/2^-[734]_\nu$ ground state. The results agree with previously known transition energies but disagree with the tentative structural assignments made in earlier work.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 23.20.Lv Gamma transitions and level energies – 29.30.Dn Electron spectroscopy – 27.90.+b A>220

1 Introduction

The systematical study of single-particle energies in heavy and superheavy nuclei provides crucial tests for theories which are used to predict and describe the next doubly magic spherical shell gap. It is of crucial importance to push the available systematics to the heaviest systems that can still be studied with sufficient precision and a large experimental effort has been undertaken in a number of laboratories to do just that. The experimental methods range from alpha-decay studies to in-beam studies (See [1,2] and references therein). Here large gamma-ray spectrometers such as Gammasphere [3] coupled to efficient recoil separators come into their own. However, in these highly charged sytems the internal conversion coefficients for M1 and E2 radiation are greater than one for transition energies less than 400 and 200 keV, respectively. This makes spectroscopy of odd nuclei especially challenging as a large fraction of the decays can proceed via highly converted transitions and gamma ray spectroscopy alone will only be able to shed light on the full level schemes in rare cases where either statistics are sufficiently high or where the decays proceed mainly via E2 transitions, such as e.g. ^{251}Md [4] or ^{255}Lr [5]. However, even in these cases it is of prime importance to observe both E2 and M1 transitions simultaneously, as the observed branching ratios in a strongly coupled rotational band serve as a good indicator of the g-factors of the underlying single particle orbitals the bands are built upon.

A previous study of ^{253}No [3] had identified two rotational bands consisting of stretched E2 transitions using Gammasphere and the FMA at Argonne National Laboratory (ANL). In this study the observed spectra had low statistics but consisted of gamma-gamma coincidence events only. The spectra were modelled assuming two different neutron configurations on which the bands could be built, i.e. the $7/2^+[624]_\nu$ and the $9/2^-[734]_\nu$ single neutron configurations. There a large intensity observed around 355 keV was observed and interpreted as an unresolved multiplet. Based on the available data the bands were tentatively interpreted as bands built on the excited $7/2^{+}[624]_{\nu}$ configuration.

One further previous study using internal conversion electron spectroscopy [6] had not reported a level scheme but compared the observed intensities to the expected conversion electron yields assuming the two different g-factors associated with these two configurations and had favoured the $9/2^{-}[734]_{\nu}$ assignment.

The present experiment has been performed to clarify the situation. It consistes primarily of a new high-statistics in-beam gamma spectroscopy study performed using JUROGAM I and RITU at the University of Jyväskylä [7,8]. Furthermore, well-established transition energies allow a fresh analysis of the previously published electron data. From both datasets the assignment of a $9/2^{-}[734]_{\nu}$ structure to the observed bands is deduced.

2 Experimental Details

The new experiment was carried out at the Accelerator Laboratory of the University of Jyväskylä using the JUROGAM gamma ray spectrometer coupled to the RITU gas filled separator [9] and the GREAT focal plane detection system [10]. The ^{253}No nuclei were produced in the ^{207}Pb(^{48}Ca,2n)^{253}No reaction at a beam energy of 219 MeV. This reaction has a cross section of approximately 1 μb, one of the largest production cross sections for nuclei in this region. The targets were isotopically highly enriched metallic ^{207}Pb foils with a thickness of 600 μg/cm^2 which were irradiated with an average beam current of $< I > \simeq 20$ pnA of ^{48}Ca beam.

A total of 11400 Recoils followed by a characteristic ^{253}No alpha decay were detected during the correlation time of roughly three ^{253}No half lives $3 \times T_{1/2} = 5.1$ min. The half-life was determined from this data set to be $T_{1/2} = (1.56 \pm 0.02)$ min, consistent with earlier values given in the literature $T_{1/2} = (1.62 \pm 0.15)$ min [11].

The earlier conversion electron spectroscopy experiment described in [6] was also performed in Jyväskylä with the same reaction but used the SACRED conversion electron spectrometer [12,13] in conjunction with RITU. A total of 1840(40) Recoils followed by a characteristic ^{253}No alpha decay were detected. Conversion electrons recorded in coincidence with the recoiling ^{253}No nuclei were collected. To reduce the large background from δ-electrons produced in the target, a high voltage barrier is inserted between the target and the detector. In this experiment the barrier was operated at -40 kV. The efficiency of the SACRED array is shown in figure 1 both for 0 and -40 kV barrier voltage.

3 Experimental Results and Discussion

The gamma ray spectrum for ^{253}No is shown in figure 2. Unlike the spectrum obtained in [3], this spectrum contains all gamma folds including singles and thus the observed transitions stand out much better. The first thing

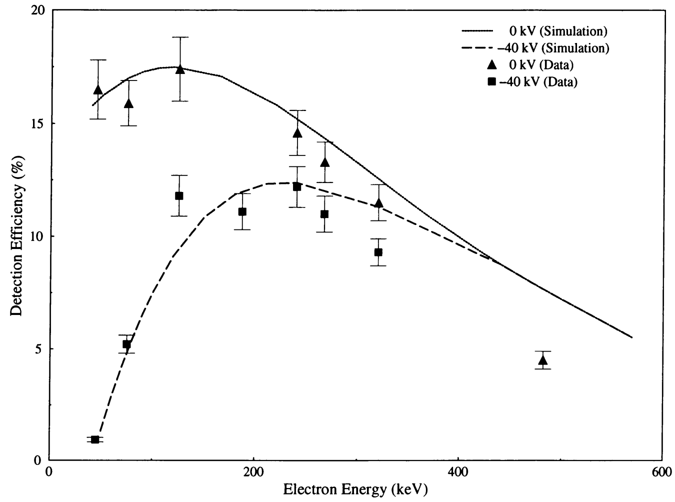

Fig. 1. Efficiency of the SACRED array. Experimental points are compared to simulated curves for two different barrier voltages of 0 and -40 kV.

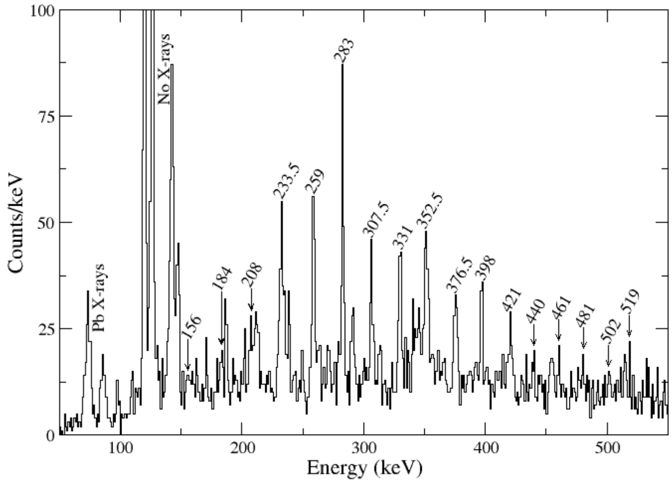

Fig. 2. Gamma ray spectrum of ^{253}No obtained with JUROGAM. The low lying M1 transitions linking the two signature partners are clearly visible.

to note is that the observed band stuctures from [3] are indeed present and agree with those found here to within the statistical uncertainties. Additionally it is now possible to see some of the weak low energy $M1$ transitions linking the two observed bands and thus we can fix the relative excitation of the two bands with respect to each other.

A key feature of the observed spectrum in [3] was the large intensity at 350–355 keV, which formed the basis of the assignment of the bands to an excited $7/2^{+}[624]$ structure. This feature is not nearly as strong in the present experiment and must therefore be considered to be a statistical fluctuation in the earlier experiment.

Knowledge of the gamma ray energies for both the E2 and M1 transitions from this experiment is vital to an analysis if the conversion electron spectrum. In figure 5 the electron spectrum is overlaid with a simulation that takes as input the experimentally observed transition energies and a background from unresolved weakly populated high-K structures similar to those observed in ^{254}No [14,15]. While the electron spectrum alone is clearly not sufficient to establish the proposed band structure, it is not in contradiction to the observed gamma ray spectrum.

We now draw up the level scheme for ^{253}No. To this end we test the following hypotheses: A) The bands are built on the ground state $9/2^-[734]$ configuration and B) The bands are built on the excited $7/2^+[624]$ configuration. To distinguish between them one can now draw upon the observed M1/E2 branching ratios as well as a comparison of the experimental moment of inertia to those predicted by model calculations.

In a strongly coupled rotational band with good K quantum number in an axially deformed nucleus without pairing the observed gamma ray branching ratios can be written as a function of spin J, quadrupole moment Q_0

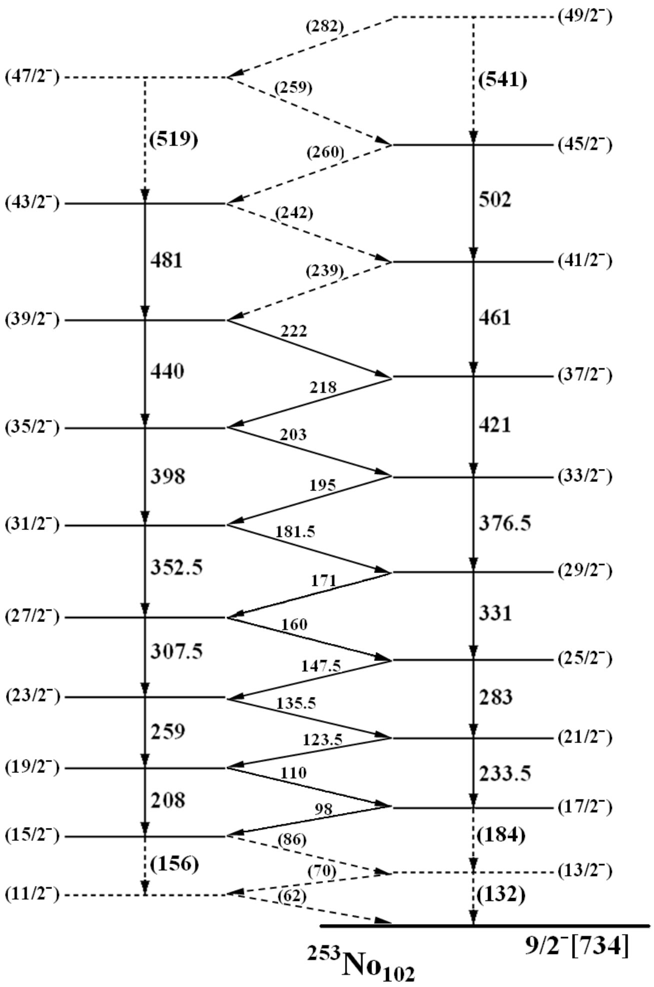

Fig. 3. Proposed partial level scheme for ^{253}No. The band is now built on the ground state configuration, and the tentative 132 keV transition is included in the scheme.

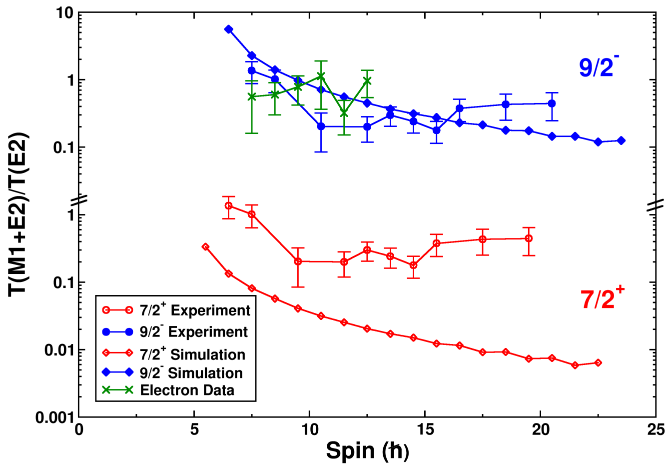

Fig. 4. Comparison of the branching ratios obtained from the gamma ray spectrum for cases A and B (filled and open circles, respectively) to rotational model calculations using the g_K values for the two cases. We also indicate the branching ratios obtained from the conversion electron study (crosses) to those taken from the gamma ray experiment. The agreement is surprisingly good. To avoid cluttering the plot only a comparison to the data for case A, which differs from case B only by 1 unit of spin, is shown.

and magnetic g-factor g_K:

$$\frac{I(M1/E2; J \to J-1)}{I(E2; J \to J-2)} = \frac{(g_K - g_R)^2}{Q_0^2} \cdot f(J, K)$$

The g-factor of the core g_R is taken as the usual $g_R = Z/A = 0.4$. To determine Q_0 from the experimentally observed bands one has to know the K-value for the band. In order not to enter a circular argument we therefore use the quadrupole moment of the neighboring ^{254}No as

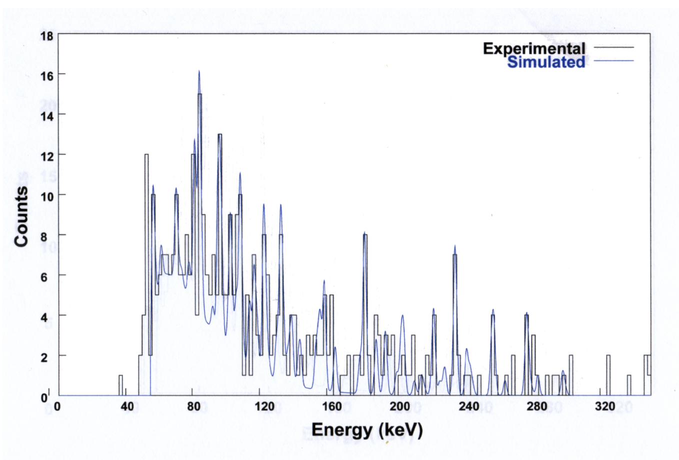

Fig. 5. Conversion electron spectrum of ^{253}No. All electrons are in coincidence with a recoil that has been correlated to a subsequent characteristic ^{253}No alpha decay. The superimposed line is a fit to the spectrum using the transition energies from the gamma ray study and a background from unresolved high-K bands analogue to that seen in ^{254}No.

a reference: $Q_0 = 13.1$ eb. This value was also used in [3]. Note that small changes to Q_0 do not greatly shift the branching ratios and thus do not adversely affect this assignment. The g-factors for the two configurations in question are taken as $g_K = +0.28$ for the $7/2^+$[624] and $g_K = -0.25$ for the $9/2^-$[734] configurations, respectively. These values are the same as in ref [6], where they were obtained from a shell model calculation with deformed Woods-Saxon potential. The resulting branching ratios are plotted together with the experimental values deduced from the gamma spectrum in figure 4. The $9/2^-$ configuration is clearly favoured.

It is also interesting to take the freely fitted intensities from the electron spectrum and to compare the obtained branching ratios to those from the gamma spectrum. This comparison is also shown in figure 4. They agree within the experimental uncertainties and give a lot more confidence in the potential for electron spectroscopy.

We therefore assign the observed band to be built on the $9/2^-$[734] ground state configuration. However, that by itself does not necessarily fix the spins as it is not guaranteed that we have observed the transitions down to the band head. Here it is instructive to compare the experimentally observed moments of inertia to those calculated in Cranked Relativistic Hartree-Bogoliubov calculations by A. Afanasiev [16] and Skyrme Hartree- Fock-Bogoliubov calculations by M. Bender *et* al. [17]. Good agreement is found for the dynamic moment of inertia in both calculations. To fix the spins we have taken the level populated by the 156 keV transition as a reference and varied its spin until the observed kinetic moment of inertia matches that of Cranked Relativistic Hartree-Bogoliubov calculations by A. Afanasiev [16]. An important feature is the observed "crossing" of the dynamic and kinetic moments of inertia at low frequencies around $\hbar\omega \simeq 150$ keV. We find that the best agreement between theory and experiment is obtained if one assumes a spin of 11/2 for the 156 keV level. The comparisons are shown in figure 6. This necessitates a further transition to be placed under the other signature band. Extrapolations with the rotational model would indicate that a transition with an energy of 132 keV could continue the band. This energy unfortunately is obscured by the strong K X-rays so that a strongly converted transition at that energy can not be readily identified in the gamma ray spectrum. The electron spectrum, however, gives a better fit if one includes a strong E2 transition at 132 keV in the fit. We therefore tentatively assign a transition at 132 keV as the $13/2 \rightarrow 9/2$ ground state transition and propose the level scheme shown in figure 3.

A number of recent studies of ^{253}No have focussed on isomeric states [20,21]. We confirm the existence of an isomeric state in ^{253}No with a half-life of $T_{1/2} = (28{\pm}3)\,\mu$s, in agreement with the value $T_{1/2} = (31.1 \pm 2.1)\,\mu$s given in [20]. We have, however, not achieved a level of statistics sensitive to the 167 keV transition observed in [20,21].

The alpha decay from the ground state of ^{253}No has been used to study excited states in ^{249}Fm [21–23,2] and we confirm their findings without being able to improve on their statistics.

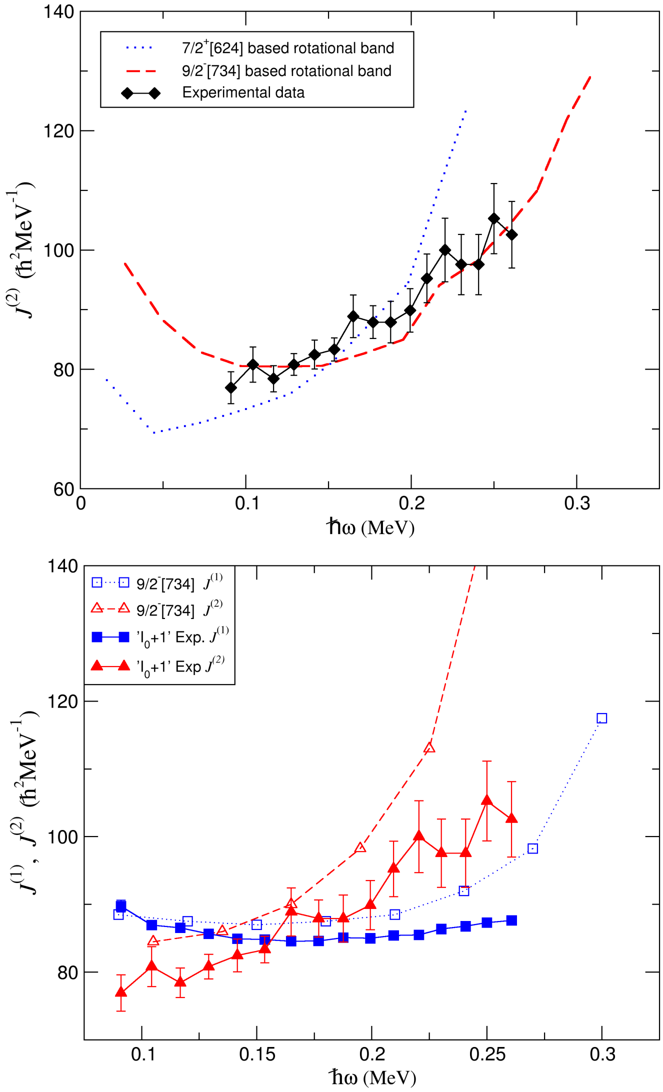

Fig. 6. Comparison of the experimental moment of inertia to two different model calculations. Top: Dynamic moment of inertia compared to the Skyrme Hartree-Fock-Bogoliubov calculations of M.Bender *et* al. [17]. Bottom: Kinetic and Dynamic moment of inertia compared to the cranked relativistic Hartree-Bogoliubov calculations of A.V. Afanasjev [16].

4 Outlook and Summary

It is obvious that even in this favourable case gamma ray spectroscopy struggles to reveal the full picture. The existing conversion electron studies can help investigate nuclei in this mass region, but so far have only been able to stand on their own in the experimentally more straightforward even-even cases [12,13,18]. However, the data presented here gives us great confidence that the goal of comprehensive internal electron spectroscopy is within reach. To achieve it, we are currently building and commissioning the SAGE spectrometer which will be optimised for simultaneous gamma ray and internal conversion electron spectroscopy. It builds on our experience with the SACRED spectrometer which placed the detector at backward angles to reduce Doppler broadening and suppress the very high background due to δ electrons. SAGE will combine the Jurogam 2 Germanium array with a highly segmented (90 segments) Si detector in a near 180 degree geometry. Electrons will be transported to the Si detector by a solenoidal magnetic field which has been integrated into the Jurogam 2 geometry to have no adverse effect on the germanium efficiency. Both the Ge and the Si parts will be instrumented using digital electronics allowing count rates of up to 30 kHz per channel into the upgraded Total Data Readout (TDR) data acquisition system [19]. This will finally allow electron-gamma cross coincidences, precise determination of conversion coefficients, multipolarities from subshell ratios and should open a new chapter in the book on spectroscopy of transfermium elements.

To summarise we have performed a new high statistics gamma ray experiment on ^{253}No. The observed band structures match those reported earlier, but the additionally observed M1 crossover transitions now allow their assignment to the $9/2^-[734]$ ground state configuration. The branching ratios obtained from a reanalysis of an earlier conversion electron study agree with this assignment. An isomeric state with a half-life of $T_{1/2} \simeq 30\,\mu$s is confirmed, as is the previously observed alpha decay into excited states of ^{249}Fm.

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References

1. R.-D. Herzberg and P.T. Greenlees, Prog. Part. Nucl. Phys. **61**, (2008), 674.
2. R.-D. Herzberg, J. Phys. G **30**, (2004) 123R.
3. P. Reiter et al., Phys. Rev. Lett. **95**, (2005), 032501.
4. A. Chatillon et al., Phys. Rev. Lett. **98**, (2007), 132503.
5. S. Ketelhut et al., *submitted to Phys. Rev. C.*
6. R.-D. Herzberg et al., Eur. Phys. J. **A 15**, (2002) 205.
7. S. Eeckhaudt, PhD thesis, University of Jyväskylä, 2006.
8. S. Moon, PhD thesis, University of Liverpool, 2007.
9. M. Leino et al., Nucl. Instr. Meth. **B 99**, (1995) 653.
10. R.D. Page et al., Nucl. Instr. Meth. **B 204**, (2003) 634.
11. K. Ashok et al., Nuclear Data Sheets **107**,(2006) 2103.
12. P.A. Butler et al., Nucl. Instr. Meth. **A 381** (1996) 433.
13. H. Kankanpää et al., Nucl. Instr. Meth. **A 534** (2004) 503.
14. P.A. Butler et al., Phys. Rev. Lett. **89**, (2002) 202501.
15. R.D. Humphreys et al., Phys. Rev **69**, (2004), 064324.
16. A.V. Afanasjev et al., Phys. Rev. **C67**, (2003) 024309.
17. M. Bender et al., Nucl. Phys. **A723**, (2003) 354.
18. J.E. Bastin etal., Phys. Rev. **C73**, (2006) 024308.
19. I.H. Lazarus et al., IEEE Transactions on Nuc. Sci. **48**, (2001) 567.
20. A. Lopez-Martens et al., Eur. Phys. J. **A 32**, (2007), 245.
21. F.P. Hessberger, Eur. Phys. J. **D 45**, (2007), 33.
22. A. Lopez-Martens et al., Phys. Rev. **C 74**, (2006) 044303.
23. F.P. Hessberger, Eur. Phys. J. **A 22**, (2004), 417.