TOWARDS IN-BEAM SPECTROSCOPY OF THE HEAVIEST ELEMENTS*

P.A. Butler[a], A.J. Chewter[a], H. Kankaanpää[b], R.D. Herzberg[a]
F. Becker[c], J.F.C. Cocks[b], O. Dorvaux[b], K. Eskola[g], J. Gerl[d]
P.T. Greenlees[b], N. Hammond[a], K. Helariutta[b]
F.P. Hessberger[d], M. Houry[c], R.D. Humphreys[a], A. Hürstel[c]
G.D. Jones[a], P.M. Jones[b], R. Julin[b], S. Juutinen[b], A. Keenan[b]
H. Kettunen[b], T.L. Khoo[f], W. Korten[c], P. Kuusiniemi[b] Y. Le Coz[c], M. Leino[b], R. Lucas[c], M. Muikku[b], P. Nieminen[b]
R.D. Page[a], T. Page[a], P. Rahkila[b], P. Reiter[e], A. Savelius[b]
Ch. Schlegel[d], C. Theisen[c], W.H. Trzaska[b], J. Uusitalo[b]
and H.J. Wollersheim[d]

[a]Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK
[b]Department of Physics, University of Jyväskylä, Jyväskylä, Finland
[c]DAPNIA/SPhN CEA-Saclay, Gif-sur-Yvette, France
[d]GSI Darmstadt, Germany
[e]Ludwig Maximilians Universität München, Germany
[f]Argonne National Laboratory, USA
[g]Department of Physics, University of Helsinki, Finland

(Received November 2, 2000)

New developments in nuclear spectroscopy of prompt emission at the target and decay emission at the focal plane of recoil separators are described here. In-beam γ-ray measurements of even–even nuclei in the rotational superheavy region, ^{252,254}No, have been carried out. These measurements have revealed the properties of the ground state rotational bands. Attempts to measure the properties of odd mass nuclei await the further development of conversion electron spectroscopy, and early results from the SACRED spectrometer used in conjunction with the recoil separator RITU are given here. The future development of sensitive focal plane instruments, to identify decay processes following the radioactive decay of the parent nucleus is also described.

PACS numbers: 21.10.–k, 23.20.Lv, 23.20.Nx, 23.60.+e

* Presented at the XXXV Zakopane School of Physics "Trends in Nuclear Physics", Zakopane, Poland, September 5–13, 2000.

1. Introduction

Better understanding of the effective nuclear interaction comes from testing the predictions and limits of applicability of nuclear models by probing nuclei under extreme conditions. One approach is to examine the quantal behaviour of nuclei having extremes in overall mass (heavy and superheavy nuclei). The application of a particular theoretical model to very heavy nuclei is a severe test of the model and demands a rigorous derivation of the nuclear Hamiltonian. At present, the predictions of different state-of-the-art models, using the Strutinsky approach and the Skyrme–Hartree–Fock method, give very different positions of the next spherical shell closure for protons beyond $Z = 82$ [1].

The small cross-sections for the production of nuclei with $Z > 100$ has, in the past, restricted the measurement of observables of very heavy quantal systems to ground state decay properties [2]. This lecture describes how recent developments in γ-ray and electron spectroscopy will lead to the availability of a much wider spectrum of experimental measurements, allowing more stringent testing of nuclear models.

2. In-beam gamma-ray spectroscopy of even–even nobelium isotopes

The most important development in gamma-ray spectroscopy of heavy nuclei has been the coupling of germanium detector arrays at the target to recoil separators capable of "tagging", or identifying prompt gamma-ray emission by direct measurement of the mass of the recoiling nucleus or by measurement of radioactive decay. In the case of Radioactive Decay Tagging (RDT), it is necessary to make both time and position measurements at the focal plane in order to correlate the decay process with the events measured at the target [3]. The technique is currently capable of identifying prompt gamma-rays from nuclei populated with cross-sections of a few hundred nanobarns. The realisation that the cross-section using the reaction ^{208}Pb(^{48}Ca,2n)^{254}No ($\approx 3\mu$b), employing doubly-closed shell projectile and target, is sufficient for RDT measurements led to the observation of the ground state rotational band in the $Z = 102$, $N = 152$ nucleus up to spin $20\hbar$ [4,5]. This measurement is significant because it confirms that ^{254}No is well deformed, with a value for $\beta = 0.32 \pm 0.02$ [6]. The quadrupole deformation is deduced from the extrapolated $2^+ \to 0^+$ transition energy and the systematic dependence of the lifetime of the 2^+_1 state on its energy [6]. This observation is consistent with expectations of several classes of mean field theories, *e.g.* [7], which all predict that the stability against fission of this mid-shell nucleus arises from shell corrections enhanced because of quadrupole deformation.

Recently, measurements have been carried out following the reaction ^{206}Pb(^{48}Ca,2n)^{252}No, which has a cross section of about 300 nb [6,8]. This experiment was carried out at Jyväskylä using the JUROSPHERE γ-ray detector array [3] in conjunction with the gas-filled separator RITU [9]. The ground state rotational band was observed up to spin $20\hbar$ and shows an upbend (see Fig. 1) at a frequency ω = 200 keV which is absent from ^{254}No. The deduced quadrupole deformation in this case is 0.31 ± 0.02 [6].

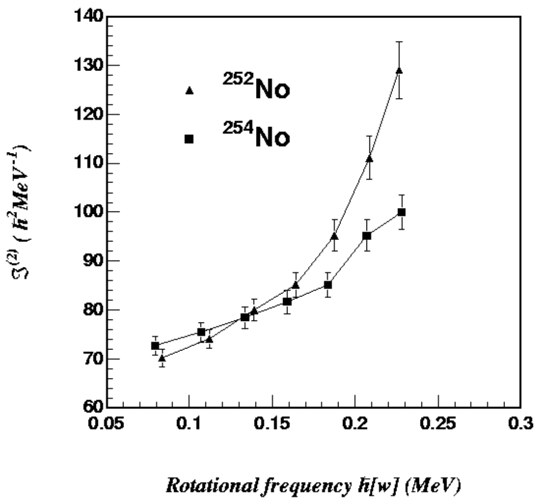

Fig. 1. Dynamical moment of inertia as a function of rotational frequency for ^{252,254}No. Taken from Ref. [6].

3. Location of next spherical shell gaps

As mentioned already, the different mean field approaches give different predictions for the location of the next spherical magic numbers beyond ^{208}Pb. Systematic studies [1,10] of three types of mean field, Strutinsky, Skyrme–Hartree–Fock (SHF), and Relativistic Mean-Field (RMF), give respectively (114,184), (124–126,184) and (120,172) for the next spherical shell closures (Z, N). The weakness of the macroscopic–microscopic approach appears to be its lack of self-consistent treatment of surface properties such as proton diffuseness [1]. The difference between the SHF and RMF approaches seems to lie in the treatment of the spin–orbit force [10]. These differences are magnified for heavy systems in which the single-particle spectrum becomes compressed, the spin–orbit splitting is attenuated, and Coulomb effects are enhanced [1].

Definitive experimental information on these positions can only come from direct measurements of superheavy nuclei lying close to the expected positions of the closed shells [11,12]. However, the various mean field parameterisations can be tested by examining the single particle properties of mid-shell deformed nuclei. For example, the $Z = 114$ shell gap is replaced by a gap at $Z = 126$ if the $p_{\frac{1}{2}}$, $p_{\frac{3}{2}}$ and $f_{\frac{5}{2}}$ single particle levels are lowered with respect to the $i_{\frac{11}{2}}$ level. In this case the position of the [521]1/2 deformed proton level, close to the Fermi level for $Z = 102$, is critical. Attempts have been made at both Argonne and Jyväskylä to study the odd mass nuclei ^{253}No and ^{255}Lr respectively by observing the recoil-tagged gamma-ray emission at the target. In both cases strong internal conversion and fractionation of intensity hinders identification of gamma-ray sequences, inferring that in both cases the yrast sequence contains strongly coupled signature partner bands with rather large values of $g_K - g_R$. This provides some information about the structure of the levels near the Fermi surface. For example, there are two sets of parameters commonly used in the Nilsson model that have been extracted from fitting experimentally measured single particle levels, with relatively little input from nuclei heavier than ^{208}Pb. For the mass 250 region, the values of μ and κ are very different for the two sets [13]. One set of parameters predicts that the yrast sequence of ^{253}No is a strongly coupled band; the other set predicts that a gamma-ray sequence should be clearly observable [14]. For ^{255}Lr, the ground state configuration [514]7/2 predicted by both Woods–Saxon and SHF models would lead to small $B(\mathrm{M1})/B(\mathrm{E2})$ ratios and modest internal conversion [15]. Recent experiments at Jyväskylä have also revealed the presence of isomeric states in even–even nuclei such as ^{254}No. Fig. 2 shows the spectrum of gamma-rays measured using the GSI Superclover [16] positioned at the focal plane of RITU, in prompt coincidence with alpha particles having energy of about 8 MeV.

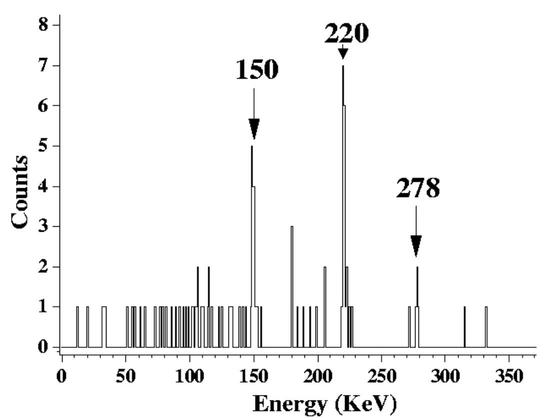

Fig. 2. Spectrum of γ-rays measured at the focal plane of RITU, in prompt coincidence with α-particles having energy $\approx$ 8 MeV, following the reaction ^{208}Pb+^{48}Ca. The beam energy halfway through the target was 216 MeV.

Three gamma lines can be clearly identified. Their nucleus of origin cannot as yet be determined and await further experiments. Nevertheless, the measured properties of the isomeric state should reveal details about the underlying single particle structure.

Further information about the location of the next spherical shell gaps can be extracted from the systematic behaviour of the $B(\mathrm{E2}: 2^+ \to 0^+)$ of nuclei lying in the shell above ^{208}Pb. According to the $N_\mathrm{p}N_\mathrm{n}$ systematics of reference [17], the value of the $B(\mathrm{E2})$ for nuclei with $Z > 100$ should be very different for the different assumptions for the proton and neutron number at the next spherical closed shell. Fig. 3 shows the values of $B(\mathrm{E2})$ obtained from lifetime versus excitation energy systematics [6] for ^{252,254}No for the two scenarios $Z = 114$, $N = 184$ and $Z = 126$, $N = 184$. Unfortunately the experimental uncertainty does not distinguish between the two possibilities. Precise measurements of the energy of the 2_1^+ state in ^{256}Rf, either by in-beam measurements using the $\sigma \approx 5$nb cross section $^{208}\mathrm{Pb}(^{50}\mathrm{Ti},2n)^{256}\mathrm{Rf}$ [18] or by the 10 % α branch following the $\sigma \approx 300$pb reaction $^{208}\mathrm{Pb}(^{54}\mathrm{Cr},2n)^{260}\mathrm{Sg}$ [19] should, however, be able to make the distinction.

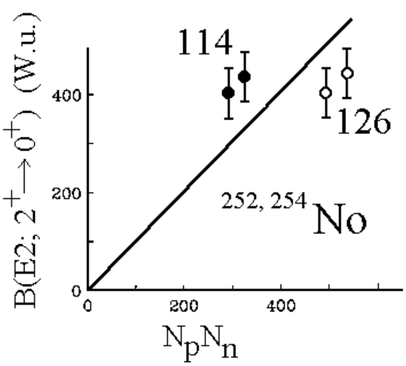

Fig. 3. Experimental $B(\mathrm{E2}: 2^+ \to 0^+)$ values versus the product N_pN_n. The values obtained for ^{252,254}No are indicated with closed and open symbols assuming that the next spherical gap is at $Z = 114, N = 184$ (closed) and $Z = 126, N = 184$ (open), respectively. The straight line is the expected trend taken from Ref. [17].

4. Outlook: target electron spectroscopy and focal plane spectroscopy

It is clear that detailed spectroscopy of very heavy nuclei that are created with sub-microbarn cross sections requires the development of new spectroscopic tools. The Liverpool–Jyväskylä SACRED silicon detector array [20] is designed to detect multiple conversion electron emission from the target. It employs a solenoidal magnetic field to transport the electrons from the target to the detector. The detector itself is segmented so as to form 25 independent elements, which have individual amplification and timing channels. An important component of the spectrometer is the electrostatic barrier, which suppresses the high flux of low energy electrons produced in atomic processes. The typical peak efficiency of the array is about 10% for electrons with incident energy between 100 and 300 keV. For recoil tagging or RDT experiments, where the heavy recoils are detected using the RITU recoil separator, the solenoid has its axis approximately parallel to the beam direction, in a collinear geometry. The annular silicon detector is placed upstream of the target, which has the advantage that the atomic electron flux is smaller in this direction and the kinematic broadening of the electrons is a minimum. A test experiment performed recently showed promising results. In these experiments the angle of the beam with field axis was about 2.5°, so that the displacement of the beam at the detector position (580 mm from the target) was about 25mm. This has the advantage that there is no necessity for a central hole in the detector, as the outer radius of the detector (divided into 6 concentric rings with 4 quadrants, with an additional central region) is 14mm. The detector and high voltage barrier was isolated from the 0.76 mbar He gas in RITU by a double window system with intermediate pumping. Each window consisted of $50\mu g/cm^2$ C foil.

Fig. 4 shows the prompt electron spectrum gated by recoil detection in RITU, for the reaction ^{124}Sn(^{48}Ca,xn). The barrier voltage was -35kV. In this experiment the resolution was limited by noise pickup on the detector and poor base-line suppression, and is far from the value expected from kinematic effects (better than 3 keV). A short run for the reaction ^{208}Pb+^{48}Ca demonstrated that events corresponding to ^{254}No could be cleanly isolated from the background, and structure corresponding to the $4^+ \rightarrow 2^+$ transition in ^{254}No was observed in this experiment.

The study of low-lying states in heavy nuclei can also be achieved by observation of their decay properties at the focal plane of the recoil separator. Typically the cross-sections for the formation of the parent nucleus is 10 times smaller than that for direct population of the daughter, but advantage can be made of higher beam currents and detector efficiencies available for decay spectroscopy.

In order to achieve the necessary level of sensitivity, a tagging detection system deployed at the focal planes of the high-transmission recoil separators must be highly segmented, provide excellent energy resolution and have the highest possible efficiency. A new focal plane spectrometer, GREAT (Gamma, Recoil, Electron, Alpha, Time/Tagging), and its associated electronics and data acquisition system will be constructed to satisfy these criteria.

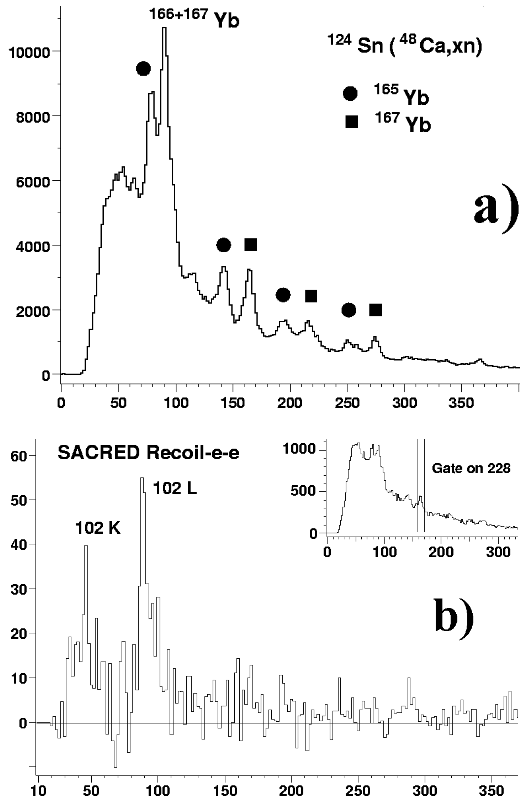

Fig. 4. (a) Recoil-gated electron spectrum following the reaction ^{124}Sn(^{48}Ca$, xn$). The beam energy halfway through the target was 215 MeV. (b) Recoil-gated electron–electron spectrum, obtained by applying a gate on the L-line of the 228 keV $4^+ \rightarrow 2^+$ transition in ^{166}Yb (see inset). This spectrum is dominated by the electron lines arising from the 102 keV $2^+ \rightarrow 0^+$ transition.

The GREAT spectrometer (see Fig 5) is designed to measure the properties of reaction products transported to the focal planes of recoil separators. GREAT comprises five distinct components:

(1) double-sided silicon strip detectors into which the reaction products are implanted and used to measure subsequent α particle, β particle or proton emission;

(2) an array of silicon PIN photodiode detectors to measure conversion electron energies with good (~ 4 keV) energy resolution;

(3) a double-sided planar germanium strip detector to measure the energies of X rays, low energy γ rays and β particles;

(4) a high efficiency segmented germanium Clover detector to measure the energies of higher energy γ rays;

(5) a multiwire proportional counter in front of the silicon strip detectors to act as an active recoil discriminator.

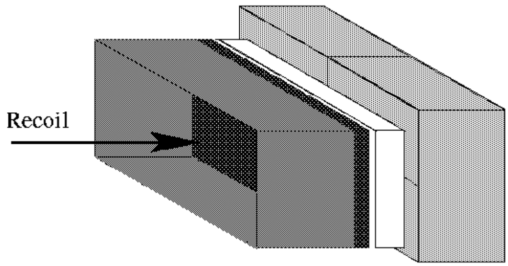

Fig. 5. Scheme of the GREAT spectrometer. The recoils pass through, in order, the multiwire proportional counter (not shown), the PIN Si box, the implantation Si detector, the planar Ge detector and the large volume Ge Clover detector.

The silicon strip detectors and the germanium detectors are segmented to enable position correlations be made with associated decays in the particle detectors of GREAT, while the separation of the photon energy range into two types of germanium detector gives the greatest flexibility and performance. GREAT will provide the capability to measure all of the decays from the radioactive reaction products for both in-beam tagging and radioactive decay studies.

5. Summary

New developments in nuclear spectroscopy of prompt emission at the target and decay emission at the focal plane of recoil separators are taking place, which will allow measurements of the structure of superheavy systems. In-beam γ-ray measurements of even–even nuclei in the rotational superheavy region, ^{252,254}No, have been carried out, revealing the properties of the ground state rotational bands up to spin $20\hbar$. Measurement of prompt conversion electrons emitted from even–even and odd mass nuclei populated at sub-microbarn cross-sections is now possible, and sensitive focal plane instruments are being constructed which can identify decay processes following the radioactive decay of the parent nucleus. In this way mean field theories that are extrapolated from medium-mass nuclear systems to the superheavy region can be tested.

We would like to thank R. Bengtsson, W. Nazarewicz and A. Sobiczewski for useful discussions. This work was supported by the Access to Large Scale Facility programme under the Training and Mobility of Researchers programme of the EU, The Academy of Finland under the Finnish Centre of Excellence Programme 2000–2005, the U.K. Engineering and Physical Sciences Research Council, and the U.S. Department of Energy.

REFERENCES

[1] S. Ćwiok *et al., Nucl. Phys.* **A611**, 211 (1996).

[2] S. Hofmann, *Rep. Prog. Phys.* **61**, 639 (1998).

[3] R. Julin *et al., Acta Phys. Pol.* **B28**, 269 (1997).

[4] P. Reiter *et al., Phys. Rev Lett.* **82**, 509 (1999); *Phys. Rev. Lett.* **84**, 3542 (2000).

[5] M. Leino *et al., Eur. Phys. J.* **A6**, 63 (1999).

[6] R.-D. Herzberg *et al.*, to be published.

[7] I. Muntian, Z. Patyk, A. Sobiczewski, *Phys. Rev.* **C60**, 041302 (1999).

[8] R.-D. Herzberg *et al.* Proc. 2nd Int. Conf. Fission and Properties of Neutron-Rich Nuclei, St Andrews, ed. J.H. Hamilton, W.R. Phillips, H.K. Carter, (1999), p. 196.

[9] M. Leino *et al., Nucl. Instrum. Methods Phys. Res.* **B99**, 653 (1995).

[10] A.T. Kruppa *et al., Phys. Rev.* **C61**, 034313 (2000).

[11] Yu. Ts. Oganessian *et al., Nature* **400**, 242 (1999).

[12] V. Ninov *et al., Phys. Rev. Lett.* **83**, 1104 (1999).

[13] R. Bengtsson, `www.matfys.lth.se/~ragnar/rob.html`.

[14] R. Bengtsson, `www.matfys.lth.se/~ragnar/butler.html`.

[15] S. Ćwiok, W. Nazarewicz, private communication.

[16] J. Gerl, I. Peter, `www-gsi-vms.gsi.de/eb/html/vega_project.html`.

[17] N.V. Zamfir *et al., Phys. Lett.* **B357**, 515 (1995).

[18] F.P. Heßberger *et al., Z. Phys.* **A321**, 317 (1985).

[19] G. Münzenberg *et al., Z. Phys.* **A322**, 227 (1985).

[20] P.A. Butler *et al., Nucl. Instrum. Methods Phys. Res.* **A381**, 433 (1996).