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Proposal to the Isolde and Neutron Time-of-Flight Committee

Studies of electric dipole moments in the octupole collective regions of heavy Radiums and Bariums

Addendum

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Abstract

It is proposed to study the electric dipole and quadrupole moments in the region of octupole collective Ba-Ce nuclei by means of Advanced Time-Delayed (ATD) $\beta\gamma\gamma$(t) method with a primary goal to provide information on the structure of the exotic nuclei of ^{147,148,149,150}Ba and ^{149}La. These results, obtained from β spectroscopy, would complement the new data obtained for the less exotic members of the A=147 and A=149 mass chains obtained at the OSIRIS fission product mass separator at Studsvik and from the prompt fission studies using the EUROGAM2 and GAMMASPHERE arrays. Currently, no information exists on the excited states in ^{149,150}Ba.

In the last few years the application of the ATD $\beta\gamma\gamma$(t) method at ISOLDE has resulted in greatly increased knowledge of absolute transition rates in the region of heavy Ra-Th nuclei and has demonstrated new and unique research capabilities in this field. We propose to extend these studies to the very exotic neutron-rich Ba nuclei, currently at the limit of accessibility. These experiments would rely on the unique method of measurement in combination with high-quality beams available at ISOLDE with adequate intensity. In part I, we ask for 1 shift of stable beam and 14 shifts of radioactive beam using a standard UC/graphite target, and in Part II (a test case), for 1 shift of stable beam and 4 shifts of radioactive beam using a UC/graphite cloth target. Part II includes a request for a target development beneficial for studies of a whole class of very short-lived nuclei.

1. Motivation

This beam request represents an addendum to the proposal submitted by the IS386 collaboration in April of 2000. The original proposal had a few sub-projects and it already included a request for 12 shifts to study the beta decays of ^{149,150}Cs to ^{149,150}Ba. The collaboration was granted 24 shifts to measure specific level lifetimes in ^{226}Ra and ^{229}Th and the beam time was delivered in 2001 and 2002. Since the experimental part and the data analysis of these measurements is coming to a close, the collaboration turns its attention to another of its main topics of interest, namely to the study of nuclear structure of the most exotic neutron-rich Ba and La nuclei.

These nuclei command a considerable interest from the theoretical and experimental points of view. Experimentally, these are probably the most neutron-rich nuclei just above ^{132}Sn accessible to detailed experimental investigation, and yet still sufficiently close to the closed proton shell Z=50, to be influenced by the rigidity of this shell closure. Thus, the structure of these nuclei could reflect whether the Z=50 shell closure is still largely intact or has already collapsed at ^{144}Sn - a nucleus which is certainly beyound any current experimental reach. For example, it is expected that ^{150}Ba with 56 protons and 94 neutrons, has 6 valence protons and 12 valence neutrons beyond the closed shells of Z=50 and N=82. Thus it's excited states and B(E2) collectivity would be somewhat similar to cerium with parameters somewhat inbetween A=148 and A=150, while a collapse of the Z=50 shell would make this nucleus resemble ^{160}Gd.

The heavy Ba-La nuclei are also of interest due to the interplay of the octupole and quadrupole collectivities [1]. In fact, this region is the second one besides the heavy Ra-Th region, where these correlations are exceptionally strong, although they are somewhat weaker than in the Ra-Th nuclei (at least at low spin and excitation energy [2]). The nuclei of interest here, ^{149,150}Ba and ^{149}La, are expected to be at the border of strong octupole collectivity [3, 4, 5, 6]. This region is of particular interest to us, since our studies in the Ra-Th region have demonstrated that in such a region the valence nucleon in the odd-A system represents a very sensitive probe of the nuclear potential, giving different B(E1) transition rates for the parity-partner bands (ΔK=0 bands) originating from different K-orbits. This is consistent, albeit not in detail, with the general predictions made by Butler and Nazarewicz in ref. [7].

Until recently, the beta decay studies on the odd-A nuclei from the heavy Ba-Ce region did not result in any specific structure interpretation due to the difficulty in accessing these nuclei with advanced spectroscopic tools. The standard information compiled on these nuclei included only lists of energy levels and gamma rays. This situation has changed with two lines of advanced experiments converging on this region. The first one is represented by the studies of intermediate spin states, mainly yrast bands, from the prompt gamma rays produced in the spontaneous fission of ^{248}Cm, or other sources, at the EUROGAM and GAMMASPHERE arrays, see for example [8, 9, 10]. The second one is the systematic study of this region in beta decay with the use of the ATD $\beta\gamma\gamma$(t) method [11] at the OSIRIS fission product mass separator at Studsvik. However, in many cases it takes the fusion of results from these two lines of studies in order to arrive with a consistent structure interpretation, as it was recently demonstrated in the case of ^{149}Ce by Syntfeld *et al.* [12].

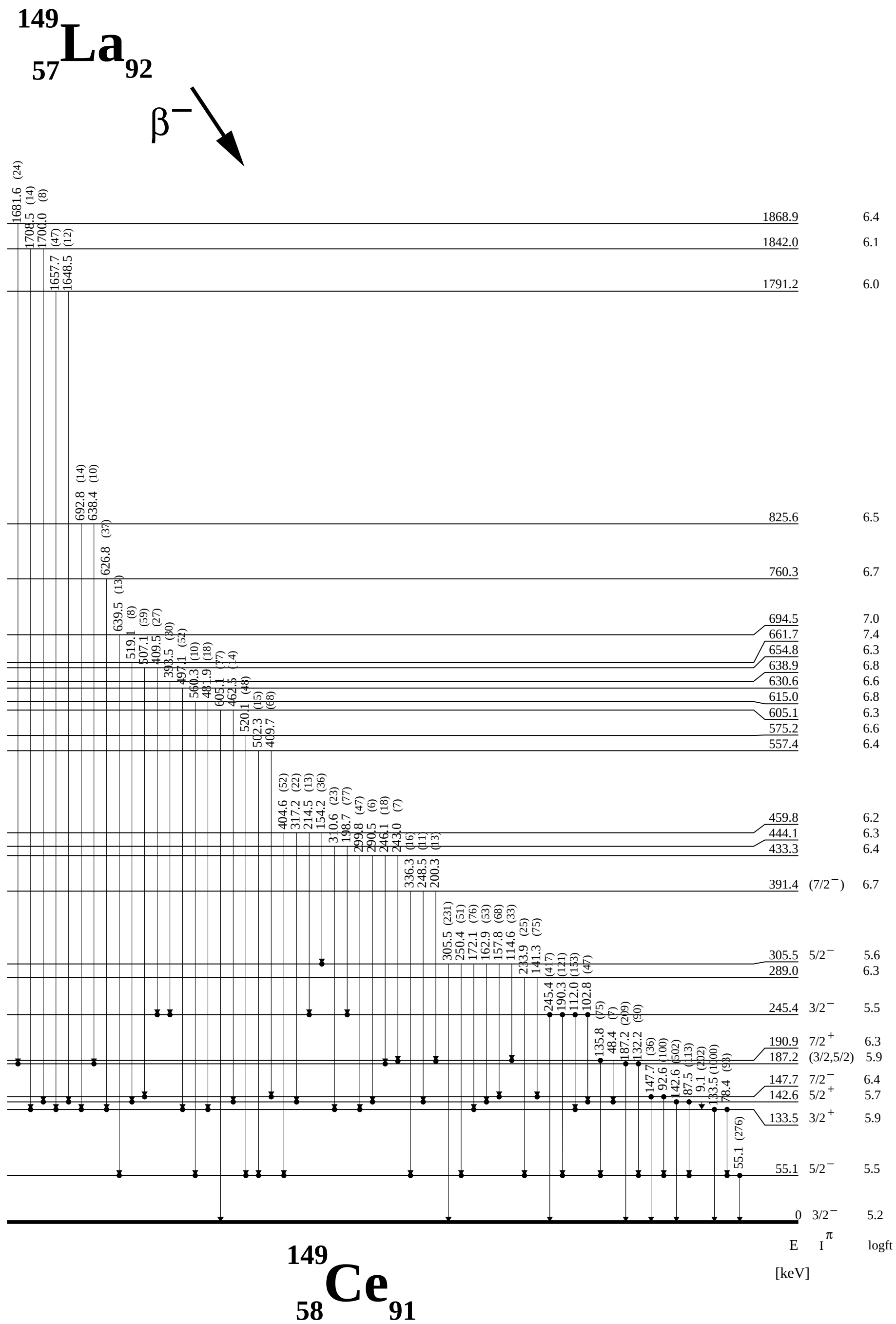

Figure 1: The level scheme of ^{149}Ce populated in the β^- decay of ^{149}La; from ref. [12]. The firm establishment of the 3/2+, 5/2+ and 7/2+ states at the energy of 133.5, 142.6 and 190.9 keV, respectively, allowed to interpret the yrast-bands deduced in the prompt fission studies; see fig 2 below.

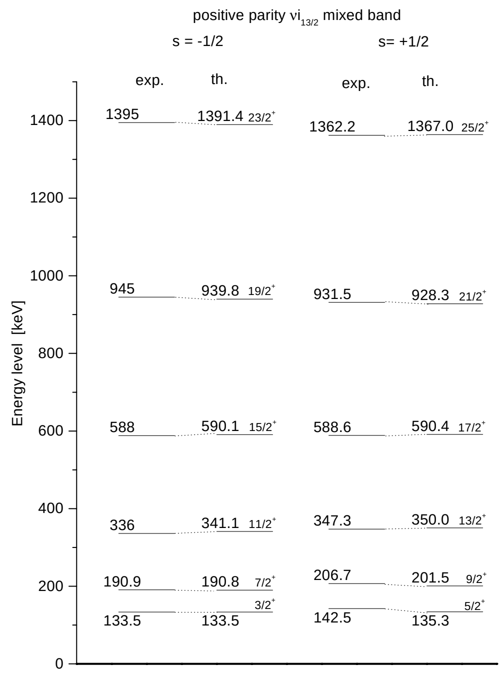

Figure 2: Comparison between the experimental levels interpreted as a mixed $\nu i_{13/2}$ band with signature splitting and the calculated Nilsson levels perturbed by Coriolis interaction, see [12] for details.

One should note, that in the deformed nuclei in this region, the yrast bands often terminate at excited states, which de-excite via very low energy and highly converted, thus "invisible", transitions. This makes it next to impossible to establish a proper connection of these bands to the ground state, and often to one another. Thus the interpretation of the observed structures becomes very tentative and sometimes even incorrect. The beta-decay studies, on the other hand, complement the former studies, by providing a unique definition of the low-lying states, and then extends the information by including the absolute transition rates.

Here, we focus our attention on the odd-A nuclei from A=147 and A=149. Recent advances in research on these chains, provide for the first time an opportunity to establish structure systematics on these nuclei, from the region near the line of stability to the most exotic one. A knowledge of a systematics of specific properties of levels or the whole bands, is crucial in order to interpret the structures of exotic nuclei. The odd-A nuclei are particularly difficult to study, yet they represent very sensitive probes of nuclear potential.

The nucleus of ^{149}Ce is the lightest and most exotic A=149 nucleus on which there is detailed spectroscopy information. The results from the beta decay work [12, 13] obtained very recently at OSIRIS (see fig.1) were crucial in order to correct the level schemes proposed in the prompt-fission studies on ^{149}Ce [10, 14]. Then, it was possible to provide a consistent interpretation of these bands (see fig.2) and the low-lying states in this nucleus. These structures follow a smooth systematics for the region, which is especially true for the signature splitting energies for the N=91 isotones. This systematics includes ^{149}Ce (new data!), ^{153}Sm, ^{155}Gd, ^{157}Dy, ^{159}Er and ^{161}Yb, see [12], and we hope to extend this systematics to include the lightest, N=91 isotone, ^{147}Ba, with the proposed work at ISOLDE.

^{147}**Ba:** There is little known about ^{147}Ba from the beta decay and prompt fission studies [9, 10]. The beta decay of ^{147}Cs is currently under investigation at OSIRIS. Our data indicate significant corrections to the previously published beta decay work. However, the ^{147}Cs decay is masked by much stronger activity of ^{147}Ba to ^{147}La, making this study very difficult. We expect much better conditions to study this decay at ISOLDE, mainly due to two factors: a higher yield of ^{147}Cs in comparison its longer-lived isobars, and due to the ISOLDE beam time structure, the combination of pulsed release with macro gating.

^{148}**Ba:** Our recently completed study of the levels in ^{148}Ba from the decay of ^{148}Cs [15], allowed to extend the level scheme and to establish the lifetime of the 2+ state at 142 keV with the precision of about 15%. However, a possibility of more detailed studies exists at ISOLDE, and this is significant, since ^{148}Ba could be the most exotic neutron-rich even-even barium, which nuclear structure could be known in considerable detail (as for such an exotic system). Moreover, we expect a population of a few states in ^{147}Ba from the beta-delayed neutron emmision of ^{148}Cs, which is estimated at 25%.

^{149}**La:** Virtually nothing is known about the structure of ^{149}La, which is the most exotic neutron-rich lanthanum isotope. Our recent study of the beta decay of ^{149}Ba performed at OSIRIS [16], indicated two cascades of transitions with no interconnections between these. One possible interpretation is that these structures are of opposite parity and prefer to de-excite within its own structure due to the strong mainly intra-band M1 transitions, while interconnecting E1 transitons have low B(E1) rates and thus are not visible in this study. We expect the intensity of ^{149}Ba beam to be about 1-2 orders of magnitute higher at ISOLDE than that at OSIRIS, which would allow to study both the decay scheme and transition rates, in considerable detail.

^{149,150,151}**Ba:** Nothing is known about the excited states in ^{149,150,151}Ba. We expect the first information on the excited states in ^{149}Ba populated from the decay of ^{149}Cs to emerge from the study of the beta decay of ^{149}Ba to La proposed above. Yet the condition would not be optimal for such a study. We observe that in the Ph.D. thesis of Köster it was noted that in the past at SC ISOLDE, with the use of a UC_x/graphite cloth target (molar ratio U:C ≈1:10, ca. 13 g/cm^2 U) the reported yields of the exotic Cs isotopes were much higher than those measured today at ISOLDE-PSB with a standard UC_x/graphite target (molar ratio U:C ≈1:4, ca. 50 g/cm^2 U). For example, the yields for SC ISOLDE were reported as 71 000, 12 000 and 1700 μC^{-1} for ^{149,150,151}Cs, respectively, in comparison to 4000 and 100 μC^{-1} for ^{149,150}Cs now. We note, that investigation at OSIRIS also points towards an advantage in using smaller targets when searching for very exotic and short-lived nuclei.

Target Development: Consequently, we ask the ISOLDE collaboration for a target development, namely to re-visit the cloth-type target for the short-lived Cs. We expect that such a development could be beneficial for studies of a whole class of very short-lived nuclei. In this respect we ask for 4 shifts of radioactive beam using a UC/graphite cloth target in order to test the yields of ^{149,150,151,152}Cs and experimental conditions to study the decays of ^{149,150,151,152}Cs to ^{149,150,151,152}Ba nuclei. Since it is known that Ba is faster released and can be produced in a cleaner way by adding CF_4 to the target and extracting molecular BaF^+, we also want during the target tests to measure the yields of very exotic Ba using this technique. Using the test results we would evaluate the feasibility of study beta decays of the most exotic Cs (and also Ba) isotopes. We expect, however, that at minimum it would be possible to study in favourable conditions the beta decays of ^{149,150}Cs in part III of our investigation.

To summarize, we propose in Part I of our beam proposal to study the beta decays of ^{147,148}Cs and ^{149}Ba using a standard UC/graphite target, and in Part II to re-visit the UC/graphite cloth target and test the yields of short-lived Cs isotopes.

2. Electric dipole moments

To a large degree, nuclear structure studies represent investigation of nuclear shapes with various types of static or dynamic deformations and their impact on the observable parameters. Strongly enhanced E0, E1, E2, E3, and E4 transitions reveal the regions where the electric monopole, dipole, quadrupole, octupole and hexadecapole collectivity plays an important role. The dominant mode and the best understood one, is the quadrupole deformation, while other modes of collectivity manifest themselves, and thus can be carefully studied, only in selected few regions where quadrupole deformation is weak and/or specific nucleon orbits are close to the Fermi surface.

The E1 moment, $\mathbf{D_o}$, is a measure of the shift between the center of charge and the center of mass of the nucleus [1], which assuming nucleons as point-like particles and neglecting the neutron-proton mass difference, is given by [1]:

$$\mathbf{D_o} = e\frac{ZN}{A}(\mathbf{r}_{p,c.m.} - \mathbf{r}_{n,c.m.})$$

where $\mathbf{r}_{p,c.m.}$=$\mathbf{r}_p/Z$ and $\mathbf{r}_{n,c.m.}$=$\mathbf{r}_n/N$ are the center-of-mass co-ordinates for protons and neutrons, respectively. The experimental information and the state of theoretical modelling of the electric dipole moment are still very limited. In the reflection-symmetric nuclei the expectation value of $\mathbf{D_o}$ is zero, thus a large static E1 moment may arise only in the intrinsic frame of reflection asymmetric systems. The size and sign of the electric dipole moment depend in a complex way on the octupole and quadrupole deformations (we consider deformations here in a static and dynamic sense). The two regions of strong interest for studies of electric dipole moments are the octupole collective heavy Ra-Th and Ba-Ce nuclei. They are, however, difficult to be accessed with a full range of experimental probes. One of the key missing information are the absolute E1 transition rates for the γ-rays connecting the ΔK=0 bands of opposite parity, which are used to define the E1 moments via a standard rotational model formula:

$$B(E1; I_i K \rightarrow I_f K) = \frac{3}{4\pi}\mathbf{D_0}^2 \langle I_i K 10 | I_f K\rangle^2 \ . \qquad (1)$$

(Although in the presence of Coriolis coupling and/or triaxiality this formula should be modified, in the case of K=1/2 band, the most critical case in this region, we have found that only negligible corrections are needed [17, 18].)

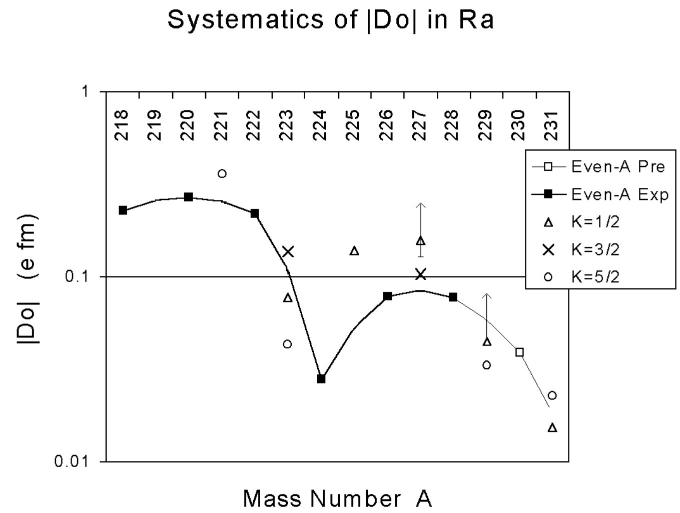

Figure 3: Systematics of electric dipole moments in Ra nuclei. A strong quenching of $|\mathbf{D_o}|$ at ^{224}Ra divides the systematics into two regions: for A<224 the sign of the $\mathbf{D_o}$ moment is predicted [7, 19] to be positive, while for A>224 — negative. Solid squares represent measured values for the even-Ra nuclei [1, 20], while an open square is an expected value if there is a smooth lowering of the curve. The solid line joining these points has no significance on its own. For odd-Ra nuclei, the E1 moments are listed for different K values of the bands. For the K=1/2 band in ^{227,229}Ra only lower limits are given. The new results for ^{227,229,231}Ra and significantly modified ones for ^{222}Ra and K=3/2 in ^{223}Ra, are from our recent measurements at ISOLDE [21, 18, 22, 23]. Values for other odd-A Ra are from [1].

3. Experimental Equipment and Methods

The main part of the proposal includes ultra-fast time-delayed measurements that will be supplemented by standard γ and conversion spectroscopy (the latter for longer-lived nuclei in the A=147 and A=149 mass chains). Our specialized experimental techniques and equipment were already carefully tested at ISOLDE in our previous studies within the IS322 and IS386 collaborations. Fig. 4 illustrates schematically the proposed experimental setup. We propose to use two stations: fast timing one at the point of beam deposition and conversion electron one. At the fast timing station there will be two BaF_2 detectors. The fast timing detectors will be prepared and calibrated at the OSIRIS fission product separator at Studsvik. The electron station will need the ISOLDE data acquisition system. A digital data acquisition system for the fast timing station will be provided by the Studsvik participant.

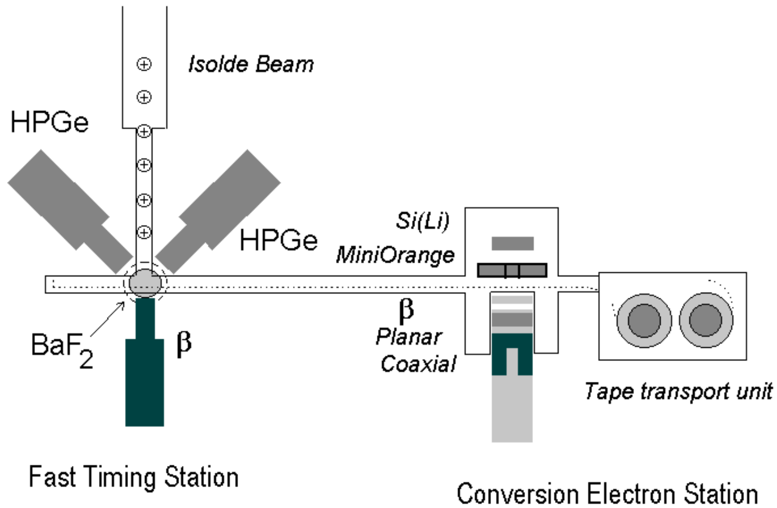

Figure 4: A schematic presentation of the experimental setup proposed for the measurements. It will include two stations: the fast timing one at the point of beam deposition and conversion electron one, interconnected by a tape transport system. Two BaF_2 detectors will be used positioned one above and one below the plane shown.

4. Summary of beam requests

In total, we request 18 shifts with radioactive beams. In part I, we ask for 1 shift of stable beam and 14 shifts of radioactive beam using a standard UC/graphite target, and in Part II (a test case), for 1 shift of stable beam and 4 shifts of radioactive beam using a UC/graphite cloth target. Part II includes a request for a target development beneficial for studies of a whole class of very short-lived nuclei.

Nucleus	# of shifts	Separator	Target	Ion source	Min.Intensity
Stable beam	1	GPS/HRS	UC	WSI	
^{147}Cs	4	GPS/HRS	UC	WSI	1x10^4
^{148}Cs	4	GPS/HRS	UC	WSI	1x10^4
^{149}Ba	6	GPS/HRS	UC	WSI	5x10^3
subtotal	15				
Stable beam	1	GPS/HRS	UC/cloth	WSI	
^{149}Cs	2	GPS/HRS	UC/cloth	WSI	7x10^3
^{150}Cs	2	GPS/HRS	UC/cloth	WSI	1x10^3
subtotal	5				
total	20				

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