

# Conversion Electron Spectroscopy in Transfermium Nuclei

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## Abstract

Conversion electron spectroscopy is an essential tool for the spectroscopy of heavy deformed nuclei. The conversion electron spectrometer SACRED has been used in conjunction with the gas-filled recoil separator RITU to study conversion electron cascades in  $^{254}\text{No}$ . The spectra reveal the ground state rotational bands down to low spin. A detailed analysis of the background seen for  $^{254}\text{No}$  shows that approximately 40% of the decay path goes via excited high K bands which may be built on an isomer.

## 1 Introduction

One of the long standing goals in nuclear structure physics is the understanding of the heaviest shell stabilised nuclei. A variety of mean field approaches are used today to gain insight into the structure of superheavy elements (SHE). For recent reviews see [1, 2, 3]. So far the bulk of the experimental knowledge in these nuclei comes from a study of their ground state properties (see [4] and references therein). However, in deformed midshell nuclei the relevant single particle orbitals lie close to the Fermi level and are available for study. Over the last years a number of in-beam gamma spectroscopy measurements have been made identifying rotational properties in  $^{252}\text{No}$  [8],  $^{254}\text{No}$  [5, 6, 7], and  $^{250}\text{Fm}$  [9].

Nuclear spectroscopy at the limits of high mass and charge faces a number of challenges. One is that the reaction cross sections leading to transfermium nuclei are usually smaller than  $1 \mu\text{b}$ . This is compounded by the fact that internal conversion processes dominate the decay paths in well deformed superheavy nuclei. As a rule of thumb in a  $Z=100$  nucleus an E2 transition of 200 keV proceeds via gamma decay and internal conversion with equal probability. For an M1 transition in the same nucleus the break even is reached around 400 keV. All transitions with energies below these values will be dominated by internal conversion.

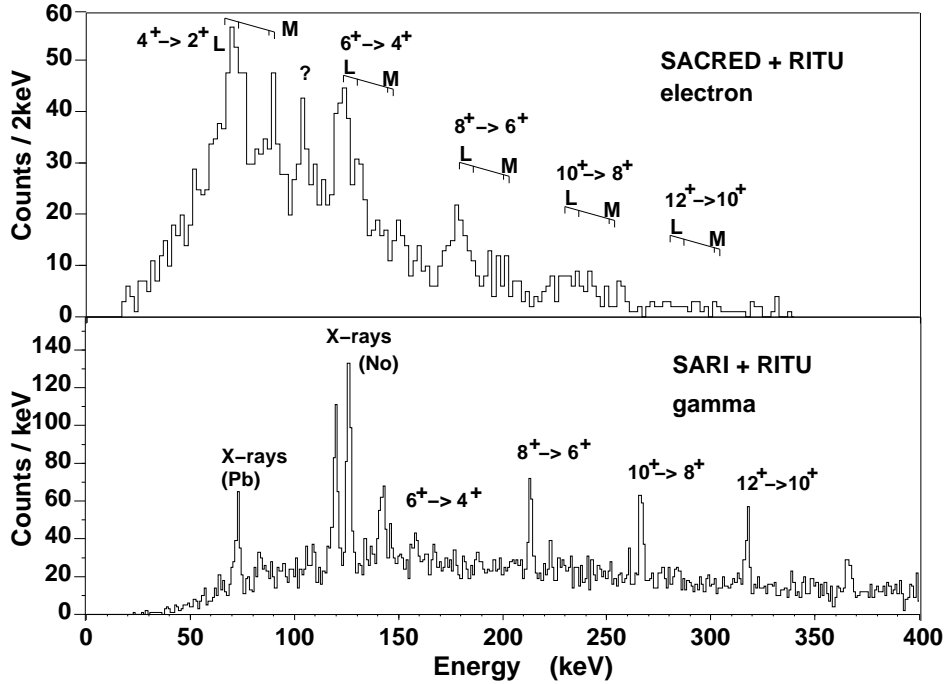


Figure 1: Comparison of the low energy part of the gamma ray spectrum (bottom) and the conversion electron spectrum (top) of  $^{254}\text{No}$ . The peak marked with a question mark does not belong to any identified gamma ray in  $^{254}\text{No}$ .

## 2 Experimental Details

The new conversion electron spectrometer SACRED consists of a circular Si detector segmented radially into 6 rings and azimuthally into 4 quadrants. Together with a central pixel that gives 25 individually read out segments and allows the study of electron-electron coincidences. The electrons are transported from the target to the detector via a solenoidal magnetic field of  $B \simeq 0.3\text{ T}$ . To suppress the background from low energy electrons generated via atomic processes, a high voltage barrier can be used with variable voltages between 0 and -50 kV. For the experiments on fermium and nobelium nuclei, the highest voltages of -35 – -45 kV had to be used. Details of the device can be found in [10, 11]. Here we use it coupled to the gas filled recoil separator RITU at the University of Jyväskylä, Finland [12] in near 180 degree geometry. The kinematic forward focusing helps further in suppressing the background from delta electrons.

$^{254}\text{No}$  recoils were produced via the reaction  $^{48}\text{Ca}$  on  $^{208}\text{Pb}$  at an average

beam energy of 216 MeV at the centre of the target. The energy was chosen to correspond to the maximum cross section in the excitation function for the 2 neutron evaporation channel leading to  $^{254}\text{No}$  and had a production cross section of  $2\ \mu\text{b}$  [6]. At this energy both competing 1n and 3n channels leading to  $^{255,253}\text{No}$  respectively have a combined cross section of 20 nb and can be neglected in the analysis of the spectrum. Two different target thicknesses  $250\ \mu\text{g}/\text{cm}^2$  and  $400\ \mu\text{g}/\text{cm}^2$   $^{208}\text{Pb}$  targets were used, giving 4710 recoils from the thin target and 2440 recoils from the thick target. For the spectroscopy of  $^{254}\text{No}$  several experimental runs were performed and are combined to show the total conversion electron spectrum in figure 1 [13].

The transitions in the ground state rotational band are clearly visible. Note the characteristic multiplet structure arising from the various L and M contributions to the spectrum. From the intensity ratios of the L and M transitions the multipole character of these transitions is firmly established as E2, supporting the earlier assignments made using gamma spectroscopy only. Figure 1 also clearly shows how the low lying transitions show up in conversion electrons but grow weak in gamma rays where the lowest visible transition is the  $6^+ \rightarrow 4^+$  transition at 159 keV. The strongest transition in the conversion electron spectrum is the  $4^+ \rightarrow 2^+$  transition at 102 keV, in accordance with extrapolations made in the rotational model [5, 6]. The lowest transition ( $2^+ \rightarrow 0^+$ ) is not visible in the electron spectrum as all electrons from it have energies below the electrostatic barrier and are therefore cut off.

A further feature of the electron spectrum in figure 1 is the background under the spectrum [14]. A detailed simulation of the spectrometer response including electron transport to the detector and backscatter from the surface [10] shows that the background under the spectrum should be much lower, with little or no counts in between the transitions. Figure 2 shows a simulation of the expected ground state band in  $^{254}\text{No}$  illustrating the response of the detector. The much better peak to background ratio than in the experimental spectrum is obvious.

Several hypotheses have been tested to the origin of the background. The quality of the simulation is shown to be in excellent agreement with experiment in the case of  $^{226}\text{U}$  [14] and it is not possible to attribute the large background to faults in the simulation. Next we tested if the background can originate from atomic processes, this was not the case. We found that the background did not scale proportional to the target thickness. For both target thicknesses the number of background counts per nobelium recoil was comparable at 0.177(8) and 0.170(10) respectively. If the background was atomic in origin then the increased thickness of material through which the No recoils need to travel on

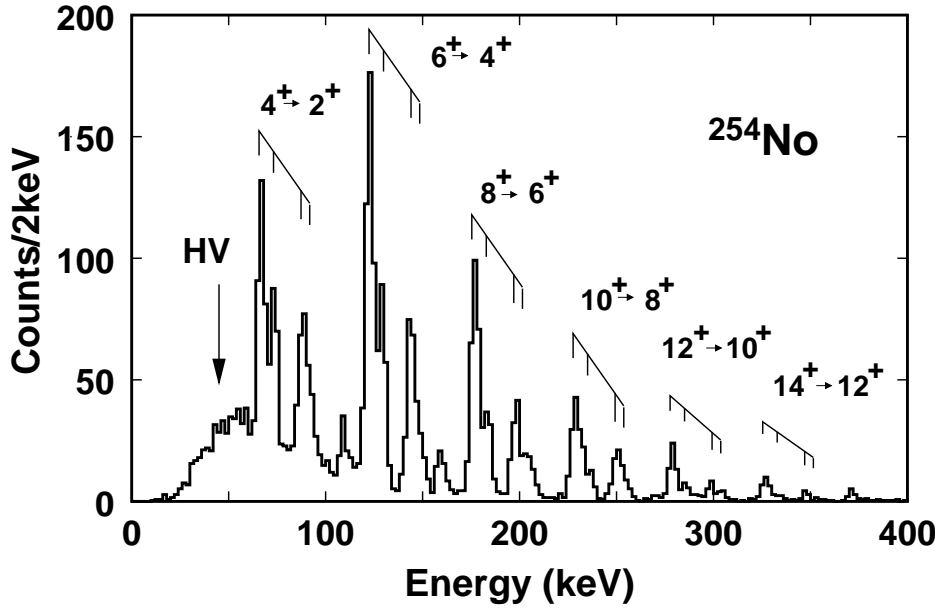


Figure 2: Simulation of the conversion electron spectrum of the ground state band of  $^{254}\text{No}$  only. Note the excellent peak to background ratio in stark contrast to the observed spectrum.

average should produce a larger number of atomic electrons per recoil for the thicker target. One can also test the shape of the atomic background by setting a timegate for SACRED away from the prompt time of flight through the separator. This spectrum has a totally different spectral shape than the observed background, peaking at the barrier voltage and decreasing exponentially (See panel d) of figure 3). It must therefore be concluded that the observed background is of nuclear origin and stems from transitions in  $^{254}\text{No}$  unobserved in gamma rays.

It is instructive to compare the conversion electron spectrum for various folds. If only a single electron is detected in SACRED (fold 1) the peak to background ratio is higher than if any number of electrons is detected, see panels a and b of figure 3. This can be understood if the average multiplicity in the background is higher than in the discrete transitions belonging to the ground state band. If the only decay path is via the ground state band, then the known transitions including the not observed  $2^+ \rightarrow 0^+$  transition give an average electron multiplicity of 3.7. The measurement of the observed yield is consistent with the simulation only if approximately 60% of the  $^{254}\text{No}$  nuclei deexcite via that path. The remaining 40% of all decays must pass through

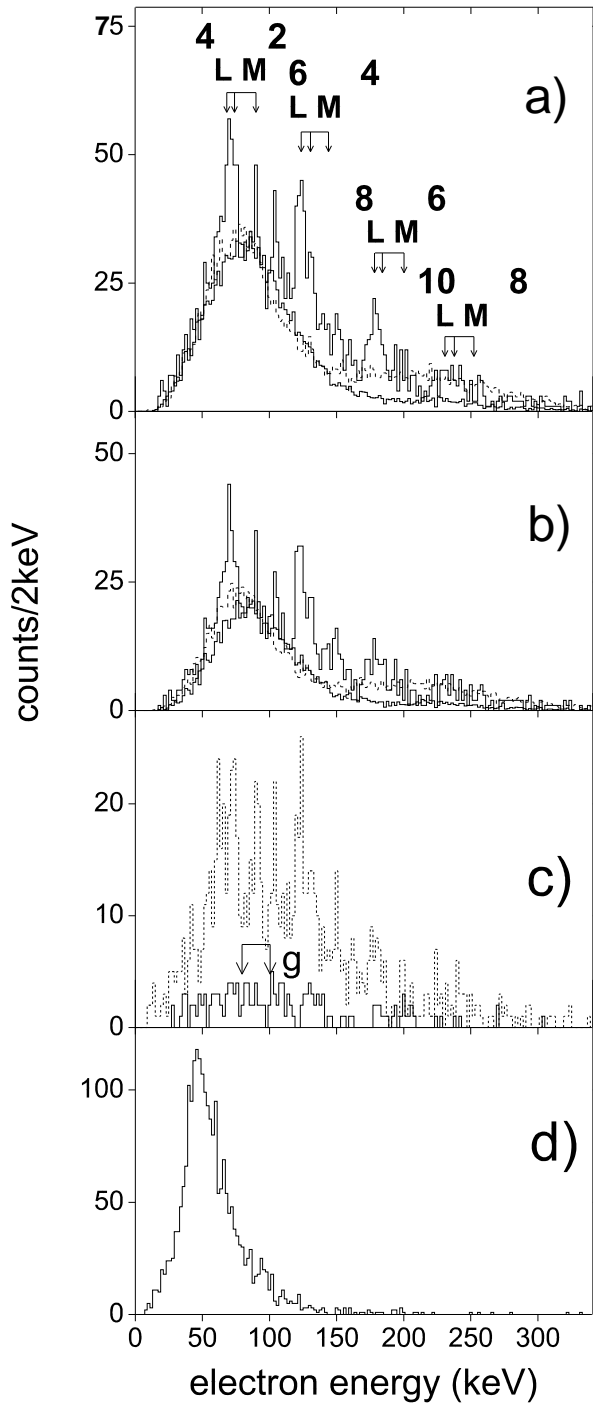


Figure 3: Panel a) shows the experimental conversion electron spectrum tagged with  $^{254}\text{No}$  recoils for all electron folds (solid bold line). The transitions between rotational states of the ground state band are labelled, but no Doppler shift correction has been applied. Also indicated are the simulated spectra for  $g_K = 0$  (solid line) and  $(g_K - g_R) = 0$  (dashed line). Panel b) shows the same as panel a) but for fold 1 events only. Note that the peak to background ratio is strongly affected. Panel c) shows the electron spectrum tagged with a  $^{254}\text{No}$  recoil and a subsequent alpha decay within 600s of the recoil implant (dashed line). One can clearly see that the background does belong to  $^{254}\text{No}$ . Also shown is the coincidence electron spectrum gated on the background region labelled “g” (solid line). None of the low lying transitions in the ground state band show up strongly. Panel d) shows the electron spectrum taken in random coincidence and show the characteristic shape of a  $\delta$  electron spectrum with a peak at the barrier voltage and a sharp exponential drop above it.

higher lying high-K bands with strong M1 transitions which are therefore invisible in the gamma ray experiments. We can now assume at least one band built on a  $K=8$  isomeric configuration populated with the same entry spin distribution as that measured in ref [7]. This assumption is justified as the background does not appear to be in prompt coincidence with the low lying transitions in the ground state band (panel c of figure 3). We assume  $g_K = 0$ ,  $g_R = 0.3$  and a constant moment of inertia of  $100 \hbar/\text{MeV}$ , somewhat larger than that in the highest transitions of the ground state band. As it is unlikely that only one high K band is populated, we simulate the population of various bands by randomizing the electron energies with a gaussian distribution with  $\sigma = 10 \text{ keV}$ . All details of this simulation can be found in [14].

### 3 Discussion

From the simulation results we conclude that the background observed in the electron spectrum of  $^{254}\text{No}$  is of nuclear origin and stems from the deexcitation of high lying high K bands. The lowest  $K = 8^-$  two quasiparticle states in  $^{254}\text{No}$  have been predicted as  $(\frac{9}{2}^- [734]_{\nu} \frac{7}{2}^+ [613]_{\nu}) 8^-$  with  $g_K = -0.3$  [16, 17],  $(\frac{9}{2}^- [734]_{\nu} \frac{7}{2}^+ [624]_{\nu}) 8^-$  with  $g_K = 0$  [18], and  $(\frac{9}{2}^+ [624]_{\pi} \frac{7}{2}^- [514]_{\pi}) 8^-$  with  $g_K = 1$  [16, 18, 17]. To test the quality of the simulation against experiment we use the ratio of integrated counts from the detection of a single electron to that of any electron  $R$ :

$$R = \frac{\int N_{single}(E) dE}{\int N_{tot}(E) dE} \quad (1)$$

Experimentally we find  $R = 0.58 \pm 0.03$ . For simulations of bands based on configurations with  $(g_K - g_R)^2 > 0$  we obtain values of  $R = 0.57 - 0.59$  in good agreement with experiment. In the special case of  $g_K - g_R = 0$ , corresponding to purely electric transitions, we find  $R = 0.64$ . Here the intensity is shifted to higher energies in the spectrum as for E2 transitions L2 conversion dominates even above the K threshold, whereas for M1 transitions K conversion becomes the dominant process thereby shifting intensity back into the energy range below the K binding energy (149.2 keV for nobelium). The dashed line in figure 3a,b clearly overestimates the spectral shape at energies above 150 keV.

If the bandhead of the band is assumed to promptly decay to the ground state band we find that the multiplicity increases to 10 and we obtain  $R = 0.47$ . From this and the lacking coincidences of the background and the lowest transitions in the ground state band we conclude that the bandhead must be isomeric. Such assignments are also consistent with experimental evidence for an isomeric state in  $^{254}\text{No}$  with a half-life  $T_{1/2} = 280(40) \text{ ms}$  [15].

## 4 Conclusion and Outlook

It appears to be clear that the in-beam study of elements around nobelium and above can only hope to yield significant results if a combination of gamma ray and conversion electron spectroscopy can be performed. In these heavy deformed systems the large moments of inertia lead to small rotational spacings and even electric quadrupole transitions will have large internal conversion coefficients. Excited bands built on two or more quasiparticle configurations are more likely to decay via a mixture of M1 and E2 transitions, depending on the g-factor of the specific configuration. Such transitions are only visible in conversion electrons. High sensitivity devices such as SACRED coupled to the gas filled separator RITU with its high transmission for SHE are ideal to study the nuclear structure in this heavy region.

In the present case the electron spectrum revealed that roughly 40% of the populated states decay via excited high-K bands which form a distinctive background under the well resolved peaks of the ground state band. The decay path is likely to pass through at least one isomer before it reaches the ground state band. It should be worth noting that a similar spectral shape is seen in  $^{250}\text{Fm}$ , however, the peak to background ratio appears to be different. A similar analysis as that presented here and in [14] is under way.

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## References

- [1] S. Cwiok et al., Nucl. Phys. **A611**, 211 (1996).
- [2] A.T. Kruppa et al., Phys. Rev. **C 61**, 034313 (2000).
- [3] M. Bender, P.-H. Heenen, P.-G. Reinhard, Rev. Mod. Phys. **75**, 121 (2003).
- [4] S. Hofmann and G. Münzenberg, Rev. Mod. Phys. **72**, 733 (2000).
- [5] P. Reiter et al., Phys. Rev. Lett. **82**, 509 (1999).
- [6] M. Leino et al., Eur. Phys. J **A6**, 1 (1999).
- [7] P. Reiter et al., Phys. Rev. Lett. **84**, 3542 (2000).

- [8] R.-D. Herzberg et al., Phys. Rev. **C65**, 014303 (2001).
- [9] R.-D. Herzberg et al., Proceedings to the International Conference Frontiers of Nuclear Structure, Berkeley, July 29 - Aug 2, 2002.
- [10] P.A. Butler et al., Nucl. Instr. Meth. **A 381**, 433 (1995).
- [11] H. Kankaanpää et al., to be published.
- [12] M. Leino et al., Nucl. Instr. Meth. **B 99**, 653 (1995).
- [13] R.D. Humphreys, PhD thesis Liverpool (2003) and to be published.
- [14] P.A. Butler et al., Phys. Rev. Lett. **89**, 202501 (2002).
- [15] A. Ghiorso et al., Phys. Rev. **C 7**, 2032 (1973).
- [16] V.G. Soloviev et al., Sov. J. Nucl. Phys. **54**, 748 (1991).
- [17] P. Stevenson, private communication.
- [18] S. Cwiok and W. Nazarewicz, private communication.