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IDENTIFICATION AND STRUCTURE OF p-RICH RARE-EARTH NUCLEI INVESTIGATED USING A He-JET FED ON-LINE MASS-SEPARATOR

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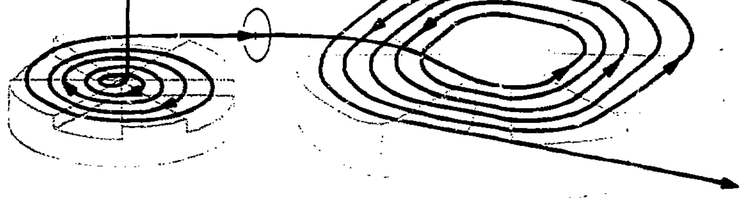

IDENTIFICATION AND STRUCTURE OF p-RICH RARE-EARTH NUCLEI INVESTIGATED USING A HE-JET FED ON-LINE MASS-SEPARATOR

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ABSTRACT

Activities produced via fusion-evaporation reactions with ^{32}S, ^{35}Cl and ^{36}Ar beams in thin ^{112}Sn and ^{106}Cd targets have been transported using a He-jet coupled to a mass separator. Gamma-ray and X-ray techniques have been used to study the excited levels of ^{138,136}Sm and ^{134,132}Nd fed in the β-decay of ^{138}Eu(12 s), ^{136}Eu(3.7 s), ^{134}Pm (21 s) and ^{132}Pm (5 s). Results are presented through systematics and discussed in the framework of recent self-consistent calculations including the γ degree of freedom.

INTRODUCTION

The region of p-rich rare-earth nuclei has been, since a couple of years very actively investigated by many experimental groups and theoreticians as well. The interest in these studies was mainly due to the occurence of strongly deformed isotopes on both sides of doubly magic $^{146}_{64}$Gd$_{82}$ nucleus. Axial macroscopic-microscopic calculations by Leander and Möller[1] have predicted large deformation near the proton drip-line and Ragnarsson et al.[2] have shown that the γ-degree of freedom could give major effects around N=76. More recently self-consistent calculations[3] of triaxial deformations have shown that some N=76 isotones exhibit a stable triaxial shape.

A lot of experimental work has been devoted to the 132 ≤ A ≤ 138 mass region both from β-decays[4,5,6] or in-beam spectroscopy[7,8] giving new information on the high spin state structure of these neutron deficient isotopes. Fusion-evaporation reactions using both n-deficient target and projectile are still a powerfull way to produce p-rich nuclei with substantial yields and forward peaking kinematics. They were used in this work in connection with ISOL techniques in order to extend the systematics of nuclear properties as far as possible from the stability valley.

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2. EXPERIMENTAL

2.1 SARA and ISOL facilities

The present work has been possible thanks to the development of an ECR ion source on the SARA accelerator at Grenoble and simultaneous construction of a He-jet fed on-line mass-separator. The principle of the connection has been described in details and performances of the system already reported[9]. The experiments described below were carried out with low energy (5-6 MeV/u), high intensity (> 3.10^{11} particles/s) beams accelerated by the first K=90 cyclotron of the SARA facility. The low consumption of the ECR ion source allowed to use enriched gas such as ^{36}Ar as projectile.

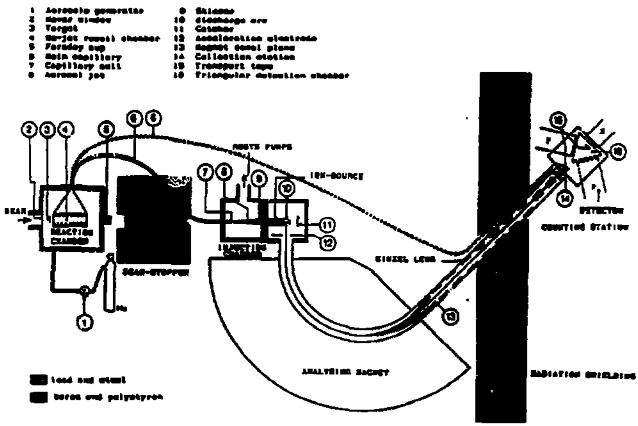


Figure 1 : Draft of the He-jet + separator coupling facility.

2.2 Layout of the separator and principle of operation

A schematic plan view of the He-jet fed on-line separator is given in figure 1. This naive representation shows how the system can be used either with the He-jet alone or with the coupled system. In the former mode of operation γ-γ , X-γ ray coincidence measurements and γ-ray multianalysis spectra for decay half-life determination are carried out. From the K_α X-ray gated γ spectra the Z identification of the daughter nucleus is obtained allowing an unambiguous identification when associated with spectra recorded after mass separation in the later mode of operation.

The radioactive products recoil from the target with mean energy corresponding to full linear momentum transfer in the fusion-evaporation process and are then thermalized in the 1-2 bars He pressurized sheet-type recoil chamber placed in the middle of the reaction chamber. He gas is fed through a temperature controled oven (400°C) in order to give optimum transfer yield with $PbCl_2$ aerosols.

A high flow pumping system composed of three roots (8000 m^3/h - 3000 m^3/h - 350 m^3/h) and a primary pump (120 m^3/h) is used to skim off the He from the injection chamber where the pressure may be maintained in the range 10^{-1} - 10^{-2} torr depending on the conductance of the main capillary.

The ion-source is a modified version[9] of the Bernas-Nier type medium current source also successfully applied by Schmeing et al.[10] who developped a high temperature version. It is worth to mention two advantages of the method when compared to more conventional systems :

i) the delay time is mainly due to the mean transit time in the capillary (100 ms is our lower limit) and

ii) the target is located far away from the hot environment of the source so that it was possible to use low melting point element targets such as Tin or Cadmium.

The measured coupling efficiencies (skimmer + source + magnet + lens transport) are in the range 1-2 % and allowed us to get a number of original results on the p-rich rare-earth isotopes near N=82.

3. RESULTS

3.1 General

Figure 2 gives the new isotopes studied in this work. Most of experiments have been carried out using 191 MeV ^{35}Cl, 170 MeV ^{32}S and 234 MeV ^{36}Ar beams on 1-3 mg/cm^2 self-supporting enriched ^{112}Sn and ^{106}Cd targets.

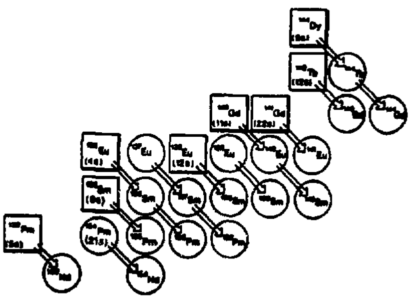


Figure 2 : Part of the nuclear chart related to the mass region investigated. Near N=82 β-decays investigated experimentally are denoted by arrows. New isotopes are indicated by solid squares.

The largest productions were generally associated with (2p,n), (2p), (2p,2n) reaction channels but rather important yields were also observed with (3p,xn) channels in good agreement with ALICE code predictions[11].

Half-lives, gamma-ray energies and intensities have been measured in the various β-decays and the decay scheme constructed on the basis of γ-γ coincidences. When possible, the direct feeding of the ground state has been estimated and thus log ft values calculated in order to get spin-parity assignments.

3.2 ^{138}Eu → ^{138}Sm

Among the data obtained in the light rare-earth region a very interesting case is that of ^{138}Sm fed by the β-decay of ^{138}Eu ($T_{1/2}$=12 s) produced via the ^{106}Cd + ^{35}Cl reaction. In figure 6 are represented two γ spectra showing the same energy range, one after mass separation and the second in coincidence with K_α X-rays of Sm.

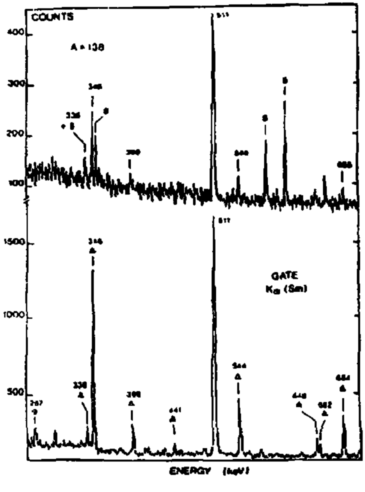


Figure 3 : Identification of 12 s ^{138}Eu. γ-rays found in coincidence with Sm-K_α gate (lower spectrum) are also observed in the mass-separated spectrum (upper part) at A=138.

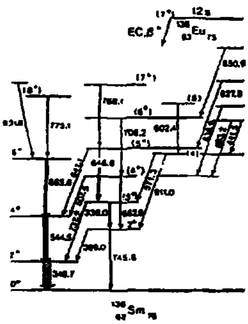


Figure 4 : Decay scheme of 12s ^{138}Eu.

From γ-γ coincidence data we have constructed the level scheme represented in **figure** 4. Both ground-state and quasi-gamma bands are populated up to the (8^+) and (7^+) levels respectively giving (7^+) as probable parent state of ^{138}Eu. The assignment of $2'^+$ below the first 4^+ state will be discussed in details later.

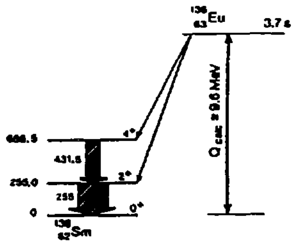


Figure 5 : Partial decay scheme of 3.7 s ^{136}Eu → ^{136}Sm.

3.3 ^{136}Eu → ^{136}Sm

A 234 MeV ^{36}Ar beam has been used to bombard a ^{106}Cd target and by means of the set-up described previously a new activity with a half-life of (3.7 ± 0.5)s was found and unambiguously assigned to ^{136}Eu → ^{136}Sm decay. A partial decay scheme is shown in **figure 5** and it is corroborated by in beam experiments on ^{136}Sm[7,12].

3.4 ^{134}Pm → ^{134}Nd and ^{132}Pm → ^{132}Nd

Using the same reaction ^{36}Ar + ^{106}Cd as in previous section it was possible to identify the (5 ± 1)s ^{132}Pm from the decay curves of the 213.0 keV and 398.5 keV γ-rays and the (21 ± 1)s ^{134}Pm from the 294.4, 494.8 and 631.3 keV γ-rays as shown in **figures 6** and **7**.

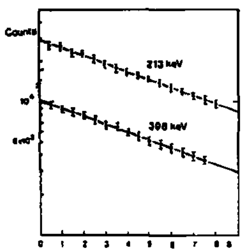


Figure 6 : Decay curves of the two γ-rays ascribed to (5 ± 1)s ^{132}Pm.

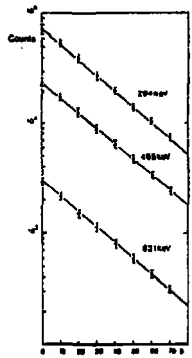
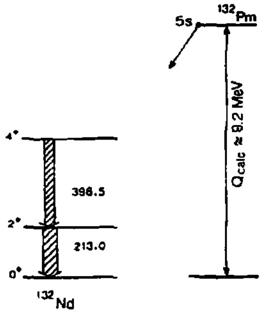


Figure 7 : Decay curves of the main γ-lines associated to the (21 ± 1)s ^{134}Pm.

From the data obtained in this experiment it has been possible to construct a partial level scheme of ^{132}Nd and ^{134}Nd shown in **figures 8** and 9 respectively. It is worth mentionning the good agreement of these results with a very recent note by M. Kortelahti et al.[13].



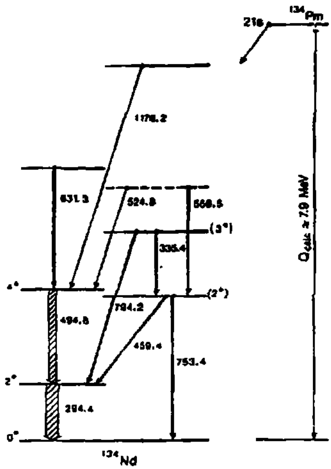


Figure 8 : Preliminary decay scheme of 5s ^{132}Pm.

Figure 9 : Partial decay scheme of 21s ^{134}Pm.

ANALYSIS OF THE RESULTS

Macroscopic-microscopic calculations have predicted from N=72,70 in Sm, Nd isotopes the emergence of a large axial prolate deformation [1] with $\varepsilon_2 > 0.28$. Experimentally, if we consider the systematics of first excited level 2^+ energies of even-even nuclei in this region (**figure 10**), we recognize the energy gap characteristic of shell closure for N=82 indicating a spherical shape. On the side N < 82, the energy of the first excited 2^+ state goes down smoothly exhibiting the onset of a deformation. The energy ratio $E(4+)/E(2+)$ of the first two excited g.s. band states of proton-rich nuclei (**table 1**) shows, near N=76, a possible γ-unstability of these nuclei with a value 2.5 whereas for the more neutron-deficient isotopes, this ratio reaches values close to 3.33 consistent with a pure axially-symmetric rotor.

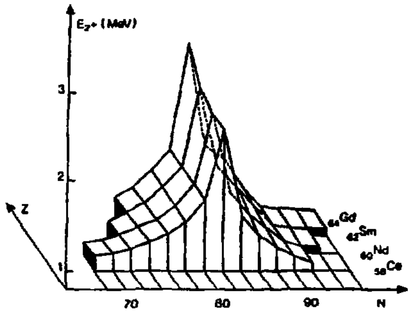


Figure 10 : Systematics of first excited level 2^+ energies of e-e nuclei around N=82 for $58 \leqslant Z \leqslant 64$.

			^{138}Gd 2.74	^{140}Gd 2.54	^{142}Gd 2.40	^{144}Gd 2.34	Z = 64
		^{134}Sm 2.94	^{136}Sm 2.69	^{138}Sm 2.57	^{140}Sm 2.35	^{142}Sm 2.33	Z = 62
^{128}Nd 3.18	^{130}Nd 3.06	^{132}Nd 2.86	^{134}Nd 2.68	^{136}Nd 2.62	^{138}Nd 2.40	^{140}Nd 2.33	Z = 60
^{126}Ce 3.06	^{128}Ce 2.93	^{130}Ce 2.80	^{132}Ce 2.64	^{134}Ce 2.56	^{136}Ce 2.38	^{138}Ce 2.33	Z = 58
N = 68	N = 70	N = 72	N = 74	N = 76	N = 78	N = 80	

Table 1 : Ratio of E_{4^+}/E_{2^+} energies in Gd, Sm, Nd, Ce isotopes.

In the case of Nd and Sm isotopes (figure 11), the level spacing of the ground state band is decreasing both side of N=82 but these two regions differ in the behavior of the second 2^+ level : on the neutron rich nuclei side, this state remains markedly above the first 4^+ level characteristic of a pure axially deformation whereas, on the proton rich side, it lies under the 4^+ level (^{138,140}Sm, ^{134,136,138,140}Nd) and the existence in ^{138}Sm, ^{134,136,138}Nd of an additionnal sequence of 3^+, 4^+, 5^+, ... levels based on this 2^+ state is characteristic of triaxial deformation with γ closed to 30° in the simple picture of a pure triaxial rotor[14]. Asymmetric equilibrium solutions have been already suggested in this region by macroscopic-microscopic calculations of ref. 2.

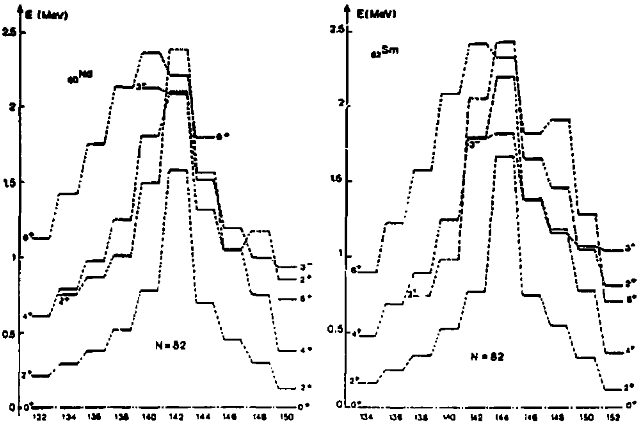


Figure 11 : Evolution of the first excited states in the even-even isotopes of Nd and Sm with $72 \leqslant N \leqslant 90$.

In order to take into account in microscopic theories possible triaxial deformations, lattice Hartree-Fock + BCS calculations for axially asymmetrical solutions[15] have been performed nowadays for the Sm e-e isotopes[3,16,17]. They have predicted the emergence of a strong axial deformation with prolate shapes for ^{134,132}Sm via triaxial shapes for ^{136,138,140}Sm, the ^{142}Sm remaining spherical as the ^{144}Sm semi-magic nucleus. For instance in agreement with our experimental data, the potential energy surface of ^{138}Sm obtained by these microscopic calculations presents an absolute minimum at $Q_0 \sim 8$b and $\gamma \sim 25°$ located ~ 0.6 MeV below two axial local minima almost degenerated in energy. The existence of such stable triaxial shapes has been also predicted for the intrinsic states in neighboring N=76 isotones of Gd and Nd and interpreted in terms of neutron shell-effects.

The He-jet coupled system used after (HI,xn) reactions has proved to be an efficient tool for the study of heavy exotic nuclei. In-beam studies of odd isotopes are highly desirable to confirm these structure effects. Therefore complementary experiments have been initiated with the "Château de Cristal", the analysis of which are underway.

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