Vol. 36 (2005) *ACTA PHYSICA POLONICA B* No 4

EXPERIMENTAL CHALLENGES FOR STUDYING NEEDLES IN A HAYSTACK*

P.A. Butler

Oliver Lodge Laboratory, University of Liverpool
Liverpool L69 7ZE, UK
and
PH-ISOLDE, CERN, CH-1211 Geneva 23, Switzerland

(Received November 30, 2004)

As a tribute to Rafał Broda and as a celebration of his sixtieth birthday, this short review examines the progress in techniques for in-beam nuclear spectroscopy of weak channels. Illustrative examples will be taken from studies of heavy octupole nuclei and deformed superheavy nuclei, in which various reaction mechanisms have been employed. Future perspectives will also be presented.

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

1. Introduction

There have been a number of developments in instrumentation and techniques for in-beam spectroscopy that, in parallel with advances in target γ-ray detection, have enabled weakly populated channels to be isolated and studied. Early applications of recoil detectors to the studies of nuclei populated in compound nucleus reactions varied from simple PPAC devices to suppress fission channels [1] or more sophisticated Wien filters and magnetic separators [2] to isolate exotic nuclei such as ^{80}Zr [3]. The availability of highly efficient and granular germanium arrays has also made it possible to resolve weak channels if additional charged particle and neutron detection are employed. In this case the resolving power of the γ-ray detectors is maximised by stopping the recoils in a thick target, so that the emitted γ-rays have no Doppler broadening. A representative example of this technique is the study of ^{98}Cd by Gorska *et al.* [4] which used germanium tapered and

* Presented at the XXXIX Zakopane School of Physics — International Symposium "Atomic Nuclei at Extreme Values of Temperature, Spin and Isospin", Zakopane, Poland, August 31–September 5, 2004.

cluster detectors in conjunction with charged particle and neutron detectors. The cross-sections accessible with this technique were of the order of 10 μ-barns. Some years ago it was also realised by Rafał Broda that the use of efficient Compton-suppressed germanium-detector arrays will also allow multi-nucleon transfer reactions to become an effective method of accessing many nuclei inaccessible by compound-nucleus reactions [5–7]. In these reactions many excited nuclei around the projectile and target are produced although the resulting complexity of the spectra demands high statistics and good energy resolution. This approach, in which γ^n coincidence techniques are employed, can allow identification and measurement of the yield of the two reaction partners and extraction of their decay schemes. In this paper we will summarise how developments in in-beam spectroscopy applied to both compound nucleus and transfer reactions have made significant contributions to the understanding of heavy octupole nuclei and nuclei in the deformed superheavy mass region.

2. Study of octupole nuclei with $Z \sim 88$, $N \sim 134$ using transfer reactions

Isotopes of Rn, Ra and Th with $N \simeq 134$ have their neutron and proton Fermi levels in close proximity to the octupole-driving neutron ($j_{15/2}$ and $g_{9/2}$) and proton ($i_{13/2}$ and $f_{7/2}$) orbitals. Thus, these nuclei are susceptible to octupole deformation [8–10]. Previously, radium and thorium isotopes have been studied in-beam using neutron-rich ^{18}O and ^{14}C beams on ^{208}Pb and ^{209}Bi targets [11,12]. In addition, ^{226}Ra ($t_{1/2} = 1600$ years) targets have been Coulomb excited [13] and ^{224}Ra has been studied [14] using heavy-ion transfer reactions with ^{226}Ra targets. Although approximately twenty octupole band structures have been observed in this region, high-spin states in many of the nuclei which are predicted to be the best candidates for strong octupole effects [15, 16] had been inaccessible experimentally. For example, the high-spin structures of ^{222}Ra and of octupole-deformed radon isotopes with $A \geq 220$ had remained unknown.

In order to exploit the Broda method, preliminary experiments were first carried out in which thick ^{232}Th targets were bombarded by heavy ions at energies between 15% and 20% above the Coulomb barrier. Selection of bombarding energy is a compromise between maximising the reaction yield and angular momentum input and minimising the excitation energy of the reaction products. At these bombarding energies the contribution to the Ge singles rate from nuclear reactions becomes comparable to that from Coulomb excitation of the target. The angular momentum transfer to the products of the binary reaction is at least 40 (^{56}Fe projectile), 50 (^{86}Kr) or 75 $\hbar$ (^{136}Xe). The average excitation energy in the deep-inelastic products is estimated to be between 25 and 35 MeV, which allows the evaporation of a few neutrons from the excited products. Figures 1(a), (b) and (c) show the target-like product yields (typically ~ 10 mb for each reaction product) measured [17] for the reactions ^{136}Xe + ^{232}Th, ^{86}Kr + ^{232}Th and ^{56}Fe + ^{232}Th, respectively.

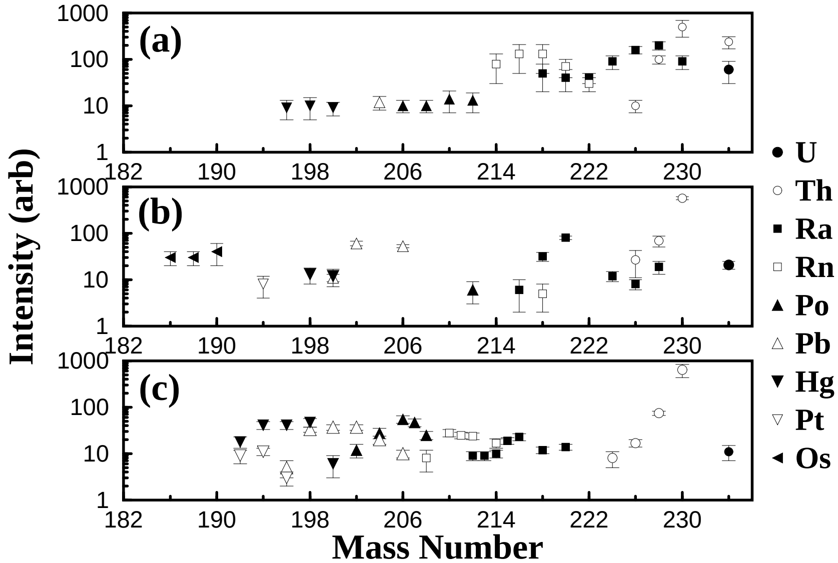

Fig. 1. A comparison of the yields of target-like nuclei produced in the (a) ^{136}Xe + ^{232}Th reaction (N/Z of beam = 1.52), (b) ^{86}Kr + ^{232}Th reaction (N/Z_{beam} = 1.39), (c) ^{56}Fe + ^{232}Th reaction (N/Z_{beam} = 1.15). In these figures the values are normalised to the yields of the 6^+ state in ^{232}Th [17].

As the reaction ^{136}Xe + ^{232}Th offered the largest yield for Rn and Ra isotopes with $N \approx 134$, this reaction was chosen to make spectroscopic measurements of these nuclei (see [18, 19]). The ^{136}Xe projectile was accelerated to an energy of 833 MeV by the 88" cyclotron at the Lawrence Berkeley National Laboratory. This bombarded a ^{232}Th target of thickness 36 mg/cm^2. De-excitation gamma rays emitted from reaction products were collected with the GAMMASPHERE (GS) gamma-ray spectrometer which consisted of 73 large volume ($\sim$75% relative efficiency) Compton-suppressed germanium detectors. The level schemes of $^{218-222}$Rn, $^{222-230}$Ra, and $^{226-234}$Th were deduced from the analysis of these data [18, 19]. The levels in ^{218,220,222}Rn having $I^\pi = 5^-$ or higher were identified for the first time. In the Ra isotopes, the following new levels were identified: $I^\pi = 5^-$ or higher in ^{222}Ra, $I^\pi = 13^-$ or higher in ^{224}Ra, $I^\pi = 19^-$ or higher in ^{226}Ra, $I^\pi = 7^-$ or higher in ^{228}Ra, and $I^\pi = 8^+$ or higher in ^{230}Ra. In

^{234}Th the levels having $I^{\pi} = 12^{+}$ and higher and the negative parity states were identified for the first time. Thus the level schemes of several Rn, Ra isotopes and Th were significantly extended. In the Rn isotopes and in ^{222}Ra two interleaving positive and negative parity rotational bands were observed for the first time. The data demonstrated that there are several nuclei in the $Z = 88$, $N = 134$ mass region — $^{220-226}$Ra and $^{222-226}$Th — whose behaviour is consistent with reflection asymmetry in their intrinsic frame. This is in contrast to Rn isotopes with similar neutron numbers and nuclei with $Z \approx 58$, $N \approx 88$ which are octupole vibrational in nature.

3. Developments in in-beam spectroscopy using the recoil decay tagging method

Experimental techniques to observe prompt electromagnetic decay from heavy nuclei (A$>$ 180) populated with cross-sections less than 10 μb have been pioneered at the JYFL laboratory of the University of Jyväskylä and further developed at the Argonne National Laboratory (ANL). In these cases the nuclear reaction cross-section is dominated by fission, and neutron-deficient or very heavy nuclei whose ground state decays by alpha-emission can be identified by the method of recoil decay tagging.

Most of the nuclear structure studies in the heavy mass region make use of fast and efficient online recoil separators. They are used in in-beam experiments where background suppression is based on requiring a delayed coincidence with a separated evaporation product. The latter method is called recoil gating, or if the product is identified on the basis of its characteristic decay properties, Recoil Decay Tagging (RDT). The task of recoil separators is to filter away the primary accelerator beam and the majority of unwanted reaction products. Their operation is based on the fact that fusion evaporation products fly out of the very thin target at close to zero degrees relative to the beam with nearly the full momentum of the heavy ion but with magnetic or electric rigidity which differs from that of the beam and the background particles. Identification of the products is usually based on the characteristics of their radioactive decay observed in the detector set-up surrounding the focal plane of the separator. The focal plane detector system is usually based on a large-area silicon detector that measures the position of the arrival and decay of the fusion evaporation products. The size of the detector is typically on the order of a few square cm.

For in-beam experiments, two separators and associated detector systems have been used. The Fragment Mass Analyser (FMA) at ANL has been used in conjunction with the very efficient GS germanium detector array. The FMA has sufficient mass resolution to uniquely determine the mass number of fusion evaporation products in the heavy element region and still a fairly high efficiency, typically on the order of 5–15%. The efficiency of GS at 1.3 MeV is approximately 10%. The BGO shields of this array provide the additional possibility of calorimetric measurements which have allowed to collect ground-breaking information on the spin-entry distribution in the region close to ^{254}No.

The gas-filled RITU separator at JYFL, Jyväskylä, has a high transmission of typically 25–40% due to its charge and velocity focusing characteristics. It has been operated in conjunction with various germanium detector arrays ranging in efficiency from 0.7% upwards. An early application of RDT using RITU demonstrated that ^{226}U has octupole deformation [20]. The presently operating JUROGAM array which consists of 43 EUROGAM Phase 1 detectors has a total efficiency of 4.5% at 1.3 MeV. The unique feature at JYFL is the possibility of for the first time recording conversion electrons in-beam using the RDT method. This has been made possible by joint Liverpool–Jyväskylä efforts in developing the SACRED electron spectrometer [21, 22]. SACRED has an efficiency of approximately 10% for energies below 300 keV and, due to the segmentation of the 28 mm diameter Si detector makes it possible to record electron–electron coincidences. The development of SACRED has allowed prompt conversion electrons emitted from weakly populated nuclei to be detected. In this way the $2^+ \rightarrow 0^+$ transition in ^{226}U and the $4^+ \rightarrow 2^+$ transition in ^{254}No (see next section) have been identified for the first time [23].

4. The study of deformed nuclei with $Z \sim 102$

A breakthrough for SHE studies using the decay-tagging technique came from its application [24, 25] to the reaction ^{208}Pb(^{48}Ca,$2n$)^{254}No, which has a cross-section of 2 μb. The experimental observation of the ground-state rotational band up to spin 18 (see figure 2) was a significant find in that it confirmed the deformed nature of the mid-shell nucleus ^{254}No and demonstrated that the deformed shell stabilisation against fission persists to high spin. Since then, experiments have been carried out to measure the rotational properties of the even–even nuclei ^{252,254}No and ^{250}Fm [26]. These nuclei have similar values of quadrupole deformation, $\beta \sim 0.28$, and for ^{252}No a gradual upbend of the dynamic moment of inertia is observed as compared to its isotonic and isotopic neighbours. Research efforts have also been directed to odd-mass systems that can reveal single particle properties near the Fermi surface. A severe experimental handicap in these studies arises from the internal conversion of the M1 transitions depopulating the strongly coupled rotational bands built on single particle states. In some cases that have been studied, such as ^{253}No and ^{255}Lr, the gamma-ray intensities are too weak to allow the extraction of quantitative information.

Gamma-ray measurements of odd mass nuclei now focus on specific cases such as ^{251}Md for which either the M1 branching is weak (cancellation of single particle and rotational g-factors) or the signature partners of the rotational band are decoupled ($K = \frac{1}{2}$ ground state).

Another promising approach is to study bands built on multi-quasiparticle states in these heavy nuclei. A recent study [28] of prompt conversion electrons emitted by excited ^{254}No nuclei has revealed that a large fraction (40%) of the decays proceed through high-K bands that probably terminate in isomeric states. The high electron multiplicity of these decay paths give rise to a quasi-continuous background. This background dominates the observed electron spectrum as can be seen in figure 2.

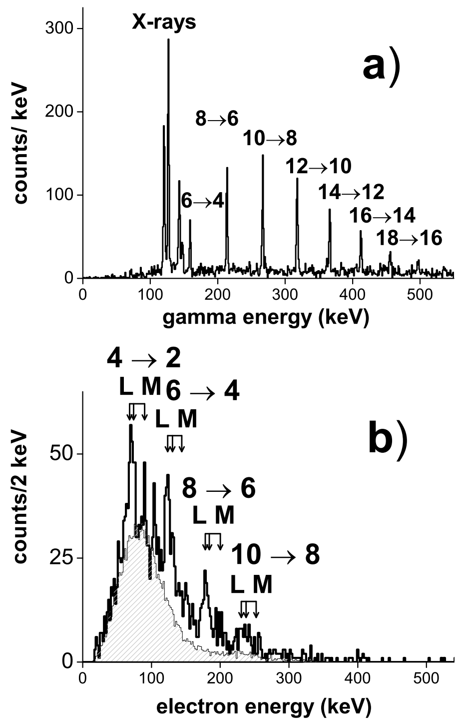

Fig. 2. Comparison of in-beam (a) γ-ray spectrum [27] and (b) conversion electron spectrum following the reaction ^{208}Pb(^{48}Ca,2n)^{254}No. In the latter the shaded region is a simulation assuming that the nucleus decays by many M1 paths built on high-K states [28].

Evidence for the presence of a long-lived isomer in ^{254}No has been presented thirty years ago and efforts are underway [29] to quantify the character (excitation energy, spin, parity) of low-lying isomers in this mass region.

5. Developments in focal plane spectroscopy: GREAT

Recently, a new detector system called GREAT [30] was installed at the RITU focal plane. This versatile system allows, in addition to the observation of the arrival and the decay chain of the fusion product, the detection of escape alpha particles, conversion electrons, beta decays, as well as X-rays and gamma rays using a segmented planar Ge detector and a large Ge clover detector. To facilitate readout of asynchronous data from the target-area and the focal plane detectors a new triggerless data acquisition system called TDR (Total Data Readout) was also developed [31]. Spectroscopic information can also be obtained by measuring the decay properties of excited states populated by radioactive decay of the parent nucleus. If the parent is sufficiently long-lived it can be chemically separated and several collective bands in ^{256}Fm, fed by the decay of a 7^- isomer, have been classified. For shorter-lived parent nuclei, electromagnetic in-flight separation is necessary. Although the cross-section for the population of the parent is smaller by one or two orders of magnitude than that of the daughter nucleus being investigated, there are two compensating factors: the measurements are made in the low background environment of the recoil separator and higher beam currents can be employed if direct radiation from the target is not detected. Recent experiments [26] using GREAT (RITU) and similar instrumentation in the focal plane of SHIP have observed the lowest three members of the rotational band in ^{249}Fm populated following the alpha decay of ^{253}No.

6. Future developments

The philosophy of spectroscopic measurements has been either to measure decay properties of nuclei in the focal plane, in which case the sensitivity of measurement is determined by the primary beam current and the recoil separator efficiency, or to measure in-beam properties directly, in which case the sensitivity is determined by the product of the recoil separator efficiency (ϵ_R), the gamma or electron array efficiency ($\epsilon_{\gamma,e}$) and the beam current. This is illustrated in figure 3, which shows how nuclei of increasing Z can be studied by in-beam or decay spectroscopy. The sensitivity of current state-of-the-art in-beam gamma-ray spectrometers such as JUROGAM and decay spectrometers such as GREAT, used in conjunction with recoil separators such as RITU, is such that in-beam or decay spectroscopy is possible for $Z = 104$ (Rf), populated directly with cross-sections of order 10 nb, or by alpha-decay with $\sigma \sim 10$–100 pb. In-beam studies of odd-mass nuclei and K-isomer bands in even–even nuclei await the construction of hybrid electron — gamma spectrometers for which the absolute efficiency for either radiation is 10% or better. The range of accessible nuclei can be extended by the use of radioactive targets, although the recoil efficiency for the asym-

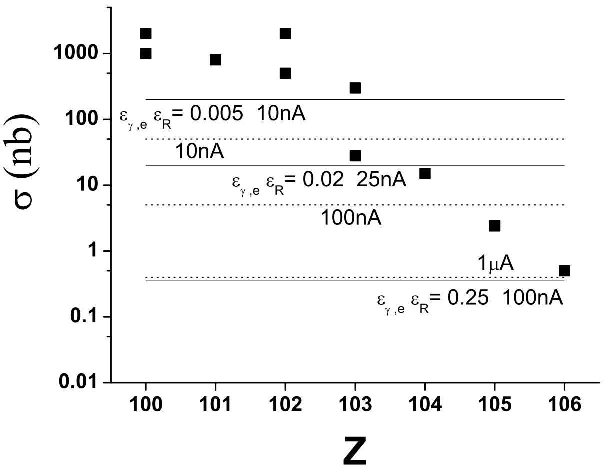

Fig. 3. Sensitivity of in-beam and decay spectroscopy experiments. Black squares are experimental cross sections for nuclei of interest. The solid line shows the limit of cross-section that can be studied in-beam; the dashed line the limit of cross-section of daughter nucleus populated by a-decay that can be studied. The three values of $\epsilon_R.\epsilon_{\gamma,e}$ for in-beam measurements (0.005, 0.02, 0.25) correspond to JUROSPHERE + RITU or GAMMASPHERE + FMA, JUROGAM + RITU and AGATA + RITU, respectively.

metric reactions will be smaller than for the cold fusion reactions employed at present. The use of radioactive beams will also extend the range of nuclei that can be studied, and sufficient beam intensities of neutron rich projectiles that neighbour ^{48}Ca such as ^{43}Ar, ^{46}K, and heavier beams such as ^{92}Kr, will be available from third generation radioactive beam facilities such as EURISOL and RIA.

This work was supported by the EU 5th framework programme ‘Improving Human Potential — Access to Research Infrastructure’ (HPRI-CT-1999-00044), 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. The author gratefully acknowledges the benefit of close collaboration in the work described here with a large number of colleagues and friends, including Rafał Broda, Bogdan Fornal, Paul Greenlees, Rodi Herzberg, Graham Jones, Rauno Julin, Teng-Lek Khoo, Matti Leino and Witek Nazarewicz.

REFERENCES

[1] J.D. Burrows *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A227**, 259 (1984).
[2] A.N. James *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A267**, 144 (1988).
[3] C.J. Lister *et al.*, *Phys. Rev. Lett.* **59**, 1270 (1987).
[4] M. Gorska *et al.*, *Phys. Rev. Lett.* **79**, 2415 (1997).
[5] R. Broda *et al.*, *Phys. Rev.* **C49**, R575 (1994).
[6] B. Fornal *et al.*, *Phys. Rev.* **C49**, 2413 (1994).
[7] R. Broda *et al.*, *Phys. Rev. Lett.* **74**, 868 (1995).
[8] P.A. Butler, W. Nazarewicz, *Rev. Mod. Phys.* **68**, 349 (1996).
[9] W. Nazarewicz *et al.*, *Nucl. Phys.* **A429**, 269(1984).
[10] I. Ahmad, P.A. Butler, *Annu. Rev. Part. Sci.* **43**, 71 (1993).
[11] J.F. Smith *et al.*, *Phys. Rev. Lett.* **75**, 1050 (1995).
[12] N. Schulz *et al.*, *Phys. Rev. Lett.* **63**, 2645 (1989).
[13] H.-J. Wollersheim *et al.*, *Nucl. Phys.* **A556**, 261 (1993).
[14] R.J. Poynter *et al.*, *Phys. Lett.* **B232**, 447 (1989).
[15] R.K. Sheline, *Phys. Lett.* **B197**, 500 (1987).
[16] W. Nazarewicz *et al.*, *Nucl. Phys.* **A467**, 437 (1987).
[17] J.F.C. Cocks *et al.*, *J. Phys. G* **26**, 23 (2000).
[18] J.F.C. Cocks *et al.*, *Phys. Rev. Lett.* **78**, 2920 (1997).
[19] J.F.C. Cocks *et al.*, *Nucl. Phys.* **A645**, 61 (1999).
[20] P.T. Greenlees *et al.*, *J. Phys. G* **24**, L63 (1998).
[21] P.A. Butler *et al.*, **A381**, 433 (1996).
[22] H. Kankaanpää *et al.*, *Nucl. Instrum. Methods Phys. Res.* **A**, in press.
[23] R.D. Humphreys *et al.*, *Phys. Rev.* **C69**, 064324 (2004).
[24] P. Reiter *et al.*, *Phys. Rev. Lett.* **82**, 509 (1999).
[25] M. Leino *et al.*, *Eur. Phys. J.* **A6**, 63 (1999).
[26] R.-D. Herzberg, *J. Phys. G* **30**, R123 (2004).
[27] S. Eeckhaudt, privte communication.
[28] P.A. Butler *et al.*, *Phys. Rev. Lett.* **89**, 202501 (2002).
[29] P.A. Butler *et al.*, *Acta Phys. Pol. B* **34**, 2107 (2003).
[30] R.D. Page *et al.*, *Nucl. Instrum. Methods Phys. Res.* **B204**, 634 (2003).
[31] I. Lazarus *et al.*, *IEEE Trans. Nucl. Sci.* **48**, 567 (2001).