STUDIES OF NEUTRON-RICH AND HEAVY NUCLEI WITH THE NEW IN-BEAM FACILITIES AT JYFL * **

R. JULIN[a], R.G ALLATT[b], P.A. BUTLER[b], K.J. CANN[b], J.F.C. COCKS[b], T. ENQVIST[a], P.T. GREENLEES[b], K. HELARIUTTA[a], G.D. JONES[a], P.M. JONES[a], S. JUUTINEN[a], P. JÄMSEN[a], H. KANKAANPÄÄ[a], P. KUUSINIEMI[a], M. LEINO[a], M. MUIKKU[a], R.D. PAGE[b], M. PIIPARINEN[a], A. SAVELIUS[a], W.H. TRZASKA[a], S. TÖRMÄNEN[a], J. UUSITALO[a]

[a]Department of Physics, University of Jyväskylä, P.O.Box 35, 40351 Jyväskylä, Finland
[b]Oliver Lodge Laboratory, Department of Physics, University of Liverpool, Liverpool, L69 3BX, UK

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In-beam γ-ray spectroscopic methods combined with binary reactions have been used for studies of intruder structures in the "neutron-rich" ^{114}Cd and ^{116}Cd nuclei. The recoil decay tagging method with a gas-filled recoil separator was used for the first observation of excited states in neutron-deficient ^{192}Po. A newly developed broad range electron spectrometer has been employed in a search for superdeformed structures in ^{222}Th.

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1. Introduction

The new K=130 Cyclotron + ECR facility of the Physics Department of the University of Jyväskylä (JYFL) provides stable beams from protons up to krypton ions for nuclear structure studies. Instruments and methods used especially in in-beam spectroscopic studies of neutron-rich nuclei near the β-stability line and heavy nuclei at JYFL are introduced in the following sections.

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2. Band structures in ^{114}Cd and ^{116}Cd from heavy ion collisions

The role of proton intruder as well as deformation driving neutron $h^2_{11/2}$ configurations in the low-lying states of even-mass Cd nuclei is not well understood. These excitations are expected to reach their lowest energy in mid-neutron shell nuclei. Due to the lack of available reactions, the extention of experimental studies to the midshell nucleus ^{114}Cd and further to the heavier Cd isotopes is difficult.

Efficient detection of $\gamma\gamma$ coincidences from quasielastic and deep inelastic heavy ion collisions offers an opportunity to study low- and moderately high-spin states in neutron-rich nuclei near the β-stability line [1]. In the present experiments a 30mg/cm^2 thick ^{116}Cd (97% enriched) target was bombarded with 370 MeV (13% above the Coulomb barrier) ^{84}Kr ions delivered by the Jyväskylä K=130 cyclotron. This target was thick enough to stop the binary reaction products. For the $\gamma\gamma$ coincidence detection the TESSA array with 12 Compton-suppressed Ge detectors was employed. The inner ball of 50 BGO elements of TESSA was also used for the γ-ray multiplicity and sum-energy recording. For obtaining information about transition multipolarities we were able to apply the γ-ray angular distribution method similar to the one used in connection with fusion-evaporation reactions.

A large number of reaction products were identified in the analysis of the $\gamma\gamma$ coincidence data. Population of yrast states up to $I \sim 10\ \hbar$ was observed in many nuclei. New yrast states in ^{114}Cd and ^{116}Cd as well as an intruder band on top of the second excited 0^+ state (0^+_3) in ^{116}Cd have been identified.

Based on the present results and other available data for the even-mass $^{106-122}$Cd isotopes the level-energy systematics for the yrast levels up to the 10^+ state and for the two lowest excited 0^+ states labeled like in Ref. [2] by 0^+_A and 0^+_B as well as for the intruder bands based on the 0^+_A states are shown in Fig. 1.

With the present results included a smooth behaviour of the yrast 10^+ states is observed. These states presumably are mainly of the neutron $h^2_{11/2}$ character minimising their excitation energy at N = 70 like the first excited 2^+_1 and 4^+_1 states. In accordance with the intruder picture involving 2p-4h proton excitations across the Z = 50 shell gap, the suggested intruder states in even Cd isotopes reach their minimum excitation energy in ^{114}Cd i.e. in the middle of the neutron shell. They form a V shaped pattern very similar to that observed for example for the 2p-1h intruder $g^{-1}_{9/2}$ bands in odd-mass Sb nuclei. Furthermore, in accordance with the (2p-4h) intruder picture, these bands in even-mass Cd nuclei have an energy pattern similar to that for the ground-state bands in the corresponding 6 valence proton Ru (0p-6h) and Ba (6p-0h) isotones.

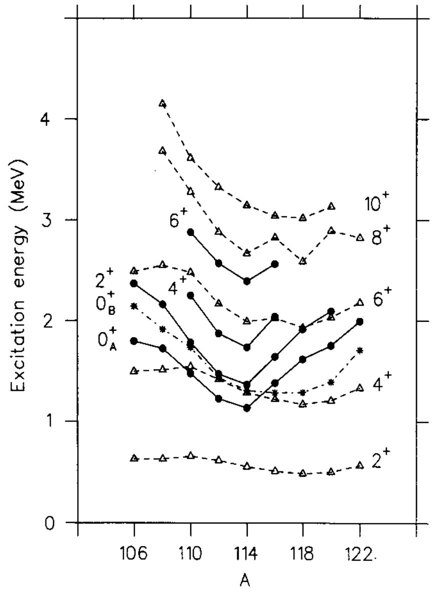

Fig. 1. Systematics of yrast levels (open triangles) and intruder bands (closed circles) in even-mass Cd nuclei. Energies of 0_B^+ states are also shown.

The role of mixing in even-mass Cd nuclei is still an intriquing question. Many of the peculiar electromagnetic properties of the low-spin states in midshell Cd isotopes have been well-reproduced by introducing a strong mixing of vibrational and intruder states [3]. However, the present and other experimental observations discussed in Ref. [2] rather indicate that the concepts of intruder and phonon states in even Cd nuclei represent different approaches, which may not fit into the same frame.

3. Recoil decay tagging measurements with RITU

The JYFL gas-filled (1 mbar of He) separator RITU (Recoil Ion Transport Unit) is a charge and velocity focusing device especially designed for separating recoiling heavy fusion evaporation products with high transmission [4]. Recoils are implanted into a 80 x 35 mm Si strip detector covering typically 70% of the recoil distribution at the focal plane. It is divided into 10 mm wide strips each of them having a position resolution of about 0.4 mm, resulting in a granularity needed in correlating the recoils with their subsequent alpha decays. During the last three years RITU has been used for discoveries of new neutron deficient At, Rn, Fr, Ra, Ac and Th isotopes and in studies of their α- decay properties.

The power of RITU in in-beam γ ray experiments utilizing the recoil decay tagging method [5][6] has been demonstrated in the studies of very neutron deficient ^{194}Po and ^{192}Po nuclei. These nuclei were produced in $^{170}Yb(^{28}Si,4n)$ and $^{160}Dy(^{36}Ar,4n)$ reactions with cross - sections of only about 500 μb and 10 μb, respectively. Prompt γ- rays from the target were detected by the DORIS array consisting of 9 TESSA type Compton suppressed Ge detectors in a truncated dodecahedron frame (eff. about 0.6% at 1.3 MeV).

Signals from the Si strip detector for the energy, position as well as the detection time of the recoils and α- particles were recorded. Singles γ- ray as well as $\gamma\gamma$ coincidence events from the DORIS array were recorded in coincidence with the detected recoils. In the analysis of the data, the events corresponding to the observation of a recoil and the subsequent α- decay at the same position within a proper maximum time interval were selected.

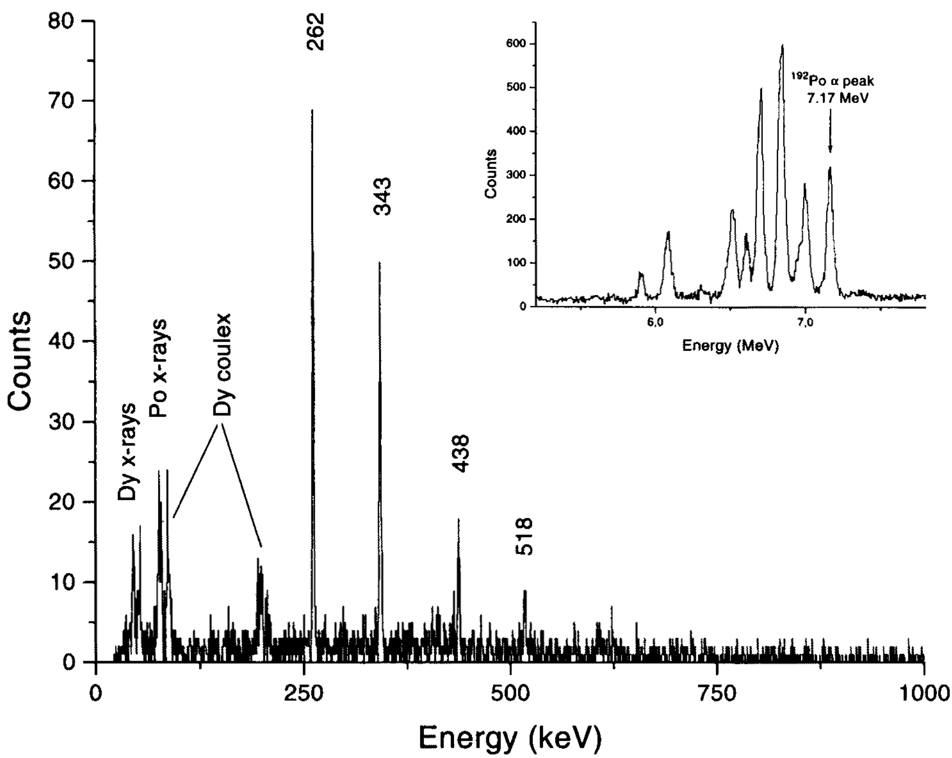

Fig. 2. A singles γ-ray spectrum gated with fusion-evaporation residues and tagged with α-particle events in the ^{192}Po α peak of the spectrum shown in the insert . In the insert, a spectrum of α particles is shown, observed within a 200 ms time interval after the detection of a recoil (in coincidence with prompt γ rays) at the same position in the Si strip detector.

For ^{194}Po, high-statistics α- tagged $\gamma\gamma$ coincidence data were collected. The resulting level scheme is in agreement with the one proposed by Younes et al. [7] except for a 2620 keV level which we identify with 12^+ instead of 11^- on the basis of our angular distribution information.

From the ^{192}Po experiment, a projected α- spectrum with the time interval of 200 ms and with a recoil-γ coincidence condition is shown in the insert of Fig. 2. The α peaks in this spectrum are identified on the basis of known α-decay energies. The half-life extracted from the projected time spectrum for the events in the ^{192}Po α peak falls into the error bars of the earlier value [8].

A gate on the ^{192}Po α peak yields a recoil gated γ- ray spectrum of Fig. 2 with new lines at 262, 343, 438 and 518 keV. Based on their intensities and the available level-energy systematics we tentatively identify those lines with an E2 cascade of the ground state band in ^{192}Po. This interpretation is also supported by the recoil gated α-tagged $\gamma\gamma$ coincidence spectra.

A level-energy systematics for the even-mass $^{192-210}$Po isotopes including our new data is shown in Fig. 3. A sudden drop of level energies when going from the heavier isotopes to ^{196}Po is observed. The new ^{192}Po results

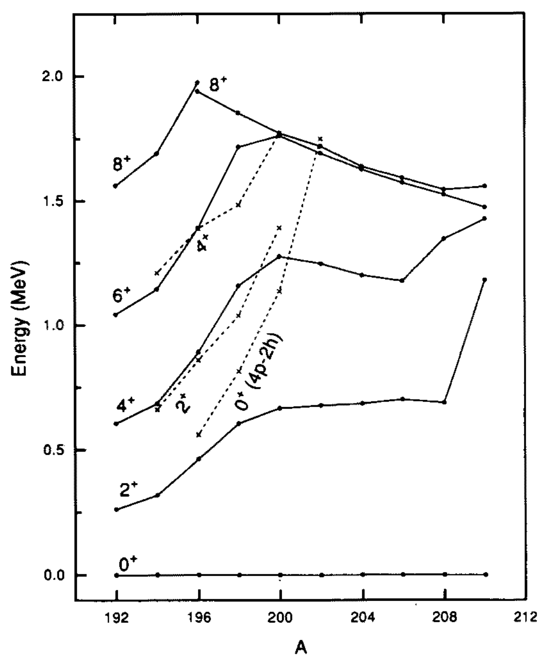

Fig. 3. Level systematics for the even-mass $^{192-210}$Po.

reveal signs of the flattening of the systematics when going towards the neutron midshell. A similar behaviour has been observed in even-mass Pt nuclei where it has been interpreted as evidence for a ground state intruder configuration [9]. That the observed band structure in ^{192}Po is indeed based on an intruding ground-state structure different from those for heavier Po isotopes is also indicated by simple mixing calculations [10]. It should be noted that based on the Nilsson-Strutinsky type of calculations, May et al. predicted that in ^{192}Po an oblate deformed minimum becomes the ground state [11].

Similarly as in the Pt nuclei [9], the relatively high rotational parameter associated with the 2_1^+ - 0_1^+ energy spacing in ^{192}Po can be explained by mixing of the 0_1^+ and 0_2^+ states with a consequent depression of the 0_1^+ ground state. This is also in agreement with the above mentioned mixing calculation results and the α- decay properties of ^{192}Po [12].

Especially on the basis of recent α- and β-decay studies by the Leuven group [10] the intruding structures in light Po isotopes are usually associated with proton 4p-2h excitations across the main shell gap. In spite of the remarkable agreement with this proton intruder picture the role of deformation driving neutron orbitals in the behaviour of yrast states of light Po nuclei cannot be ruled out. Younes et al. [13] have shown that the ^{192}Po level energies can be quite well reproduced without any proton-intruder configurations.

4. In-beam conversion electron spectroscopy using the SACRED array

A conversion-electron spectrometer consisting of an superconducting solenoid magnet and a Silicon Array for ConveRsion Electron Detection (SACRED) has been constructed [14] and installed at the dedicated beam-line of the JYFL accelerator laboratory.

SACRED consists of a Si PIN detector divided to 25 pixels of 5x5mm. Presently, the pixels are connected to operate as 17 separate detectors with separate preamplifiers. The SACRED array has been designed for detecting high-multiplicity electron events from highly converted electromagnetic transition cascades in heavy nuclei, especially for searching for superdeformed structures. As shown in the sketch of Fig. 4 the electrons emitted from the target are collected through the solenoid field and spread over the SACRED array sitting outside the magnetic field. Electron cascades are separated by requiring coincidences between the individual pixels. In first measurements performance of the spectrometer in e^--e^- coincidence measurements was demonstrated in the recoil-shadow mode of operation.

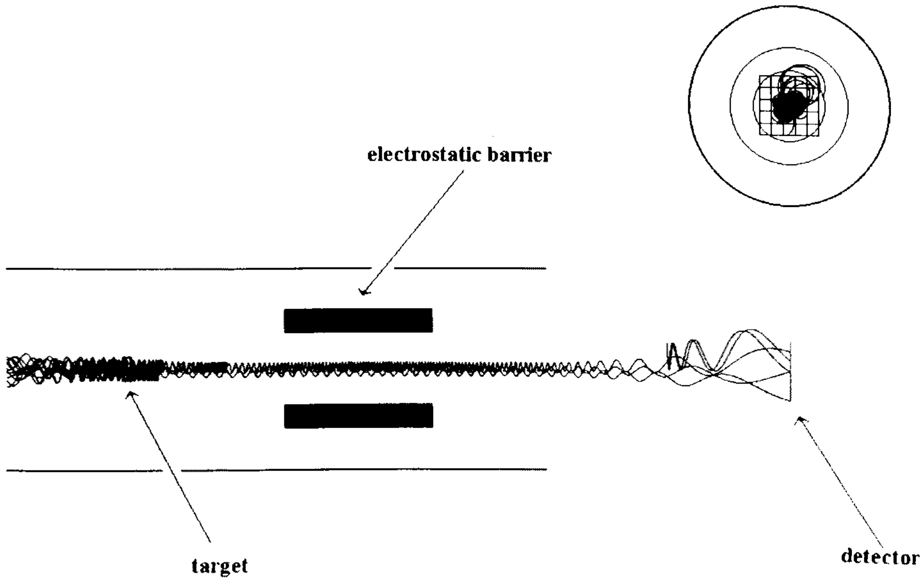

Fig. 4. A scheme of the solenoid and SACRED showing trajectories of electrons in the magnetic field of the solenoid and the electric field of the barrier.

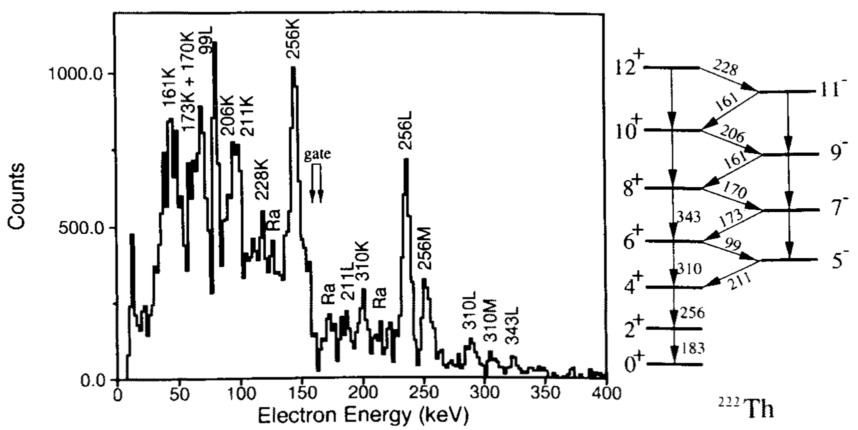

Fig. 5. Prompt electron spectrum in coincidence with the L conversion electrons of the ground-state 183 keV transition in ^{222}Th following the ^{208}Pb(^{18}O,4n) reaction.

A HV deflector (Fig. 4) acting as an electrostatic barrier up to 40 kV against low-energy electrons has been designed for the spectrometer. In this way, the most intense part of the disturbing low-energy delta electrons can be suppressed, rendering it possible, for the first time, to perform prompt in-beam broad range e^--e^- coincidence measurements.

Figure 5 shows a background-corrected electron spectrum in coincidence with the L conversion electrons of the ground-state 183 keV transition in ^{222}Th following the ^{208}Pb(^{18}O,4n) reaction at a bombarding energy of 95 MeV. The fraction of the total cross section for this channel is approximately 1%. A partial decay scheme is shown, which identifies those transitions which can clearly be observed in the spectrum.

A double-gated e^-–e^--e^- coincidence spectrum extracted from this coincidence data for ^{222}Th reveals a structure which we tentatively interpret as arising from a rotational-like E2 cascade with energies between 90 and 180 keV. While further measurements are necessary to confirm this identification, these measurements indicate that the SACRED spectrometer system is sensitive to the detection of weakly populated highly converted transitions, in this case approximately 10^{-4} of the total nuclear cross section.

REFERENCES

[1] R. Broda *et al.*, *Phys. Lett.* **B251**, 245 (1990).
[2] J. Kumpulainen *et al.*, *Phys. Rev.* **C45**, 640 (1992).
[3] K. Heyde *et al.*, *Nucl. Phys.* **A586**, 1 (1995).
[4] M. Leino *et al.*, *Nucl. Instr. Meth.* **B99**, 656 (1995).
[5] R.S. Simon *et al.*, *Z. Phys.* **A325**, 197 (1986).
[6] E.S. Paul *et al.*, *Phys. Rev.* **C51**, 78 (1995).
[7] W. Younes *et al.*, *Phys. Rev.* **C52**, R1723 (1995).
[8] M.E. Leino, S. Yashita and A. Ghiorso, *Phys. Rev.* **C24**, 2370 (1981).
[9] J.L. Wood, K. Heyde, W. Nazarewicz, M. Huyse and P. Van Duppen, *Phys. Rep.* **215**, 101 (1992).
[10] N. Bijnens *et al.*, *Phys. Rev. Lett.* **75**, 4571 (1995).
[11] F.R. May, V.V. Pashkevich and S. Frauendorf, *Phys. Lett.* **68B**, 113 (1977).
[12] N. Bijnens *et al.*, to be published.
[13] W. Younes *et al.*, Proceedings of the Conference on Nuclear Structure at the Limits, Argonne, 1996, to be published.
[14] P.A. Butler *et al.*, *Nucl. Instr. Meth.* in press.