EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Study of octupole deformation in n-rich Ba isotopes populated via β decay

September 27, 2013

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CERN-INTC-2013-030 / INTC-P-390
27/09/2013

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Abstract: We propose to exploit the unique capability of the ISOLDE facility to produce $^{150-151-152}$Cs beams to investigate their radioactive β-decay to $^{150-151-152}$Ba. The interest to study this mass region is twofold: from one side these nuclei are expected to show octupole deformations already in their low-lying state, and, on the other hand, gross information on the β decay is highly demanded for nuclear astrophysical model, given the fact that the r-process path lies in the proximity of accessible nuclei. The experiment will be performed with the ISOLDE Decay Station (IDS) setup using the fast tape station of K.U.-Leuven, equipped with 4 Clover Germanium detectors, 4 $LaBr_3(Ce)$ detectors and 1 LEP HPGe detector. Information on the β decay, such as lifetimes and delayed neutron-emission probabilities, will be extracted, together with the detailed spectroscopy of the daughter nuclei, via $\gamma - \gamma$ coincidences and lifetimes measurement of specific states.

Requested shifts: 24 shifts, (split into 1 runs over 1 years)

1 Motivation

1.1 Octupole deformation Ba isotopic chain

Ba isotopes are located in a region of the Segrè chart characterized by a variety of shape phenomena, including shape coexistence and possible static octupole deformations. Higher order deformations can have a strong influence on γ-decay rates and on quasi-particle energies of the nuclei, which are, in turn, inputs for the various theoretical models developed to describe nuclei in this region (see for egs. [1, 2, 3, 4, 5]).
The shape of the nuclear many-body system depends on the number of nucleons and the interactions between them: for instance, spherical forms occur in the ground state of a nucleus with a magic number of protons and neutrons, with major shells completely filled. The spherical symmetry is broken at the increase of excitation energy or angular momentum, or if more nucleons are added to the existing configuration. In these cases, the deformation can be expressed in terms of a multipole expansion, the quadrupole term being the most important deviation from sphericity. Quadrupole deformed shapes can be axially-symmetric (oblate and prolate deformation) or asymmetric (triaxial shape). In some cases, it is expected that the nuclei assume even more complicated shapes, involving higher multipolarities, for example octupole deformations (pear-like shapes), which are reflection asymmetric in the intrinsic frame. Such shape can occur in a dynamic way, through octupole vibrations, or with permanent octupole deformations [6].
Strong octupole correlations appear when the Fermi level lies between the subshell of normal parity and an intruder orbital with angular momentum which differs by three units, $\Delta J = \Delta I = 3$. This condition is fulfilled for proton numbers Z= 34, 56 and 88, or for neutron numbers N= 34, 56, 88 and 134.
The experimental observables providing information on the nuclear shape are electric moments of excited states and electromagnetic transition rates between them. In particular, strong octupole correlations leading to reflection asymmetric shapes are characterized by phenomena such as interleaved positive- and negative-parity rotational bands, in even-even nuclei, or parity doublets, in odd-A nuclei, giving rise to enhanced electric dipole (E1) and octupole (E3) transitions that connect rotational states of opposite parity. In case of stable octupole-deformed nuclei, the electric-dipole strength is expected to remain constant at increasing values of the angular momentum. The appearance of alternating-parity bands is due to quantum interference between the two degenerate intrinsic states characterized by the same value of the octupole momentum but with different sign (in a pictorial way the pear-shaped distributions point in different directions). These levels are connected by E1 transitions with large B(E1) values. However this regular pattern seem to appear only at medium spin values (I>5), and it is usually lost at high values of spin. This is confirmed by the non-appearance of backbending phenomena at increasing spin values, and it is a consequence of the stabilizing effect of octupole deformation on angular momentum, given the larger moment of inertia of octupolar shapes.
In the Ba isotopic chain alternating-parity bands, with large and constant B(E1) transition moments, have been found in $^{140-144}$Ba; the neighboring nucleus, ^{146}Ba, shows instead slower E1 transition rates than ^{144}Ba. This is understood in terms of a vanishing of the electric dipole moment D_0, which cancels out due to shell effects [7]. Most calculations

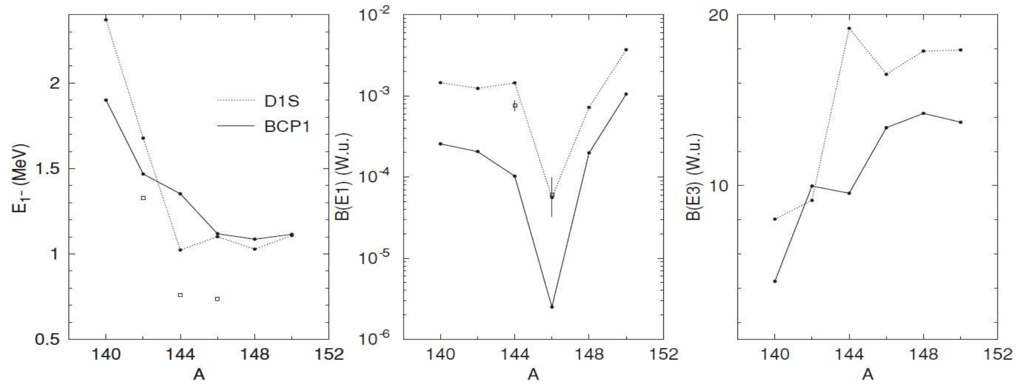

Figure 1: Systematics of excitation energies, B(E1) and B(E3) in even-even Ba isotopes obtained with the HFB mean field approach with the axially symmetric octupole moment as a constraint [5].

suggest that the ground state of ^{146}Ba shows, however, the largest octupole deformation of all barium isotopes, but at medium spins the situation changes and, while the other barium isotopes gain octupole deformation, ^{146}Ba becomes reflection-symmetric [8]. The same effect is expected to be present in the heavier even-even isotopes [9].
Experimental evidences point, instead, towards a restoration of the dipole moment [10]. The behavior of the alternating-parity states in ^{148}Ba is in fact resembling the situation of ^{144}Ba more than that of ^{146}Ba, with no sign of backbending at increasing values of the angular momentum. It is therefore important to continue such studies in the heavier members of this chain.
There are two main approaches applied to describe the collective motion of nucleons leading to reflection-asymmetric deformations. The first embodies alpha-cluster models (see for example Ref. [4]), based on the assumption that quadrupole and octupole deformations (related to even and odd multipolarity transitional moments) arise as a consequence of the collective motion of the nuclear system in the mass asymmetry coordinate. The second is developed in a mean field framework constrained by the axially-symmetric octupole moment (see for example [5]). Both approaches seem to predict octupole fluctuations around the ground state solution for $^{144-148}$Ba.
In the case of ^{150}Ba, the mean field calculations indicate some degree of instability against the octupole degree of freedom. In addition, calculations of the B(E3) transition probabilities show that the bigger B(E3) values are obtained for the nuclei with the lower 1^- excitation energies, as Fig. 1 shows. Given the downward trend of the yrast 1^- states with increasing neutron number, it is of interest extending the systematics of the 1^- level up to $^{150-152}$Ba in order to locate the maximum of octupole deformation in the A$\sim$150 region.
In general, given the expected coexistence between the typical quadrupole deformation and the less frequent octupole correlations, and the scarce experimental information on $^{150-152}$Ba, the measurement of experimental observables providing information on the nuclear shape of these isotopes is highly demanded.

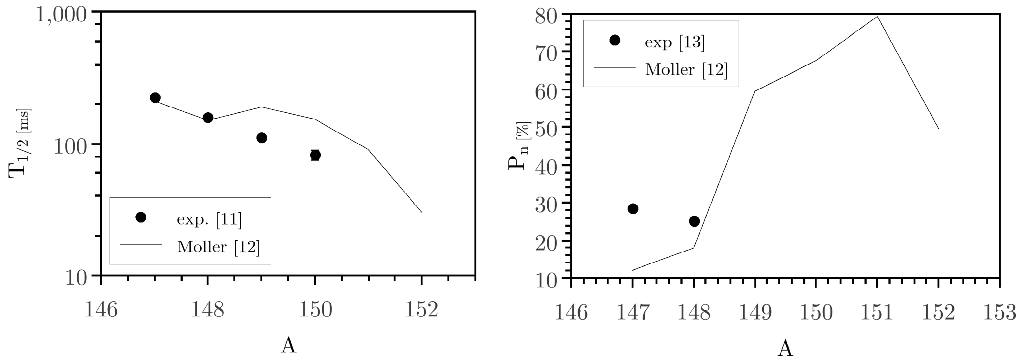

Figure 2: Left panel: Experimental [11] and theoretical [12] half-lives for Cs chain. In the right panel the measured and predicted P_n values (same references).

The measurement of the low-lying structures populated in the β decay will allow to complement the data already available from spontaneous fission studies, which so far failed to identify uniquely the decay scheme of these nuclei, owing to the large background present in the low- energy part of spectra acquired in such experiments. Moreover decay spectroscopy will complement prompt-spectroscopy studies that are under current investigation.

1.2 Beta-decay properties

The Ba isotopes of interest, ranging from A=150 to 152, will be accessed, for the first time, via the β decay of $^{150-152}$Cs.

The measurement of gross quantities such as decay half-lives and β-delayed emission probabilities P_n, are of great relevance for the understanding of the rapid neutron-capture process (r-process) around the second abundance peak, since in this mass region the r-process path lies in the proximity of accessible nuclei. If the half-lives are necessary to define the correct timescale and waiting points of the astrophysical process, the P_n values determine the r-process path, and influence fission rates calculations.

Apparent beta-feedings and tentative logft values of yrast and non-yrast low energy levels populated in the daughter $^{150-152}$Ba can be measured, providing a first access to the nuclear structure of these very neutron-rich Ba isotopes characterized by deformed shapes of even and odd multipolarity.

The predicted large P_n values will allow to also investigate, at the same time, the neighbouring odd isotopes, which are not known either.

As one can see in Fig. 2, both half-lives and known P_n values are not thoroughly reproduced by theory, with large variations mostly for this second quantity. Half-lives appear to be shorter than predicted, while P_n values are smaller.

It should be noticed that an attempt to measure the level scheme of ^{150}Ba has been made in 2004 within the IS386 ISOLDE collaboration. Despite observing a number of γ transitions de-exciting levels in ^{148,149}Ba, no γ-ray transitions were identified in ^{150}Ba following the β decay of ^{150}Cs, although other members of the A=150 mass chain were

present. This may suggest that there could be a strong ground state to ground state β transition and thus a weaker population of the excited states in ^{150}Ba. However, the measurements in 2004 were made in the "saturation mode" where no tape was used to remove the long-lived activities, and the detector setup was optimized for fast-timing measurements.
In comparison to the previous attempt, the use of the IDS setup is optimized for γ spectroscopy. The setup proposed here will have a higher β efficiency, $\sim$ 100% versus 40%, and, by using a fast tape transport system, it will be possible to suppress long-lived impurities by about 1-2 orders of magnitude.
Consequently, it is expected that the IDS station would allow to identify the γ transitions in ^{150}Ba even if they would represent only 0.3% of the β decay intensity of ^{150}Cs. This is a lower limit deduced by the previous measurement using a tape system.

2 Experimental details

The unique capability of the ISOLDE facility to produce intense beams of neutron-rich $^{150-152}$Cs will be exploited to investigate the low-energy structure of their daughter nuclei $^{150-152}$Ba, populated by β decay and/or β-delayed neutron emission.
Low-lying states will be populated in daughter nuclei, and we will have access to the first 2^+, 4^+, 1^- and, possibly, 3^- states.
The radioactive beam species will be produced in proton-induced fission reactions using a UCx target equipped with a standard surface ionizer. The yields reported by the ISOLDE database are shown in table 1. The yield for ^{152}Cs is obtained extrapolating from the intensity of neighbour isotopes.
The proposed β-decay experiment will use the IDS setup consisting of the tape station of K.U.-Leuven equipped with a fast plastic scintillator around the implantation point having almost 100% efficiency for β triggering, coupled to a combination of four Clover Germanium detectors and four $LaBr_3$(Ce) detectors to register β-delayed gamma rays. The use of one LEP-Ge detector will help identifying the implanted species by measuring their characteristic X rays, and will enhance the efficiency for low-energy γ transitions. The expected total photopeak efficiencies of the Clover detectors will be 1% at 1.3 MeV. The present intensity of the Cs beams will allow to make $\gamma - \gamma$ coincidence studies to define the correct transition sequences and help discriminate transitions populated by delayed neutron emission. The intensity ratios of transitions in the two daughter nuclei will set a lower limit for the P_n value. The presence of fast $LaBr_3$(Ce) detectors will give us access to lifetime information in the ps-ns range on the states in the daughter nuclei, therefore we will also be able to get information on the transition probabilities, B(E2) and B(E1).

3 Beam time estimate

Given the yields reported in table 1, and a γ efficiency of 2.5% for low-energy transitions, we estimate to get the count rates per day reported in table 2. This is estimated starting

Table 1: Yields of cesium isotopes from UC_x target. Yields are given in atoms per μC of primary beam

Nucleus	Y [μC^{-1}]	Q_β [Mev] [12]
^{150}Cs	1.2 10^4	11.6
^{151}Cs	1.7 10^3	10.6
^{152}Cs	1.0 10^2	12.4

Table 2: Expected count rates per day with assumptions indicated.

Event	Assumption	Events/s	Events/day
Implanted ^{150}Cs	β efficiency 100%	24000	
Formation of ^{150}Ba	P_n = 20%	1.9E4	1.7E9
$2^+ \to 0^+$	E_γ < 200 keV, I_β=0.05	24	2E6
Implanted ^{151}Ba	β efficiency 100%	3400	
Formation of ^{151}Ba	P_n = 30%	2380	2E8
$2^+ \to 0^+$	E_γ < 200 keV, I_β=0.05	3	2.6E5
Implanted ^{152}Ba	β efficiency 100%	200	
Formation of ^{152}Ba	P_n = 40%	120	1E7
$2^+ \to 0^+$	E_γ < 200 keV, I_β=0.05	0.2	1.5E4

from a proton beam of 2 μA. β feeding to the 2^+ state is roughly estimated based on the previous run and set to a lower limit value of 5% in each case.
The knowledge coming from previous experiment on ^{149}Ba we will be able to disentangle β and β-n delayed transitions in the decay ^{150}Cs→^{150}Ba, and then extract information useful to determine also the β-delayed transition in the decay of ^{151,152}Cs.
We plan to run the 3 beams (^{150,151,152}Cs) one after the other.

Summary of requested shifts:

We request **24 shifts** (8 days) divided as follows:
4 shifts with ^{150}Cs beam
8 shifts with ^{151}Cs beam
12 shifts with ^{152}Cs beam.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT
The experimental setup comprises: (*name the fixed-ISOLDE installations, as well as flexible elements of the experiment*)

Part of the equipment	Availability	Design and manufacturing
ISOLDE fast-tape station	☒ Existing	☒ To be used without any modification
Standard radiation detectors and electronics	☒ Existing	☒ To be used without any modification ☐ To be modified
	☒ New	☒ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[Part 2 of experiment/ equipment]	☐ Existing	☐ To be used without any modification ☐ To be modified
	☐ New	☐ Standard equipment supplied by a manufacturer ☐ CERN/collaboration responsible for the design and/or manufacturing
[insert lines if needed]		

HAZARDS GENERATED BY THE EXPERIMENT (if using fixed installation:) Hazards named in the document relevant for the fixed [COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH] installation.

Additional hazards:

Hazards	ISOLDE fast-tape station	Standard radiation detectors and electronics	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid		NL2 for 4 HPGe Clover detectors, total Dewar volum: 30 l	
Electrical and electromagnetic			
Electricity		mak 4kV for Ge Clover detectors	
Static electricity			

Magnetic field	[magnetic field] [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material [material]	Plastic tape		
Beam particle type (e, p, ions, etc)	$^{150-152}$Cs		
Beam intensity	2.4E4 → 200 pps		
Beam energy	< 100 keV		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☒ [ISO standard]		
• Isotope		60Co, 137Cs, 152Eu	
• Activity		< 10 microCi	
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance	[dose][mSV]		
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300 MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chem. agent], [quant.]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chem. agent], [quant.]		
Corrosive	[chem. agent], [quant.]		
Irritant	[chem. agent], [quant.]		
Flammable	[chem. agent], [quant.]		
Oxidizing	[chem. agent], [quant.]		
Explosiveness	[chem. agent], [quant.]		
Asphyxiant	[chem. agent], [quant.]		

Dangerous for the environment	[chem. agent], [quant.]		
Mechanical			
Physical impact or mechanical energy (moving parts)	[location]		
Mechanical properties (Sharp, rough, slippery)	[location]		
Vibration	[location]		
Vehicles and Means of Transport	[location]		
Noise			
Frequency	[frequency],[Hz]		
Intensity			
Physical			
Confined spaces	[location]		
High workplaces	[location]		
Access to high workplaces	[location]		
Obstructions in passageways	[location]		
Manual handling	[location]		
Poor ergonomics	[location]		

Hazard identification:

Average electrical power requirements (excluding fixed ISOLDE-installation mentioned above): [make a rough estimate of the total power consumption of the additional equipment used in the experiment]