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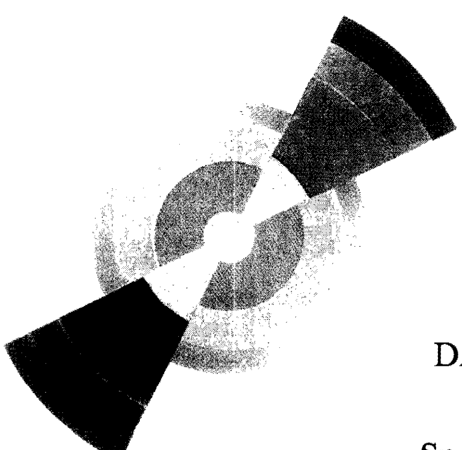

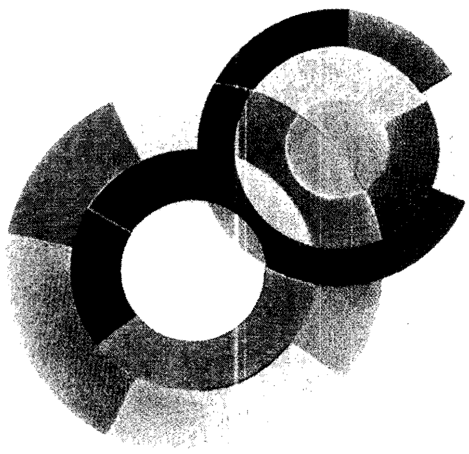

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Spectroscopy of the odd transfermium ^{251}Md and ^{255}Lr nuclei γ using, electron and α spectroscopy

A. Chatillon, C. Theisen, E. Bouchez, E. Clément,
J.L. Charvet, R. Dayras, A.Drouart, A. Görgen,
A. Hürstel, W. Korten, Y. Le Coz, C. Simenel, J. Wilson
et al

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Département d'**A**strophysique, de Physique des **P**articules, de Physique **N**ucléaire et de l'**I**nstrumentation **A**ssociée

DSM/DAPNIA, CEA/Saclay F - 91191 Gif-sur-Yvette Cédex
Tél : (1) 69 08 24 02 Fax : (1) 69 08 99 89
http : //www-dapnia.cea.fr

Couverture : Sylvie Cabrit et Marc Sauvage

SPECTROSCOPY OF THE ODD TRANSFERMIUM ^{251}MD AND ^{255}LR NUCLEI USING γ, ELECTRON AND α SPECTROSCOPY

A. CHATILLON, CH. THEISEN, E. BOUCHEZ, E. CLÉMENT, R. DAYRAS, A. DROUART, A. GÖRGEN, A. HÜRSTEL, W. KORTEN, Y. LE COZ, C. SIMENEL, J. WILSON
CEA Saclay, DSM/DAPNIA/SPhN, F-91191 Gif/Yvette Cedex

S. EECKHAUDT, T. GRAHN, P.T. GREENLEES, P. JONES, R. JULIN, S. JUUTINEN, H. KETTUNEN, M. LEINO, A-P. LEPPÄNEN, V. MAANSELKÄ, P. NIEMINEN, J. PAKARINEN, J. PERKOWSKI, P. RAHKILA, J. SARE'N, C. SCHOLEY, J. UUSITALO, K. VAN DE VEL
University of Jyväskylä, Department of Physics, P.O. Box 35, FIN-40014

G. AUGER, B. BOURIQUET J.M. CASANDJIAN, R. CEE, G. DE FRANCE, R. DE TOURREIL, M.G. ST LAURENT, CH. STODEL, A. VILLARI, M. REJMUND
GANIL, Boulevard Henri Becquerel, B.P. 55027, F-14074 Caen Cedex 5

N. AMZAL, J.E. BASTIN, P.A. BUTLER, R-D. HERZBERG, P.J.C. IKIN, G.D. JONES, A. PRITCHARD
Department of Physics, Oliver Lodge Laboratory, Oxford Street, Liverpool L69 7ZE, UK

S. GRÉVY
LPC, 6 boulevard du Marchal Juin, F-14050 CAEN Cedex

K. HAUSCHILD, A. KORICHI. A. LOPEZ-MARTENS
CSNSM, Bat. 104-108, F-91405 Orsay

F.P. HESSBERGER
GSI, Planckstraße 1 , D-64291 Darmstadt

S.M. LUKYANOV, YU. E. PENIONZHKEVICH, YU. G. SOBOLEV
JINR Dubna, 141980, Moscow Region, Russia

O. DORVAUX, B. GALL, F. KHALFALLAH, M. ROUSSEAU
IReS, 23 rue du Loess, BP28, F-67037 Strasbourg

A rotational band has been observed in ^{251}Md using RITU and the γ-ray spectrometer Jurogam at the University of Jyväskylä. Interpreted as having a $1/2^-$ configuration, this is the first firmly established rotational band in an odd-Z transfermium nucleus. In order to disentangle the single-particle structure, the α decay of ^{255}Lr has been studied both at Jyväskylä and at GANIL. From the preliminary analysis, we have observed for the first time the α decay fine structure of ^{251}Md and two excited states in ^{247}Es. Four α lines from the ^{255}Lr decay have been observed, originating from two initial states, which establishes the ordering of the levels.

1. Introduction

Very heavy and super-heavy elements (SHE) above Z=100 are very fragile objects: due to the strong Coulomb repulsion, they are stabilized only by shell effects. Thus, SHE elements are ideal laboratories for the study of nuclear structure under extreme conditions. The quest to study SHE elements has been a major and fascinating topic since decades and has been largely discussed during this conference. Some of the main questions addressed in the study of SHE elements are:

- The limit of stability of the nuclear chart. The SHE island of stability was predicted many years ago. However, the location of this island is still subject to debate and theoretical models still diverge concerning the associated magic numbers.
- Reaction mechanisms are still not fully understood and cross-sections cannot be predicted accurately.
- The placement of SHE in the Mendeleyev table is a key question of chemistry, which can also be used to identify new decay chains.

Since fusion-evaporation cross sections to produce the heaviest elements are very small (in the pb range), the access to spectroscopic information is limited and only quantities such as Q_α and $T_{1/2}$ are accessible with present-day techniques. Transfermium elements with $100 < Z \leq 104$ are produced with much higher cross-sections, in the μb range, and detailed nuclear spectroscopy can be performed. Masses, collectivity and fission barriers are important questions related to single-particle properties.

Recently, due to the advance of experimental techniques, impressive new results have been obtained at Jyväskylä and Argonne using prompt γ and electron spectroscopy in even-even isotopes ^{250}Fm and ^{252,254}No [1, 2]. The deformation has been deduced and compared to theoretical predictions. However, due to pairing correlations and strong mixing around the Fermi level, little insight into the single-particle structure can be gained from the study of even-even nuclei. More can be learned in this respect from the study of odd-mass nuclei. First results from prompt γ and electron spectroscopy performed in the odd-N ^{253}No [3] and odd-Z ^{255}Lr [2] nuclei are still puzzling. Few excited states have been observed in odd isotopes using α decay spectroscopy, but spin and parity, in particular for the ground state, have not yet been firmly established.

We have chosen to concentrate on ^{251}Md for the following reasons:

- Important insights into the single-particle structure can be expected from prompt γ-ray spectroscopy of ^{251}Md, as will be explained in the next section.
- ^{251}Md is virtually a blank spot on the nuclear chart: it was first synthesized in 1971 at Berkeley [4]; an α decay experiment of the mother ^{255}Lr was performed in 1976 [5], but no relevant information could be deduced. Therefore, almost nothing is known in ^{251}Md.
- ^{251}Md is relatively easy to produce using the cold fusion reaction ^{205}Tl(^{48}Ca,2n)^{251}Md, or after α decay of ^{255}Lr using the ^{209}Bi(^{48}Ca,2n)^{255}Lr reaction.

Two complementary techniques have been used: prompt spectroscopy in order to deduce collective properties, and spectroscopy after α decay to disentangle the single-particle structure.

2. Theoretical predictions and status

The single particle structure of ^{251}Md has been predicted using WS [6], HFB with Skyrme [7] or Gogny [8] interactions and RMF [9] models. WS and HFB+Skyrme models predict a $1/2^-$ ground state and $7/2^-$ and $7/2^+$ low lying excited states, while HFB+Gogny calculations predict an almost degenerate $1/2^-$ or $7/2^-$ ground state. The $1/2^-$ orbital is of particular importance since it is a down-sloping orbital from the $2f_{5/2}$ shell lying just above the Z=114 spherical gap. The presence of neighbouring $1/2^-$, $7/2^-$ and $7/2^+$ states implies M3 and E3 transitions which should be isomeric. Evaluated data [10] suggest a $1/2^-$ ground state and the presence of 2 excited states at around 100 keV, but there is no real experimental basis for this scenario.

In odd nuclei, rotational bands are split into two E2 branches connected by M1 transitions that are highly converted. The ratio of M1 and E2 transitions is a function of the gyromagnetic g_k factor, which is extremely sensitive to the wave function. Very different decay patterns are therefore expected for different configurations. For the $7/2^-$ configuration, mainly E2 decays are expected, proceeding via γ decay, while for the $7/2^+$ configuration the connecting transitions with M1 character are expected to be much stronger than the in-band E2 transitions, so that the decay proceeds predominantly via internal conversion. In the case of the $K=1/2^-$ band, signature splitting occurs and the decoupling parameter a is the relevant quantity. E2 decay from the favored $\alpha = +1/2$ partner band is expected in this case. In the ideal experimental case, combined γ and electron spectroscopy should be performed. However, these three different patterns can also be disentangled using γ spectroscopy alone. A systematic investigation of the electromagnetic properties of predicted rotational bands in the transfermium region shows that ^{251}Md is one of the most interesting nuclei for prompt γ-ray spectroscopy, as a clear distinction of single-particle structure can be expected.

3. Prompt spectroscopy

Experiments were performed at the University of Jyväskylä using the RITU gas-filled separator [11]. Recoils and their subsequent α decay were detected using the GREAT focal plane setup [12]. In the first experiment, the excitation function of the reaction ^{205}Tl(^{48}Ca,2n)^{251}Md was measured in November 2002. The ^{48}Ca beam was delivered at an energy of 221 MeV; Ni degraders were used to vary the incident energy. A 400μg/cm^2 ^{205}Tl target deposited on a 20 μg/cm^2 C backing prepared at LMU Munich was used. An optimum bombarding energy of 215$\pm$2 MeV at the middle of the target was found. Assuming a transmission of 30% for the RITU separator, the cross section corresponds to around 1μb. The excitation function is correctly reproduced by HIVAP calculations.

In June 2003, prompt γ spectroscopy was performed using the Jurogam array consisting of 43 Compton-suppressed Ge detectors coupled to RITU. A ^{48}Ca beam of 218 MeV energy and with an average intensity of 8pnA impinged on a ^{205}Tl target. Using the Recoil Tagging technique, the spectrum shown in figure 1 was obtained after a two week experiment. Among many peaks present in the spectrum, a rotational band emerges clearly. Note also the presence of intense Md X-rays corresponding to hidden highly converted transitions. A $7/2^+$ band head is excluded since corresponding E2 transitions should be marginal. A $7/2^-$ band head should lead to two partner bands which are not seen using γ-γ coincidences. The structure is therefore only compatible with a $1/2^-$ band head having a large signature splitting. We have in addition used a version of the Harris spin assignment procedure described in [13]. The Harris procedure parametrizes the dynamic moment of inertia $J^{(2)}$ as a function of the rotational frequency ω: $J^{(2)} = J_0 + 3J_1\omega^2 + 5J_2\omega^4$, with $E_\gamma = \hbar\omega/2$. The spins are then obtained using $I(\omega) - a = J_0\omega + J_1\omega^3 + J_2\omega^5 + \frac{1}{2}$. The procedure rules out a 7/2 band head. In order to reproduce the half integer spins, the decoupling parameter of a 1/2 band must be around $a \simeq 1$.

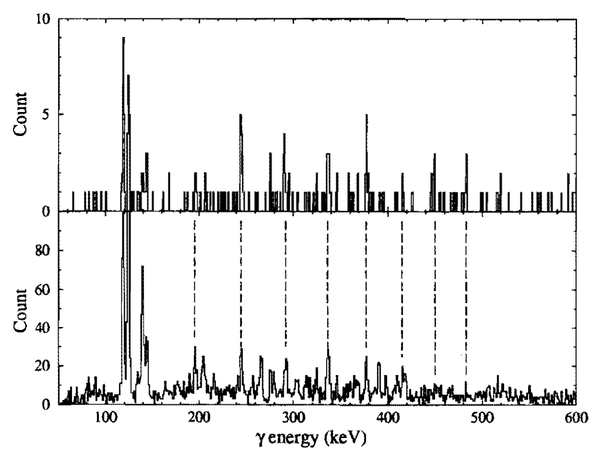

Figure 1. Bottom: Rotational band of ^{251}Md obtained using γ spectroscopy. The top spectrum shows the results of gates set on the main rotational bands using γ-γ coincidences.

Experimental and theoretical [7] dynamic moments of inertia $J^{(2)}$ are compared in figure 2. Experimental values are consistently ~10 units higher compared to the theoretical ones, but the ordering is correctly reproduced. It is interesting to note the striking similarity between the N=152 isotones ^{250}Fm, ^{251}Md and ^{252}No.

4. Spectroscopy after α decay of ^{255}Lr

In the previous section, the collective properties of ^{251}Md were presented, giving evidence for a $1/2^-$ band head configuration. However, no information related to the position of this orbital could be deduced using γ-ray spectroscopy alone.

Spectroscopy after α decay, taking advantage of the fine structure decay, is an appropriate tool for deducing single particle properties. Descendants

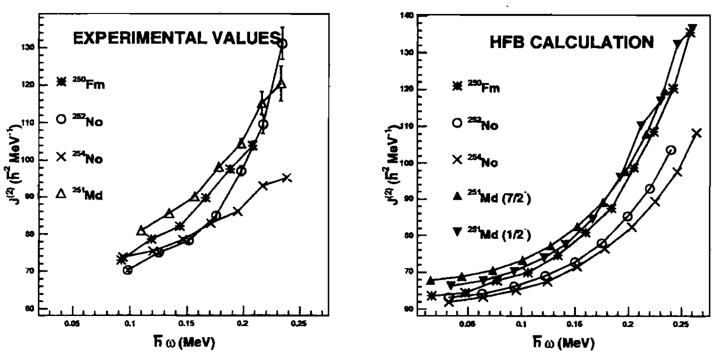

Figure 2. Dynamic moment of inertia for transfermium nuclei. Experimental values are shown on the left and are compared to theoretical values on the right.

of ^{255}Lr can be measured in a single experiment: ^{251}Md and the α daughter ^{247}Es, but also ^{255}No and the daughter ^{251}Fm produced after electron capture.

Two experiments using the reaction ^{209}Bi(^{48}Ca,2n)^{255}Lr were performed: the first one at the University of Jyväskylä using RITU and GREAT, and the second one at Ganil, France. This second experiment will be described in more detail in this section.

The experiment was performed in December 2003. A $^{48}Ca^{8+}$ beam with an average intensity of 1eμA was used at an energy of 219.4 MeV, chosen at the maximum of the excitation function previously measured [14]. Targets were mounted on a rotating wheel installed before the Wien filter of the LISE spectrometer [15]. Eighteen ^{209}Bi targets prepared at Ganil (450 μg/cm^2 on a 30 μg/cm^2 C backing) were installed on the wheel, rotating at 1500 rpm. 35 μg/cm^2 C stripper foils were installed behind the targets on a second wheel. The beam was synchronized with the wheel rotation; γ radiations around the targets were continuously measured using a BaF2 detector, and the wheel position was correlated with events detected at the focal plane, thus monitoring the target quality. Beam was separated from fusion-evaporation and transfer products in the Wien filter and stopped in a water-cooled Cu shield. A beam rejection of $\simeq 2.10^{10}$ was reached.

A position sensitive "galotte" detector (emissive foil and micro channel plate detector) was installed after the Wien filter for a time-of-flight measurement. The new BEST array (Box for Electron Spectroscopy after Tagging) was used at the focal plane to detect recoils, alphas and electrons. It consists of a 48x48 double sided Si strip detector (300 μm thick) for recoils and α measurements and a tunnel of 4 four-fold segmented Si detectors

(1mm thick) for electrons and escaped α particles. All Si detectors were cooled to -20°. An energy resolution of 7-10 keV was obtained for electrons below 500 keV in the tunnel detector. The compact Si box was surrounded by 4 segmented Ge clover detectors from the Exogam collaboration.

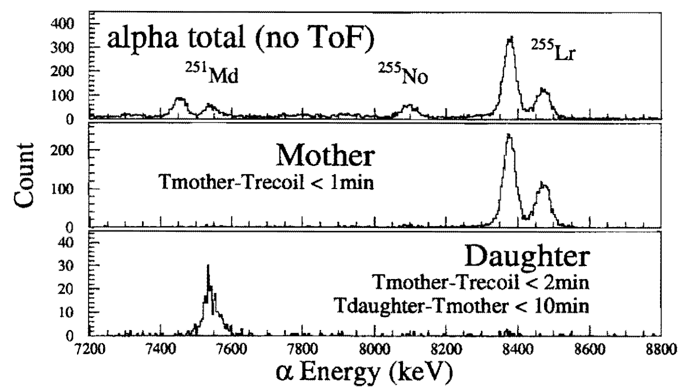

Figure 3. Top: Spectrum of the total Si strip detector in anti-coincidence with the time-of-flight or tunnel detector. Middle: mother recoil-alpha gated spectrum. Bottom: daughter recoil-alpha-alpha gated spectrum.

Examples of α spectra are shown in figure 3. In the total α spectrum, the decay from ^{255}Lr, its α daughter ^{251}Md and ^{255}No produced after electron capture are clearly seen. Using genetic correlations, the α decay from the mother and daughter can be separated very cleanly (the α decay branch of ^{251}Md corresponds to $\simeq$ 6 %). In addition to the known α line of 7544 keV, a new line at 7596 keV from the ^{251}Md decay is observed. From ^{255}Lr, four α lines are observed. These lines can be divided in two groups having a lifetimes of $\sim$30 s (8310 and 8375 keV) and $\sim$2.5 s (8441 and 8471 keV), corresponding to two distinct initial states. The decay curve of group 1 is characteristic of a two step process, the first step having a lifetime of $\simeq$ 2.5 s. Therefore, the initial state of group 1 (ground state) is fed by the initial state of group 2.

The α-γ correlations show that the 7544 and 7596 keV lines from ^{251}Md are in coincidence with a 290 and a 235 keV γ line respectively (the sum of γ and α energies are equal within uncertainties). We have therefore observed for the first time two new excited states in ^{247}Es. Since no electron lines are observed in coincidence with the ^{251}Md decay, these two γ transitions have likely E1 or E2 character.

Electron-α correlations do not reveal any electron line in coincidence with the ^{255}Lr or the ^{251}Md α decay. Since four α lines from the ^{255}Lr decay are observed, excited states in ^{251}Md should be populated. Corresponding transitions in ^{251}Md are either below the detection threshold, or isomeric in agreement with the prediction of close $1/2^-$, $7/2^+$ and $7/2^-$ states. Further analysis of isomeric transitions in ^{251}Md and ^{255}Lr is in progress and should allow us to propose level schemes. We have also observed very clean γ and electron lines in coincidence with the ^{255}No decay.

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