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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

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Abstract

It is proposed to study the electric dipole moments in the regions of octupole collective Ra-Th and Ba-Ce nuclei by means of Advanced Time-Delayed (ATD) $\beta\gamma\gamma(t)$ method with a primary goal to provide new and critical data on the properties of E1 moments. The proposal focuses on the nuclei of ^{225,226,229}Ra, ^{229,233}Th and ^{149,150}Ba.

The ATD $\beta\gamma\gamma(t)$ method was first tested at ISOLDE as part of the IS322 study of Fr-Ra nuclei at the limits of octupole deformation region. The results have greatly increased the knowledge of electric dipole moments in the region and demonstrated that new and unique research capabilities in this field are now available at ISOLDE. Based on the experience and new systematics, we propose a specialized study with the aim to determine the missing key aspects of the E1 moment systematics. We propose a) to measure the lifetimes of the 1^-_1 and 3^-_1 states in ^{226}Ra with ~15% precision, which in combination with the recently performed Coulomb excitation studies, will allow to determine for the first time the sign of dipole moment, b) to measure with high precision the level lifetimes in ^{229}Th for a dual purpose of modelling the M1 transition rates and to establish the E1 moments, c) to measure selective electric dipole moments in ^{225,229}Ra and ^{233}Th, and d) to establish the excitation energy of the negative parity band in ^{150}Ba. These experiments would rely on the unique method of measurement in combination with high-quality beams available at ISOLDE with adequate intensity.

1. Introduction

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:

$$B(E1; I_i K \rightarrow I_f K) = \frac{3}{4\pi}\mathbf{D}_0{}^2 \langle I_i K 1 0 | I_f K\rangle^2 \, . \tag{1}$$

(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 [2, 3].)

The situation has changed with the introduction [4] of the Advanced Time-Delayed $\beta\gamma\gamma$(t) method [5] at ISOLDE. The method was first tested at ISOLDE as part of the IS322 study of Fr-Ra nuclei at the limits of octupole deformation region. Since it was not included into the original proposal, neither the selection of cases nor the beam time requirements were optimal for the fast timing measurements. The analysis of most of the collected data has been completed by now and has yielded about 25 new level lifetimes and about 20 meaningfull lifetime limits in 3 even-even (^{222,224,228}Ra) and seven odd-A nuclei (^{227}Fr, ^{223,227,229,231}Ra, and ^{229,231}Th). Most of these results have already been published [2, 3, 6, 7, 8] or will be published shortly [9, 10, 11]. They have vastly increased the knowledge of electric dipole moments in the Ra-Th region, especially for the odd-N nuclei (9 new values vs 7 previously known), and demonstrated that new and unique research capabilities in this field are now available at ISOLDE. One should note, that besides the cases of ^{227}Fr and ^{231}Ra, none of them was extracted from a dedicated measurement. The activity was generally part of the isobaric contamination or used for calibration of the conversion electron detector.

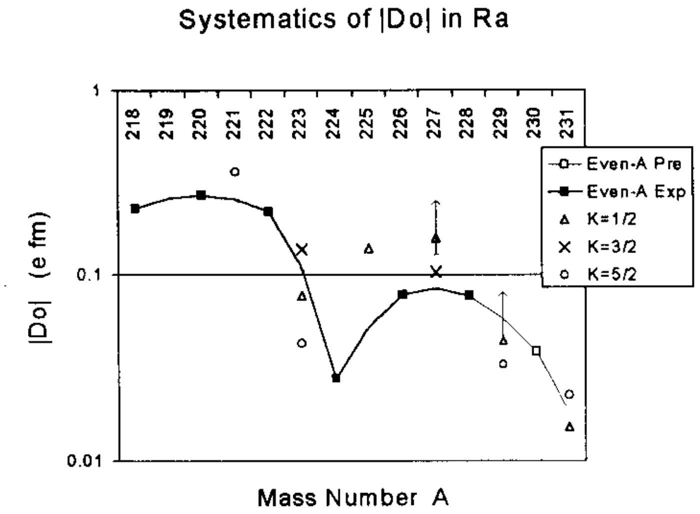

Figure 1: Systematics of electric dipole moments in Ra nuclei. A strong quenching of $|\mathbf{D}_o|$ at ^{224}Ra divides the systematics into two regions: for A<224 the sign of the $\mathbf{D}_o$ moment is predicted [12, 13] to be positive, while for A>224 — negative. Solid squares represent measured values for the even-Ra nuclei [1, 14], 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 [6, 3, 9, 10]. Values for other odd-A Ra are from [1].

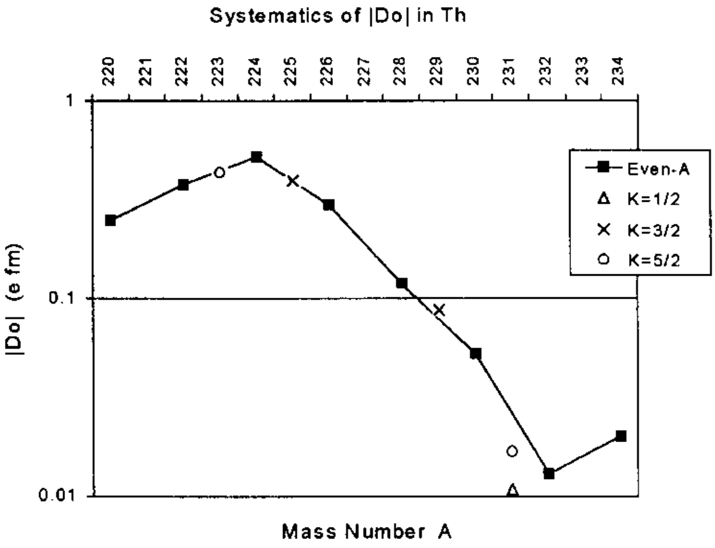

Figure 2: Systematics of E1 moments in Th nuclei. A small quenching of $|\mathbf{D}_o|$ at A=231/232 is in agreement with the dynamic model calculations by Egido and Robledo [13]. Similarly to Ra, the sign of the E1 moment is predicted [13] to be positive below the quenching and negative for heavier nuclei. Solid squares represent measured values for the even-Th nuclei [1, 14, 15]. The solid line has no significance on its own. For odd-Th nuclei, the E1 moments are listed for different K values of the bands. The new results for ^{229,231}Th are from our recent measurements at ISOLDE [11, 2]. Values for other odd-Th are from [1].

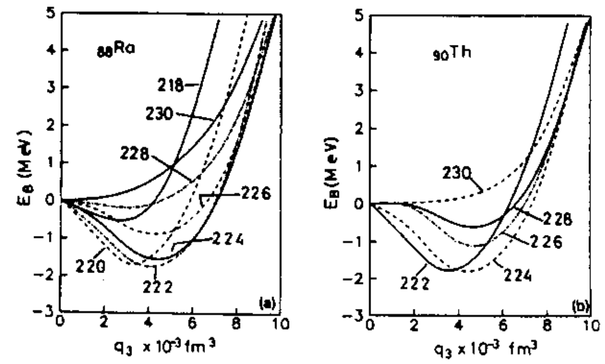

Figure 3: The barrier heights E_B for the radium (a) and thorium (b) isotopes versus the constrained octupole moment illustrating a fast changing depth of the octupole potential in the Ra-Th region. The numbers to each curve are the mass numbers for the given isotopes; from the constrained Hartree-Fock plus BCS calculations in [13].

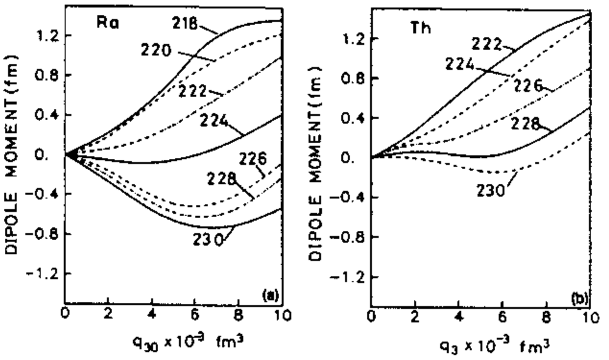

Figure 4: The dipole moments of the radium (a) and thorium (b) isotopes versus the constrained octupole moment illustrating a complex relation between the dipole and octupole moments. Note, a cancellation of the E1 moment for ^{224}Ra and similarly for ^{230}Th, as well as changing of its sign from positive to negative at these nuclei; from [13]. Additional calculations by Egido and Robledo show curves for ^{232,234}Th qualitatively similar to those for ^{228,230}Ra.

2. The Physics Case

The new experimental results for the Ra-Th region are summarized in Figs. 1 and 2, while Figs. 3 and 4 and Table 1 illustrate the situation on the theoretical side. The theoretical calculations [12, 13] correctly predict the quenching of $\mathbf{D_o}$ at ^{224}Ra, and with the help of our new results, there seems to be a confirmation of a previously neglected issue of a small quenching of $\mathbf{D_o}$ in Th. This is particularly vivid if one compares the isotones of ^{229}Ra and ^{231}Th, which have very similar energy level systematics and quadrupole collective properties [2, 3]. A current re-calculation of the case by Egido and Robledo reveals that for heavy Th there is a similar phenomenon of quenching with an associated change of sign of $\mathbf{D_o}$, see Fig. 4. However, it takes place in the region of dynamic octupole instability. Both calculations [12, 13] predict $\mathbf{D_o}$ to change sign from positive to negative at the quenching point of ^{224}Ra (see Fig. 4 and Table 1). When comes to the absolute values, the calculations of Ref. [12] generally underpredict, while the calculation of Ref. [13] overpredict in many cases the values of $\mathbf{D_o}$. By mapping the upper limits of the octupole correlation Ra and Th regions, there is a more clear notion of the effect of octupole vibrations, which effects were not included in calculations [12].

Table 1: Theoretical intrinsic electric dipole moments for the octupole-unstable actinide nuclei (at low excitation energy) calculated using the shell-correction method based on the reflection-asymmetric Woods-Saxon model [12]. Note quenching of $\mathbf{D}_{\rm o}$ and change of its sign at ^{224}Ra, as well as configuration dependence of the E1 moments for ^{219,225}Ra and ^{227}Th.

Neutron number	Nucleus	K	$\mathbf{D}_{\rm o}$ $(e \cdot fm)$		Nucleus	K	$\mathbf{D}_{\rm o}$ $(e \cdot fm)$	
			even-A	odd-A			even-A	odd-A
130	^{218}Ra	0	0.25		^{220}Th	0	0.34	
131	^{219}Ra	1/2		0.18	^{221}Th	1/2		0.31
		3/2		0.16		3/2		0.28
		5/2		0.21		5/2		0.35
132	^{220}Ra	0	0.17		^{222}Th	0	0.30	
133	^{221}Ra	1/2		0.15	^{223}Th	1/2		0.29
		3/2		0.11		3/2		0.26
		5/2		0.13		5/2		0.29
134	^{222}Ra	0	0.09		^{224}Th	0	0.27	
135	^{223}Ra	1/2		0.04	^{225}Th	1/2		0.18
		3/2		0.03		3/2		0.22
		5/2		0.04		5/2		0.20
136	^{224}Ra	0	0.01		^{226}Th	0	0.16	
137	^{225}Ra	1/2		−0.06	^{227}Th	1/2		0.12
		3/2		−0.03				
		5/2		−0.04		5/2		0.05
138	^{226}Ra	0	−0.09		^{228}Th	0	0.07	
139	^{227}Ra	1/2		−0.07				
		7/2		−0.09				

An interesting and challenging experimental issue is verification of predictions that values of $\mathbf{D}_{\rm o}$ depend on the configuration of a valence nucleon in a given odd-A nucleus. In other words, the unpaired valence nucleon becomes a sensitive probe of the collective nuclear potential testing the delicate interplay of the quadrupole and octupole deformations. The calculations of Ćwiok and Nazarewicz [16] show that for odd-A nuclei in the Ra-Th region the amount of octupole correlations is state-dependent. These predictions are reflected in the calculated electric dipole moments, $\mathbf{D}_{\rm o}$, in Ref. [12], which take the deformation parameters from [16]. As seen in Table 1 they predict a moderate configuration dependence of $\mathbf{D}_{\rm o}$ for a few odd-A nuclei in the Ra-Th region, including ^{219}Ra, ^{225}Ra and ^{227}Th, while for ^{223}Ra they predict almost constant $\mathbf{D}_{\rm o}$ value of ~0.04 e·fm for the K=1/2, 3/2, and 5/2 bands. The latter prediction is not confirmed by experimental results as shown in Fig. 1. However, the schematic model calculations [12] were intended to reproduce general features of $\mathbf{D}_{\rm o}$ systematics rather than to provide detailed local predictions.

The main issue is whether there is any systematical evidence for the orbit dependence of the E1 moment. This can be tested if E1 moments for two or more intrinsic configurations are known in a given nucleus. Prior to our ISOLDE work such data in the Fr-Th region was available only for ^{221}Fr and ^{223}Ra [1]. Our recent studies of ^{227,229,231}Ra and ^{231}Th [6, 3, 9, 2], indicate that in the case of ^{221}Fr, ^{223,229,231}Ra and ^{231}Th (and possibly also in ^{227}Ra, but large uncertainties exclude firm conclusions), thus practically in all known cases, there is a strong configuration dependence of the E1 moment. Consequently, these results confirm the general prediction made by Ćwiok and Nazarewicz [16] that for odd-A nuclei in this region the amount of octupole correlations is state-dependent. The next experimental issue is to verify how exactly does this configuration dependence evolves. Thus, whether the $\mathbf{D}_o$ values for a given K band form a systematic trend over a few adjacent odd-A nuclei (e.g.: for K=1/2 from A=223 to 231 in Ra and A=229 to 233 in Th)?

In order to respond to the challenges listed above, we propose the following:

1) to study for the first time the sign of the electric dipole moment in ^{226}Ra. This is a combined effort with Coulomb excitation studies already performed at Jyväskylä. The aim here is to measure precisely the level lifetimes of the first excited 1^- and 3^- states in ^{226}Ra. Details of the proposed measurement are described in Section 3.

2) to study selected E1 moments in the Ra-Th region:

a) in ^{225}Ra: We propose a fast timing measurement on ^{225}Ra populated in the decay of ^{225}Fr. As seen in Fig. 1 the E1 moment for the K=1/2 band in ^{225}Ra has a quite outstanding value, which in our view needs verification. It is based on the lifetime of the $3/2^-$ 31.6 keV state, which was measured only once before and with very poor statistics [17]. Moreover, in the same measurement we expect to determine the E1 moment for the K=3/2 and 5/2 bands. This way we get a full set of results for the nucleus located just above quenching of $\mathbf{D}_o$, which complements the case of ^{223}Ra located just below the point of quenching.

b) in ^{229}Ra and ^{229}Th: We propose a combined measurement using the activity of ^{229}Fr, that will be focussed in 20% on determination of a precise value of $|\mathbf{D}_o|$ for the K=1/2 band in ^{229}Ra and 80% on precise lifetime measurements in ^{229}Th. The latter case serves a dual purpose: firstly, to provide spectroscopic information for modeling the M1 transition rate and for prediction of level lifetime of the first excited state in ^{229}Th at ~3.5 eV, and secondly, to determine the E1 moment for the K=1/2 and 5/2 bands in this nucleus. Experimentally the structure of the low-lying states in ^{229}Th is complex due to strong Coriolis mixing of the K=3/2 and 5/2 bands for both, positive and negative parities. Precisely determined lifetimes for a series of low-lying states would provide a key assistance in order to determine structure of the low-lying states. In our recent lifetime measurements in ^{229}Th, where the decay of ^{229}Ac to Th was present as a small amount of isotopic impurity, we got three additional level lifetimes with modest precision. One value for the K=3/2 band is already listed in Fig. 2. A detailed motivation for precise measurement of selected level lifetimes in ^{229}Th for the purpose of modeling de-excitation from the first excited state at ~3.5 eV, is given in Section 4.

c) in ^{233}Th: We propose to investigate the β decay of ^{233}Ac to ^{233}Th (with Ac produced from the β-decay of ^{233}Ra) in order to measure the E1 moment of the K=1/2 band. The level scheme of ^{233}Th is relatively well known, thus there is a strong possibility to measure also the E1 moment of the K=3/2 band if significantly populated. Both of these E1 moments are expected to have values larger than in the case of ^{231}Th, which we expect to represent the centre of quenching. Together the results for ^{229,231,233}Th should reveal the systematics of $|\mathbf{D}_o|$ in the subregion covering the area where quenching takes place in Th.

In addition to the studies in the Ra-Th region, we propose to investigate selected aspects of octupole/dipole collectivity in the region of heavy Ba-Ce, which represents a second region of interest. Here we propose:

3) to investigate the structure of ^{150}Ba populated in the β decay of ^{150}Cs, in order to determine the ground state positive parity band and the excitation energy of the negative parity band in this nucleus. No excited states are presently known in this very exotic nucleus. We propose to perform fast timing measurements to determine the ground state quadrupole deformation and possible lifetime limits for the first excited 1^- or 3^- states.

Motivation: there is a strong interest in the systematics of the negative parity bands in heavy Ba. Unlike the even-Ra nuclei, where the systematics for both the 1_1^- and 3_1^- states follow a curve closely resembling a symmetric parabola, the 1_1^- and 3_1^- states in even-Ba rapidly come down and stay at a nearly constant level from ^{144}Ba to ^{148}Ba. The results for ^{150}Ba would indicate whether this trend continues or whether the negative parity states move up and define a minimum in their systematics. This would be an important constrain for the theoretical modeling in this region. Since ^{150}Ba is a strong neutron emitter, it will be neccessary to investigate also the β decay of ^{149}Cs to ^{149}Ba.

This work is intended to be complementary to a large systematical study of the odd-A nuclei in the heavy Ba-Ce region performed by the Studsvik-Warsaw collaboration at the OSIRIS fission product separator at Studsvik. These studies involved so far ^{139}Cs, ^{138,139,140}Xe, ^{143,145,147,148}Ba, ^{145,147,149}Ce, with some work already published [18, 19] or in an advanced stage of preparation [20, 21]. This work is also complementary to the very active program at the EUROGAM/EUROBALL and GAMMASPHERE arrays in probing the yrast bands in the octupole collective neutron-rich Ba-Ce region using prompt γ-rays in spontaneous fission, see for example a summary of such studies in [1].

3. Measurement of the E1/E3 phase in ^{226}Ra

From a historical perspective, the calculation of the electric dipole moment in pear-shaped nuclei has presented a challenge, since the earliest calculations using the liquid-drop model predicted opposite signs for the electric dipole moment, defined with respect to the intrinsic nuclear frame [22, 23].

There has been a long standing prediction [24, 12, 13] that the sign of the E1 moment changes for Ra isotopes as the mass is increased from 222 to 226. This arises from the shell correction to the bulk (droplet) contribution which becomes increasingly negative as N increases. The latter macroscopic-microscopic calculations successfully reproduce the near exact cancellation for the E1 moment which has been observed for ^{224}Ra [25] and also for a much lighter nucleus ^{146}Ba [26, 27].

The experimental challenge is to measure the sign of the electric dipole moment. While a measurement of this quantity in isolation is impossible, it is in principle possible to measure the sign of the E1 moment relative to the E3 moment for a mixed nuclear transition. While γ-ray decay properties depend very weakly on the E3 admixture and Coulomb excitation at close nuclear distances has little dependence on the E1 admixture, the latter can become sensitive to the relative amount of E1 and E3 for an optimal distance of closest approach. Calculations using the semi-classical Coulomb excitation least squares search code GOSIA [28] suggest that, if the bombarding energy of a mass 40 projectile is about 1.5 MeV/A, the populations of the 1^- and 3^- states in ^{226}Ra are very sensitive to the assumed relative sign of the E1 and E3 matrix elements.

3.1 Status of Coulex experiment

In January 2000 we carried out measurements of excitation probabilities of the low-lying states in ^{226}Ra at the University of Jyväskylä. The beam was 60 MeV ^{40}Ar, i.e. a bombarding energy 30% of the Coulomb barrier. In the experiment a PPAC was employed to detect backscattered ^{40}Ar ions over an angular range 117^o - 149^o with precision of 2^o. The excitation probabilities were determined by measuring the intensities of γ-rays detected using an array of 12 Compton suppressed Tessa and Eurogam phase I detectors, with a total peak efficiency at 200 keV of about 2%. Following five days irradiation we were able to measure the intensities of the composite $1^- \rightarrow 0^+$, and $3^- \rightarrow 2^+$ 253 keV transition and $1^- \rightarrow 0^+$ 186 keV transition. Preliminary analysis of these quantities gives uncertainties of 5% and 15% respectively. The predicted changes in intensity of these transitions if the E1/E3 phase is changed are 17% and 37% respectively. However, in fitting the data using GOSIA these effects can be compensated by allowing the magnitudes of the matrix elements to vary. While all E1, E2 and E3 matrix elements connecting the low lying states in ^{226}Ra have been determined in previous experiments [29] (we have also made measurements using 81 MeV ^{40}Ar ions), the uncertainties on the crucial matrix elements connecting the 1^- and 3^- states are large enough to wash out effects due to phase.

3.2 Proposed measurement on ^{226}Ra

We wish to measure the lifetime of the 1^- and 3^- states to an accuracy of 15% or better. This will ensure that the uncertainty in the $< 0^+||E1||1^- >$, $< 2^+||E1||1^- >$, $< 2^+||E1||3^- >$ and $< 4^+||E1||3^- >$ matrix elements will be at most 7.5% - a factor of $\sim$2 better than that measured already. This will restore the sensitivity to the E1/E3 phase of the fit to the low energy data.

4. Half-life and magnetic moment of the ≈3.5 eV isomer in ^{229}Th

We propose to reinvestigate the β and γ spectroscopy of the ^{229}Ac to ^{229}Th decay, with a special effort to measure subnanosecond lifetimes of the excited states in ^{229}Th. Theoretical analysis of data obtained for the rotational bands build on the $K^\pi=5/2^+$ ground state and on the ≈3.5 eV $3/2^+$ isomer will allow derivation of the partial γ-decay half-life and magnetic moment of this isomer, see Fig. 5. Additionally search for the (visual and/or ultraviolet) electromagnetic radiation de-exciting the isomer will be undertaken.

Precision γ-spectroscopy studies performed by Helmer and Reich [30] on the ^{233}U → ^{229}Th alpha decay place the first excited state of the daughter nucleus at unusually low energy of 3.5±1.0 eV. The spin and parity of this state is presumably $3/2^+$, while that of the ground state is $5/2^+$. These two states are interpreted as the $3/2^+[631]$ and $5/2^+[633]$ Nilsson-model orbitals. The $3/2^+$ state is expected to be an isomer. Its partial γ-decay half-life has been estimated to be in the range of hours [31].

4.1 Interest in the $3/2^+$ isomeric state

There are at least two reasons for a special interest the 3.5 eV $3/2^+$ state. First, it offers a unique possibility to study coupling between the nuclear and atomic degrees of freedom [32, 33, 34]. Second, it gives a chance to observe the nuclear-spin mixing that is expected to take place in case of hydrogen-like ions ^{229}Th^{89+} circulating in a storage ring [31, 34], e.g.: ESR at GSI.

The first effect can manifest itself via the so-called electronic bridge [32]. It means a competition to the γ-decay from a two-step process: a part of the excitation energy is transferred to one of the valence electrons to shift it to another orbit. The rest of the energy is carried away by a "red-shifted" γ-ray photon. The enhancement of the isomeric

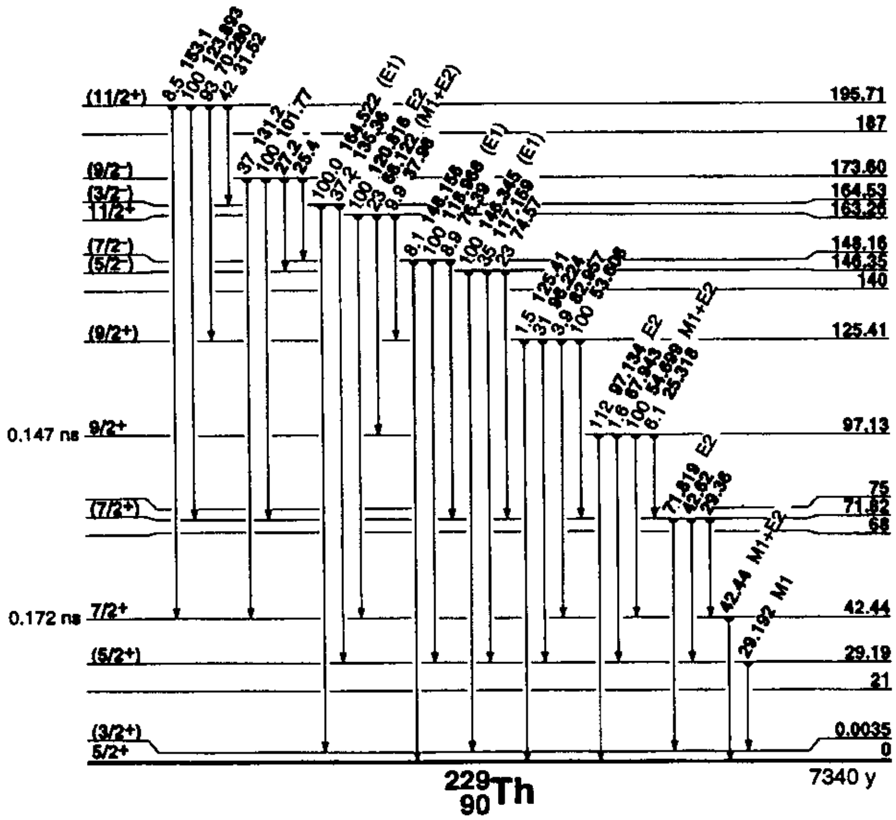

Figure 5: A partial decay scheme of ^{229}Th.

transition depends upon its energy. As predicted by the theory [34], it can be as high as three orders of magnitude [34]. To verify this theory one needs (i) the isomer energy with uncertainty below ±0.1 eV, (ii) the half-life of the isomer in a neutral atom, and (iii) the partial half-life for the isomeric M1 γ transition. For predictions of the mixing of the $5/2^+$ ground state and the $3/2^+$ isomeric state in a hydrogen-like ion of ^{229}Th one needs additionally the magnetic-moment value for the isomer.

4.2 Proposed measurements and analysis on ^{229}Th

The ^{229}Fr activity will be produced in a proton-induced spallation of ^{238}U and mass separated. The A=229 isobars form a chain of the β-decays:

$$^{229}\mathrm{Fr}(50\ \mathrm{s}) \rightarrow {}^{229}\mathrm{Ra}(4.0\ \mathrm{min}) \rightarrow {}^{229}\mathrm{Ac}(1.04\ \mathrm{hr}) \rightarrow {}^{229}\mathrm{Th}.$$

Our experiments will focuss on the last of these decays, and will include: (a) measurements of level lifetimes in the subnanosecond range by the ATD $\beta\gamma\gamma$(t)method, (b) carefull intensity re-measurement of the low energy γ transitions, and (c) search for visible and/or ultraviolet radiation related to de-excitation of the isomer, recorded by an appriopriate photomultiplier. Positive results from measurement (c) would allow to plan a more sophisticated experiment, like that described in [35].

Nuclear-spectroscopy data on the intensities and multipolarities of γ transitions between levels of the K=3/2 and K=5/2 bands, combined with the measured lifetimes, will be used to derive the partial γ-decay half-life for the isomeric M1 transition. In the first step, simple rotational-model formulas will be used. In the next step, the role of Coriolis coupling will be analysed taking into account interactions of all single-particle orbitals from the involved neutron subshells.

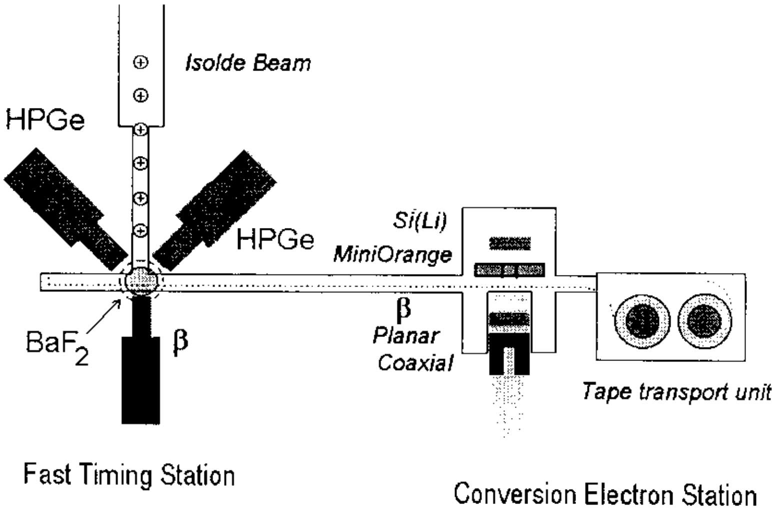

Figure 6: A schematic presentation of the experimental setup proposed for the measurements. It will include two stations: the fast timing one at the point of beam deposition and conversion electron one, interconnected by a tape transport system. Two BaF_2 detectors will be used positioned one above and one below the plane shown.

At present two lifetimes in the $K=3/2^+$ and $5/2^+$ bands are known: $T_{1/2}=172\pm6$ ps for the 42.44 keV $7/2^+$ level and 147 ± 12 ps for the 97.13 keV state [36]. First of them can be utilized if the 13.25 keV M1 γ-transition to the 29.19 keV state is identified, and the intensity of this transition relative to the 42.44 keV line is determined accurately enough. Second lifetime was already used to derive the partial lifetime of the 25.318 keV M1 transition and to estimate the lifetime of the 3.5 eV state [31]. It is hoped now (i) the lifetime of the 97.13 keV level will be re-measured with a higher accuracy, (ii) lifetime data will be obtained for the 29.19 keV $5/2^+$ and 71.82 keV $7/2^+$ (possibly, also 125.41 keV $9/2^+$) levels of the $K=3/2^+$ bands. To get the magnetic moment of the isomeric state one will have to assume the same g_R factor for both rotational bands. For the ground state band it was established by Bemis *et al.* [37] as $g_R=0.309\pm0.016$ μ_N.

5. 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. Our specialized experimental techniques and equipment were already carefully tested at ISOLDE in our previous studies within the IS322 collaboration. Fig. 6 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. One modification will be included: at the fast timing station there will be one additional BaF_2 detector with a smaller crystal than previously used. It will be specially prepared for lifetime measurements with γ-rays of low energy where it will have superior timing resolution. This will complement the "standard size" BaF_2 crystal used for a wide range of γ energies. That detector due to the large dynamic energy range covered, is not optimal for low energy measurements below ~150 keV. However, this energy range is very important to the present proposal. 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. The data acquisition system for the fast timing station will be provided by the Studsvik participant.

During the measurements on ^{229}Th, we request access to a second beam line for test measurements of low-energy photons that could have their origin in the decay of the 3.5 eV level. We treat those measurements as test only, and no separate beam time is requested for that purpose.

6. Summary of beam requests

In total, we request 50 shifts, from which 47 are shifts with radioactive beams. vskip 12pt

Nucleus	# of shifts	Separator	Target	Ion source	Min.Intensity
Stable beam	1	GPS/HRS	UC or ThC	WSI	
^{226}Ra	10	GPS/HRS	UC or ThC	WSI	$1\text{x}10^4$
^{225}Ra	8	GPS/HRS	UC or ThC	WSI	$1\text{x}10^4$
subtotal	19				
Stable beam	1	GPS/HRS	UC	WSI	
^{229}Th	12	GPS/HRS	UC	WSI	$8\text{x}10^3$
^{233}Th	6	GPS/HRS	UC	WSI	$5\text{x}10^2$
subtotal	19				
Stable beam	1	HRS	UC	WSI	
^{150}Ba	8	HRS	UC	WSI	$1\text{x}10^2$
^{149}Ba	3	HRS	UC	WSI	$1.5\text{x}10^3$
subtotal	12				
total	50				

References

[1] P.A. Butler and W. Nazarewicz, Rev. Mod. Phys. **68** (1996) 349, and references therein.

[2] A.J. Aas *et al.*, Nucl. Phys. **A654** (1999) 499.

[3] L.M. Fraile *et al.*, Nucl. Phys. **A657** (1999) 355.

[4] H. Mach *et al.*, in *Nuclear Shapes and Nuclear Structure at Low Excitation Energy*, edited by M. Vergnes, D. Goutte, P.H. Heenen, and J. Sauvage, (Editions Frontieres, Gif-sur-Yvette, 1994), p. 391.

[5] H. Mach, R.L. Gill, and M. Moszyński, Nucl. Instrum. Methods Phys. Res. A **280** (1989) 49, and the references therein.

[6] A.J. Aas *et al.*, Nucl. Phys. **A611** (1996) 281.

[7] W. Kurcewicz *et al.*, Nucl. Phys. **A621** (1997) 827.

[8] K. Gulda *et al.*, Nucl. Phys. **A636** (1998) 28.

[9] L. Fraile *et al.*, to be published.

[10] H. Mach *et al.*, to be published.

[11] K. Gulda *et al.*, to be published.

[12] P.A. Butler and W. Nazarewicz, Nucl. Phys. **A533** (1991) 249.

[13] J.L. Egido and L.M. Robledo, Nucl. Phys. **A494** (1989) 85, see also ibid **A524** (1991) 65.

[14] J.F.C. Cocks *et al.*, Nucl. Phys. **A645** (1999) 61.

[15] B. Ackermann *et al.*, Nucl. Phys. **A559** (1993) 61.

[16] S. Ćwiok and W. Nazarewicz, Nucl. Phys. **A529** (1991) 95.
[17] T. Ishii *et al.*, Nucl. Phys. **A444** (1985) 237.
[18] A. Lindroth *et al.*, Phys. Rev. Lett. **82** (1999) 4783.
[19] A. Nowak *et al.*, Eur. Phys. J. **A 6** (1999) 1.
[20] A. Lindroth *et al.*, NFL Annual Report 1999, Uppsala University, in press.
[21] A. Syntfeld *et al.*, NFL Annual Report 1999, Uppsala University, in press.
[22] A. Bohr and B.R. Mottelson, Nucl. Phys. **4** (1957) 529, also Nucl. Phys. **9** (1958) 687.
[23] V.M. Strutinsky, At. Energ. **4** (1956) 150.
[24] G.A. Leander *et al.*, Nucl. Phys. **A453** (1986) 58.
[25] R.J. Poynter *et al.*, Phys. Lett. **B232** (1989) 447.
[26] W.R. Phillips *et al.*, Phys. Rev. Lett. **57** (1986) 3257.
[27] H. Mach *et al.*, Phys. Rev. **C 41** (1990) R2469.
[28] T. Czosnyka *et al.*, Bull. Amer. Phys. Soc. **28** (1983) 775.
[29] H.J. Wollersheim *et al.*, Nucl. Phys. **A556** (1993) 261.
[30] R.G. Helmer and C.W. Reich, Phys. Rev. **C49** (1994) 1845, and references therein.
[31] S. Wycech and J. Zylicz, Acta Phys. Pol. **B24** (1993) 637.
[32] E.V. Tkalya, Pisma Zh. Eksp. Teor. Fiz. **55** (1992) 216, [JETP Lett. **55** (1992) 211].
[33] F.F. Karpeshin *et al.*, Phys.Lett. **B282** (1992) 267.
[34] F.F. Karpeshin *et al.*, Phys. Rev. **C57** (1998) 3085.
[35] R.W. Shaw *et al.*, Phys. Rev. Lett. **82** (1999) 1109.
[36] H. Ton *et al.*, Nucl. Phys. **A155** (1970) 245.
[37] C.E. Bemis *et al.*, Physica Scripta **38** (1988) 657.