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In-beam spectroscopy of ^{253,254}No

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Abstract. In-beam conversion electron spectroscopy experiments have been performed on the transfermium nuclei ^{253,254}No using the conversion electron spectrometer SACRED in nearly collinear geometry in conjunction with the gas-filled separator RITU at the University of Jyväskylä. The experimental setup is discussed and the spectra are compared to Monte Carlo simulations. The implications for the ground-state configuration of ^{253}No are discussed.

PACS. 21.10.-k Properties of nuclei; nuclear energy levels – 23.20.Lv Gamma transitions and level energies – 23.20.Nx Internal conversion and extranuclear effects – 27.90.+b $A \geq 220$

1 Introduction

For many years the quest to find the limits of stability for nuclei has been a major driving force in nuclear physics (see *e.g.* [1–3] and references therein). The problem is compounded by the fact that beyond $Z = 100$ the liquid-drop contribution to the nuclear binding energy vanishes and shell corrections are dominant in determining nuclear stability. Theoretical calculations for the next spherical superheavy nucleus beyond the stable $^{208}_{82}\mathrm{Pb}_{126}$ have predicted several candidates with nucleon numbers between $(Z, N) = (114, 184)$ [4], $(Z, N) = (120, 172)$ [5] and $(Z, N) = (126, 184)$ [6]. The experimental effort to create nuclei close to this region is considerable. Recent advances include the creation of element 114 [7], 116 [8], and 118 [9]. For a recent review of the topic see, *e.g.* [1,2].

However, the experimental data available for the heaviest nuclei is rather sparse and in many cases does not go beyond nuclear masses deduced from alpha-decay Q-values, decay modes, half-lives, and, in the case of odd mass nuclei, fine structure in the alpha-decays. While this data is of great importance and can reveal a lot of information about the nuclei in question, it lacks the immediate sensitivity of in-beam spectroscopic data to the details of the single-particle structure.

The nobelium nuclei are the heaviest systems available for in-beam spectroscopy today. Pioneering experiments on ^{254}No have looked both at the ground-state rotational bands [10,11] as well as the entry distribution of rotational levels as a function of the beam energy [12]. The second nucleus studied was ^{252}No [13], where a similar rotational band has been observed. Both nuclei are

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well deformed and can be populated in fusion-evaporation reactions with cross-sections of 2 μb for ^{254}No down to 220 nb for ^{252}No [13]. While the analysis of the ground-state rotational bands of these even-even nuclei already reveals important clues about the single-neutron structure, an experiment on the odd mass ^{253}No nucleus is clearly much more sensitive to the single-particle structure. In this contribution preliminary data on the conversion electron spectroscopy of ^{253,254}No is shown and compared to experimental and theoretical systematics in this region.

2 Experimental setup

The conversion coefficients α strongly depend on the charge of the decaying nucleus. Internal conversion increases with Z and increases with decreasing transition energy. As transition energies between the ground state and the first-excited 2^+ state in deformed even-even actinide and transactinide nuclei are typically of the order of 40–60 keV, this means that a substantial amount of the decay proceeds via internal conversion. In odd-even nuclei the situation is further complicated as the orbit occupied by the unpaired nucleon determines the observed band structure. The deciding factor whether strong $E2$ or $M1$ cascades are observed in the odd mass nucleus is the g-factor g_K of the orbital. The $B(M1)$ values in a band with a given K quantum number are given by [14]

$$B(M1; K, J \to K, J\pm1) = \frac{3}{4\pi}(g_K - g_R)^2 K^2 \left(\mathcal{C}^{J\pm1 K}_{JK10}\right)^2 \mu_N^2, \quad (1)$$

where g_R is usually taken as Z/A. For the nobelium nuclei this amounts to $g_R \simeq 0.4$. Therefore, a large negative g_K value will lead to strong $M1$ transitions whereas a positive $g_K \simeq g_R$ will mean that the decay proceeds predominantly via $E2$ transitions.

The background from delta electrons produced in atomic processes with very large cross-sections is a serious problem in conversion electron spectroscopy. The problem is compounded by the strong dependence on the atomic number of the target. In the reactions ^{48}Ca(^{206,207,208}Pb, 2n) leading to nobelium nuclei this background is daunting.

The SACRED (Silicon Array for ConveRsion Electron Detection) detector [15] in its near-collinear geometry is a very efficient device for the study of conversion electron spectra. Coupled with the gas-filled recoil separator RITU [16] at the University of Jyväskylä, it allows spectroscopy on reaction channels as weak as 200 nb.

The SACRED spectrometer consists of a set of four normal conducting magnetic coils generating a 0.3 T solenoidal field to transport the conversion electrons from the target to the detector. The geometry is chosen such that the solenoid axis forms an angle of 177.5 degrees with the beam axis, allowing the beam to pass close to the detector rather than having to pass through the center of the detector, as a true collinear geometry would demand. As the largest efficiency for low-energy electrons is close to the magnetic-field axis, an annulus in the detector center would have resulted in a large loss of efficiency. The 25 element Si detector is circular with six quadranted annuli surrounding a central element. To improve resolution the detector is cooled to −20 °C by radiation to a copper plate in thermal contact with a liquid nitrogen bath.

The background from delta electrons is suppressed twofold. Firstly, the geometry of the setup ensures that the majority of the delta electrons goes forward. The main suppression, however, is achieved via an electrostatic barrier of typically −35 to −50 kV placed between the target and the detector. The array and the coupling to RITU have been described in detail elsewhere [17,18].

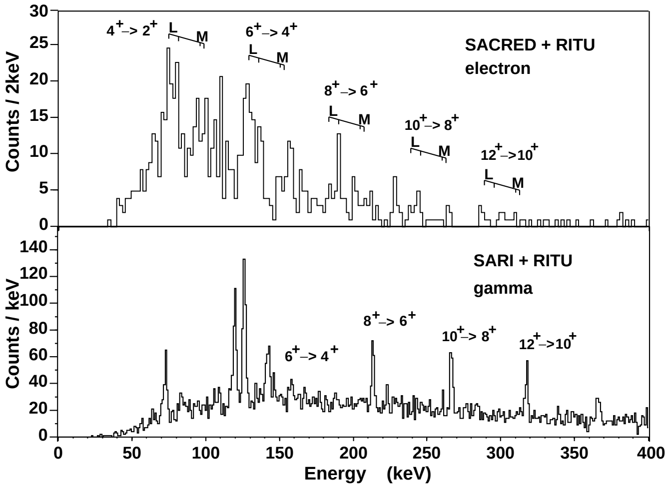

Fig. 1. Comparison of the conversion electron spectra (top panel) and the gamma-ray spectra (bottom panel) of ^{254}No.

3 Experimental data and discussion

3.1 ^{254}No

Figure 1 shows a comparison of the gamma-ray spectrum of ^{254}No (bottom panel) [11] with the conversion electron spectrum at the top. As expected, the conversion electron spectrum is most suited for the study of low-energy transitions below 200 keV. Note that the electron spectrum is preliminary.

The conversion electron spectrum also served to uniquely identify the multipolarity and electromagnetic character of the observed transitions. In table 1 we list the K, $L_{\mathrm{I+II}}$, L_{III} and $M_{\mathrm{I+\cdots+V}}$ conversion coefficients for the lowest two transitions under the assumption of the three most likely cases of $E1$, $E2$, and $M1$ radiation, respectively. As no simultaneous gamma-spectra were taken in this experiment absolute conversion coefficients are not given but rather the ratios $M_{\mathrm{I+\cdots+V}}/L_{\mathrm{I+II}}$ and $L_{\mathrm{III}}/L_{\mathrm{I+II}}$ can be used. Magnetic dipole transitions are ruled out from these ratios. Electric dipole transitions are also rather unfavoured. From the observed 1050 recoils one would expect roughly 100 conversion electrons in the combined L-M transitions for both the 102 and 159 keV transitions in case of $E2$ radiation in good agreement with the intensities observed in the spectrum. $E1$

Table 1. Comparison of calculated and measured internal conversion ratios for the lowest transitions in ^{254}No. The $E2$ character of the observed transitions is clearly shown.

	$E2$	$M1$	$E1$
E_γ	102 keV $E2$	102 keV $M1$	102 keV $E1$
α_K	–	–	–
$\alpha_{L_{\mathrm{I+II}}}$	13.55	9.94	0.088
$\alpha_{L_{\mathrm{III}}}$	7.27	0.03	0.030
$\alpha_{M_{\mathrm{I+\cdots+V}}}$	6.11	2.49	0.030
$\alpha_{M_{\mathrm{I+\cdots+V}}}/\alpha_{L_{\mathrm{I+II}}}$	0.45	0.25	0.38
$I_{M_{\mathrm{I+\cdots+V}}}/I_{L_{\mathrm{I+II\,exp}}}$	0.8(3)	0.8(3)	0.8(3)
$\alpha_{L_{\mathrm{III}}}/\alpha_{L_{\mathrm{I+II}}}$	0.54	0.003	0.38
$I_{L_{\mathrm{III}}}/I_{L_{\mathrm{I+II\,exp}}}$	0.8(2)	0.8(2)	0.8(2)
E_γ	159 keV $E2$	159 keV $M1$	159 keV $E1$
α_K	0.108	12.4	0.143
$\alpha_{L_{\mathrm{I+II}}}$	1.99	2.77	0.0314
$\alpha_{L_{\mathrm{III}}}$	0.82	0.0076	0.0077
$\alpha_{M_{\mathrm{I+\cdots+V}}}$	0.82	0.69	0.0098
$\alpha_{M_{\mathrm{I+\cdots+V}}}/\alpha_{L_{\mathrm{I+II}}}$	0.41	0.25	0.31
$I_{M_{\mathrm{I+\cdots+V}}}/I_{L_{\mathrm{I+II\,exp}}}$	0.64(15)	0.64(15)	0.64(15)
$\alpha_{L_{\mathrm{III}}}/\alpha_{L_{\mathrm{I+II}}}$	0.41	0.0027	0.25
$I_{L_{\mathrm{III}}}/I_{L_{\mathrm{I+II\,exp}}}$	0.55(14)	0.55(14)	0.55(14)

radiation would produce about 15 conversion electrons for both the 102 and 159 keV transitions. From this it is clear that the only sensible assignment is that of a $E2$ transition in accordance with expectations about the rotational structure of this nucleus and the findings in [10,11].

The background in the figure is still under study. Possible sources are random contributions from delta electrons or the conversion electrons from high-lying weakly populated high-K bands. Further experiments aimed at understanding the present background are planned.

3.2 ^{253}No

In order to get a feeling for the data we schematically illustrate the expected behavior of ^{253}No for bands based on different configurations. Figure 2 shows a schematic level scheme for ^{253}No in which the first band is taken to be identical to that of ^{254}No and the signature partner band is taken at the half-way points. It must be stressed, that this is for illustratory purposes only and has nothing to do with the real level scheme of ^{253}No. The arrows indicate the dominant decay paths in each case for the configurations given.

The spectrum shown in the top panel of fig. 3 is the total conversion electron spectrum of ^{253}No. The same background as in fig. 2 is scaled to the number of recoils nuclei in each experiment and subtracted from the spectrum. The remaining spectrum is then compared to the results of two Monte Carlo simulations based on two assumptions: a) the transitions observed are built upon a 7/2[624] single-neutron orbital with $g_K = 0.28$ and b) the transitions observed are built upon a 9/2[734] single-neutron orbital with $g_K = -0.24$. A simple comparison of the two spectra already indicates that the bulk of the transitions proceeds through low-energy $M1$ transitions rather than an $E2$ cascade. The simulations of these bands at this point are rather schematic and need to be refined, but the experiment is clearly more consistent with assumption b). The ground-state band of ^{253}No has also been calculated with the Hartree-Fock-Bogolyubov method with Lipkin-Nogami approximate particle projection [19]. There the ground-state band is also calculated based on the 9/2[734] quasineutron configuration.

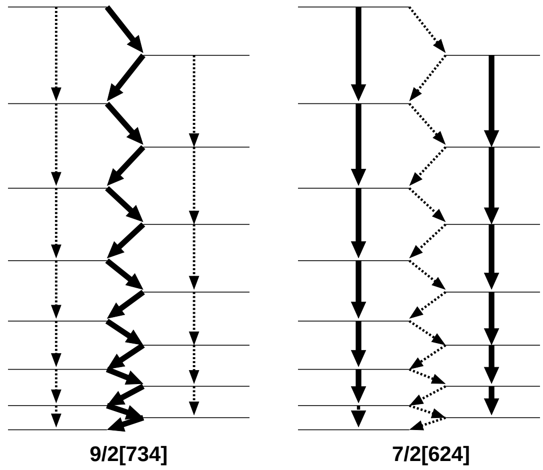

Fig. 2. Schematic level scheme for ^{253}No. The 7/2[624] configuration will have strong $E2$ cascades while the 9/2[734] configuration will have strong $M1$ decays.

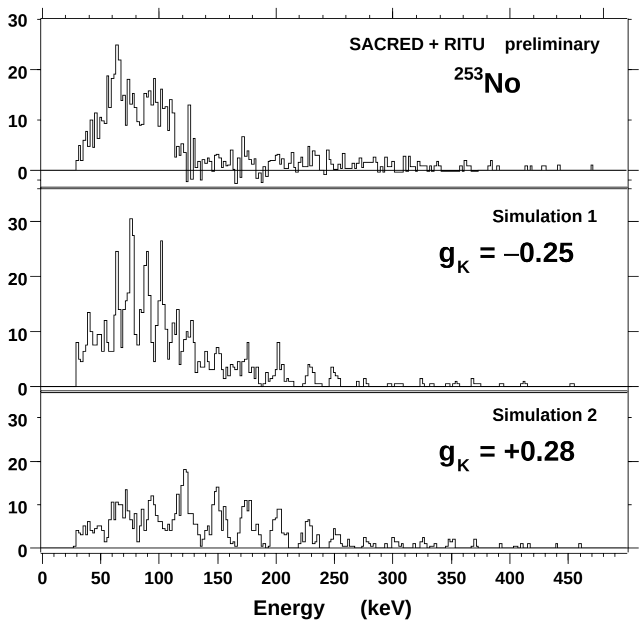

Fig. 3. The top panel shows the electron spectrum for ^{253}No after a background has been subtracted (see text). The two lower panels show the results of two simulations based on the configurations given.

A recent experiment at the Argonne National Laboratory using GAMMASPHERE and the FMA has also studied ^{253}No. There, a number of weak transitions are observed which could form a band structure based on the excited 7/2[624] quasineutron configuration [20]. The gamma-ray work is complementary to the conversion electron data and further analysis is clearly needed to understand this nucleus. This work is in progress and will be published elsewhere.

4 Summary

Conversion electron spectra have been taken with the SACRED conversion electron spectrometer coupled to the gas-filled recoil separator RITU. The ground-state band of ^{254}No has been observed down to the $4^+ \rightarrow 2^+$ transition previously unobserved in in-beam gamma-ray spectroscopy. The electron spectrum of ^{253}No has also been measured. The data indicates the presence of strong magnetic dipole transitions which places constraints on the configuration of the ground state indicating a 9/2[734] quasineutron structure in agreement with theoretical predictions.

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