EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

(Following HIE-ISOLDE Letter of Intent I-093)

Magnetic moment and lifetime measurements in ^{140}Ba

October 1, 2012

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Abstract

With this proposal we pursue two objectives: The measurement of the sign and magnitude of the magnetic moment of the first excited 2^+ state in ^{140}Ba and the determination of the lifetime of the 2_3^+ level in the same nucleus which is proposed to be of mixed-symmetry (ms) character. The result of the $g(2_1^+)$ measurement will help to understand the observed severe discrepancy between the available experimental information on magnetic moments of 2_1^+ states in the chain of Ba isotopes above the N=82 shell closure and Monte Carlo shell model calculations which on the other hand very nicely describe their excitation energies and reduced transition probabilities along the transition from spherical towards deformed shapes. The measurement of the lifetime of the 2_3^+ level at an excitation energy of 1994 keV would allow to unambiguously determine the character of this state. In case that it indeed contains most of the mixed-symmetry strength in this nucleus as it had been proposed before its lifetime should be very short, in the order of 50-200 fs, and thus accessible for a measurement on the basis of the observed Doppler shifts. From this experimental information the $B(M1; 2_3^+ \rightarrow 2_1^+)$ value could be deduced allowing for an extension of the systematics of ms states from the stable N=84 isotones down to radioactive ^{140}Ba.

Requested shifts: 15(+3) shifts, (split into 1 run over 1 year)
Beamline: MINIBALL + TF chamber (IEM Madrid)

Physics Motivation

1) g(2_1^+) in ^{140}Ba

In the even neutron-rich Ba isotopes above the N=82 neutron shell closure the collectivity increases from the spherical semi-magic isotope ^{138}Ba$_{82}$ to the axially deformed symmetric rotor ^{148}Ba$_{92}$. This development of collectivity manifests itself in a smooth decrease of the excitation energy of the first excited 2$^+$ state, E(2_1^+), and a simultaneous increase of the probability to excite this state, B(E2; $0_1^+ \rightarrow 2_1^+$). As shown in Fig. 1, the variation of these two quantities in the transitional region is very nicely described by calculations performed in the framework of the Monte Carlo shell model (SM) and presented in Ref. [1]. Furthermore, also the electric quadrupole moment of the 2_1^+ state in ^{140}Ba, Q_{exp}=-0.52(34) eb, which has recently been measured with MINIBALL at REX-ISOLDE [2], is found to be in perfect agreement with the SM value, Q_{SM}=-0.51 eb. In the light of this consistent picture obtained from experiment and theory for the transitional Ba isotopes on the basis of the quantities E(2_1^+) and B(E2), the evident discrepancies found between experiment [3-5] and the same SM calculations [6] for the magnetic moments of the first excited 2$^+$ states is all the more surprising (compare Fig. 1, right). In the shell model the 2_1^+ g factor is nearly constant and close to the ratio Z/A for the isotopes above A=144 when collectivity is fully developed. In the lighter transitional isotopes, on the other hand, the single-particle degree of freedom seems to dominate leading to rapid changes in the magnitude of the magnetic moment. In contrast, the available experimental data show a smooth degrease of g(2_1^+) with increasing neutron number in agreement with calculations performed using the IBA-2 model [4]. The discrepancy between the experimental trend and the SM calculations is largest for ^{140}Ba with expected values of g(2_1^+)=+0.5 and g_{SM}(2_1^+)=+0.1 (the latter due to the negative magnetic moments of neutrons in the $f_{7/2}$ and $p_{3/2}$ orbits), respectively. Unfortunately, this magnetic moment has not yet been determined experimentally. We therefore propose here to measure g(2_1^+) in ^{140}Ba to study to which extent the SM calculations correctly reproduce the single-particle content of the wavefunction of the 2_1^+ state. Since the magnetic moment is the much more sensitive measure of the single-particle structure of a state as compared to the B(E2) value in the case of a severe disagreement for the g factors, the agreement with respect to the B(E2) value would have to be re-assessed.

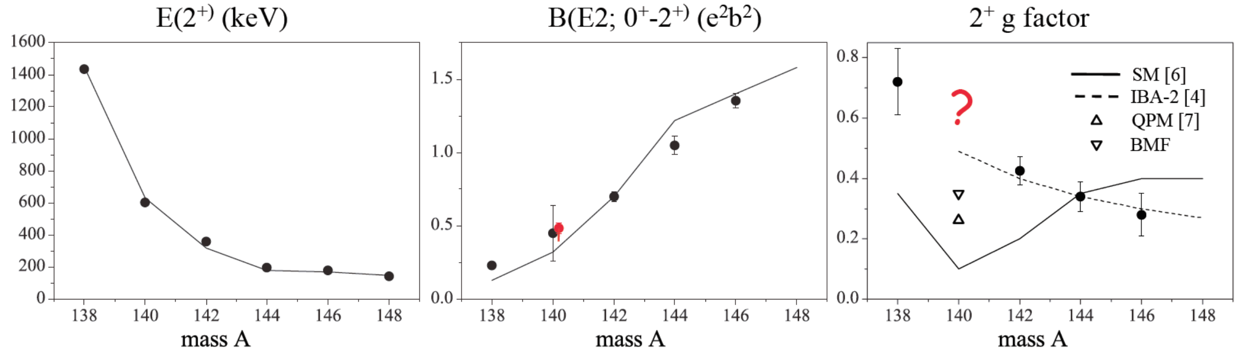

Figure 1: Properties of the first excited 2$^+$ states in the even Ba isotopes (Z=56) above the N=82 shell closure from experiment (filled circles) and SM calculations (lines): excitation energies, E(2_1^+) (left), reduced transition probabilities, B(E2; $0_1^+ \rightarrow 2_1^+$) (middle) and g factors, g(2_1^+) (right). See text for references.

It is worth mentioning that recent beyond-mean-field (BMF) calculations, which were shown in Ref. [2] to reproduce the electromagnetic properties of the 2_1^+ state in ^{140}Ba as good as the SM, predict a value of g(2_1^+)=0.35 for its g factor. A similar value in the middle between the experimental trend and the SM, namely $g(2_1^+)=0.27$, is obtained in calculations using the quasiparticle-phonon model (QPM) [7]. The latter calculations, which nicely reproduce the experimental excitation energies of the first three 2^+ and the first 3^- states as well as the $B(E2; 0_1^+\rightarrow 2_1^+)$ value will be used below to estimate the population of the 2_3^+ state in the experiment we propose here.

2) $\tau(2_3^+)$ in ^{140}Ba

The second goal of this proposal is related to the study of mixed-symmetry (ms) states in weakly collective vibrational nuclei [8]. These states play an important role for the understanding of the effective proton-neutron interaction in collective valence shell excitations and have been systematically studied in a number of N=80 and N=84 isotones close to the N=82 neutron shell closure (compare Fig. 2). These studies revealed that the underlying single-particle structure has an important influence on the properties of ms states. In particular, it has been shown that the observed fragmentation of ms states in the Z=58 isotopes ^{138,142}Ce is related to the lack of shell stabilization at the proton $g_{7/2}$ subshell closure [10,11]. While the stable N=80 and N=84 isotopes have recently been studied in large detail mainly using Coulomb excitation in inverse kinematics, the available information about ms states in radioactive nuclei, which is required in order to extend the range of the studies, is still scarce. Only very recently, the one-phonon mixed-symmetry 2^+ state has been identified for the first time in an unstable nucleus, namely the N=80 isotone ^{132}Te [12], allowing to complete the N=80 systematics down to Z=52. Within the N=84 chain, ^{140}Ba constitutes the next piece in the puzzle being situated next to the two stable nuclei ^{142}Ce and ^{144}Nd both studied in detail in the past [11,13]. In ^{140}Ba the 2_3^+ state at an excitation energy of 1994 keV has been suggested in Ref. [14] to be the ms 2^+ state. However, this assignment is based only on the small multipole mixing ratio of the $2_3^+\rightarrow 2_1^+$ transition while the crucial experimental information, namely the lifetime of this state, is still missing. Since the branching ratio for the decay of the 2_3^+ state to the 2_1^+ level and the ground state, respectively, is experimentally known from a β-decay study [15], the lifetime information will allow us to extract the absolute M1 strength of the $2_3^+\rightarrow 2_1^+$ transition. A large value of this strength would imply a safe assignment of ms character to the 2_3^+ state. Mixed-symmetry 2^+ states are very short lived with typical lifetimes of a few hundred

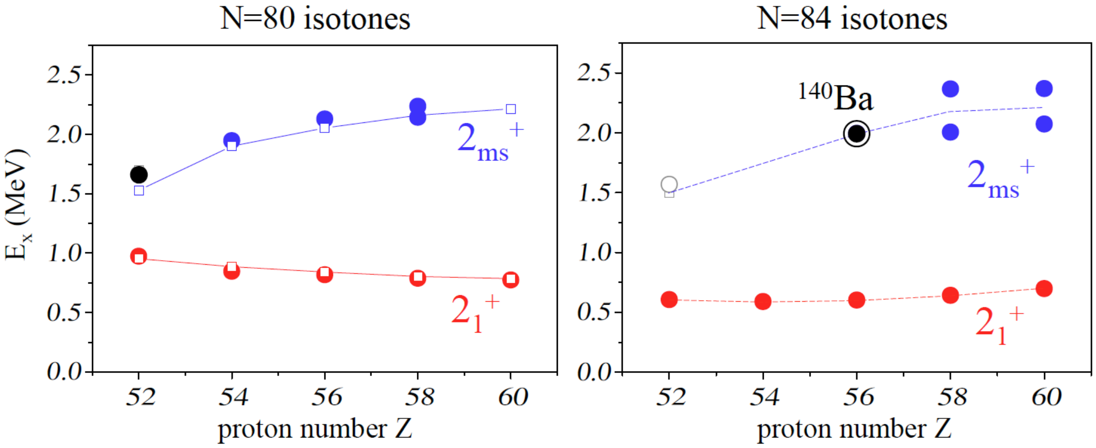

Figure 2: Systematics of the excitation energies of the first excited, fully symmetric (red circles) and mixed-symmetry (blue circles) 2^+ states in the N=80 (left) and N=84 (right) isotones. Radioactive isotopes are marked by black circles. For N=80, the SM calculations from Ref. [9] are included for comparison (open squares).

femtoseconds or less. We intend to determine this lifetime from the Doppler shifted energy of the $2_3^+ \rightarrow 2_1^+$ 1392 keV transition, which depends on the lifetime when a thick target is used (see below). Furthermore, it would be very interesting to study whether the ms state in ^{140}Ba is fragmented like the one in ^{142}Ce and ^{144}Nd or concentrated in a single isolated state as in the case of ^{136}Ba.

Experimental technique

We propose to measure the g factor of the 2_1^+ state in ^{140}Ba at an excitation energy of 602 keV using the transient field technique (TF) in combination with Coulomb excitation in inverse kinematics. The transient field technique in combination with Coulomb excitation in inverse kinematics ensures high detection efficiency of coincident γ-rays due to kinematic focussing of the target ions in the beam direction and provides high spin alignment of the excited states followed by strongly anisotropic γ-angular correlations. The latter is a prerequisite to be sensitive to the spin precessions in the TF. Furthermore, the inverse kinematics implies relatively high recoil velocities of the Ba ions and therefore large transient fields. We plan to use the new TF target chamber which has been employed for the first time in experiment IS483 performed in November 2011. In that experiment the g factor of the first excited 2^+ state in ^{72}Zn has been measured at MINIBALL using the same experimental technique [16].

The radioactive ^{140}Ba ions will be produced by bombarding a UCx target with 1.4 GeV protons. The average beam intensity on the secondary target is estimated to 5×10^6 ions/s based on the measured current of 30 epA (33^+) before defocussing onto MINIBALL in experiment IS411 in 2007. The target will consist of a C layer to Coulomb excite the ^{140}Ba beam ions, a Gd layer magnetized by an external field in which the excited Ba ions experience precessions during their passage through the transient field and a Cu backing which serves as a stopper for the excited nuclei providing a hyperfine interaction-free environment. Deexcitation γ-rays are detected by four MINIBALL Cluster detectors positioned close to the horizontal plane at ±65° and ±115° with respect to the beam axis in coincidence with forward scattered C ions. These C target ions will be detected in four rectangular Si detectors positioned above, below, to the left and to the right of the beam axis covering an angular range of 20° to 40° degrees. Note that for the g factor analysis only two of the Si detectors can be used (due to a too small spin alignment for a particle detection close to the horizontal plane).

The thick multi-layer precession target will allow to determine simultaneously to the precession measurement for the $2_1^+ \rightarrow 0_1^+$ transition the lifetime of the 2_3^+ state in ^{140}Ba at an excitation energy of 1994 keV. This lifetime can be deduced from the Doppler shift or Doppler lineshape (depending of the lifetime) of the 1392 keV $2_3^+ \rightarrow 2_1^+$ transition observed in the MINIBALL detectors. The same technique has already been successfully applied using similar multilayer precession targets before [17,18].

Beam time estimate

In the following we give an estimate of the beam time requested for the determination of the 2_1^+ g- factor in ^{140}Ba with an accuracy of about 10% in the case of g=0.3 and 20% for g=0.1. The estimate is based on the following assumptions:

- Multilayer-Target: 1.0 mg/cm^2 C+9.0 mg/cm^2 Gd+1.0 mg/cm^2 Ta+6.5 mg/cm^2 Cu
- Beam: ^{140}Ba at an energy around 470 MeV corresponding to 3.36 MeV/u with an average intensity of 5x10^6 particles/s on the reaction target.
- γ-ray detection efficiency: 0.5% at 0.6 MeV and 0.3% at 1.4 MeV for each crystals of the four MINI-BALL Cluster detectors positioned at ±65° and ±115° with respect to the beam axis in a horizontal plane (at a distance of 10 cm from the target).
- Detection of recoiling target ions: Four 20x20 mm^2 segmented Si detectors placed 1 cm above, below, to the left and to the right of the beam axis 3 cm behind the target (note that only the vertical ones can be used for the g factor analysis).

Taking into account the target properties and standard transient field parametrizations, a precession angle of about 140 mrad/g is expected for the 2_1^+ state in ^{140}Ba. The logarithmic slope of the $2_1^+ \rightarrow 0_1^+$ angular correlation within a Cluster positioned at Θ=65° with respect to the beam varies in the range 1.0-2.5. From standard Coulomb excitation calculations and assuming the particle detection geometry described above we can infer an integral cross section of σ=17 mb for the excitation of the 2_1^+ state. The statistics needed to reach a certain accuracy of the measured magnetic moment of course depends on its (unknown) absolute value. Within **15 shifts** with beam on target we would reach the envisaged uncertainties of 10% in the case of g=0.3 and 20% for g=0.1.

The integral excitation cross section (considering four Si detectors) for the 2_3^+ state is estimated to σ=0.34 mb on the basis of the theoretical value B(E2; $0_1^+ \rightarrow 2_3^+$)=0.055 e^{2}b^2 [7]. Note that this value is close to the ones experimentally determined for ms 2^+ states in ^{138,142}Ce and ^{144}Nd [10,11,13] and therefore considered realistic. Taking into account the known branching ratio b=0.78(8) of the $2_3^+ \rightarrow 2_1^+$ transition we expect a total of about 100 counts per crystal in the 1392 keV line accumulated in **15 shifts** with beam on target. Since in our setup at least four crystals are positioned at roughly the same polar angle Θ with

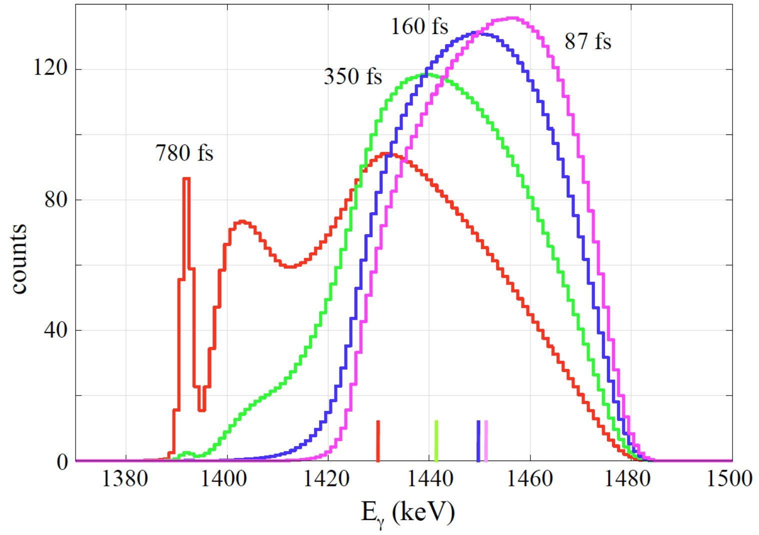

Figure 4: Simulated lineshapes of the 1392 keV, $2_3^+ \rightarrow 2_1^+$ transition in ^{140}Ba assuming different lifetimes of the 2_3^+ state, namely $\tau(2_3^+)$=87, 160, 350 and 780 fs. The simulations have been performed for a MINIBALL crystal positioned at Θ=50° with respect to the beam and assuming the beam and target properties listed above.

respect to the beam spectra can be added and the statistics is sufficient to determine the position-dependent Doppler shifted energy of this transition from which the lifetime of the 2_3^+ state can be deduced with sufficient precision. Note that the B(M1; $2_{ms}^+ \rightarrow 2_1^+$) values are typically larger than 0.1 μ_N^2 which in the case of the 2_3^+ state in ^{140}Ba corresponds to a lifetime of τ=160 fs. The sensitivity of the centroid position of the 1392 keV line on the lifetime of the 2_3^+ state is illustrated in Fig. 4. For example, at a detection angle of Θ=50° lifetime values of 160 fs and 350 fs correspond to a difference in the centroid position of 7 keV.

Summary of requested shifts:

15 shifts of beam on target plus 3 shifts for beam preparation and calibrations.

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Appendix

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises: *MINIBALL + TF Chamber (IEM Madrid)*

Part of the Experiment	Availability	Design and manufacturing
1: MINIBALL	☒ 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
2: TF Chamber (IEM-Madrid)	☒ 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

HAZARDS GENERATED BY THE EXPERIMENT

Hazards named in the document relevant for the fixed MINIBALL installation. The TF chamber itself does not pose any additional hazard, with the exception of the target cooling, which is done with liquid/gas nitrogen. The hazards due to cooling are indicated in the table below.

Additional hazards:

Hazards	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[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	[fluid], [pressure][Bar], [volume][l]	liquid N_2 - few liters $\sim$100 mbar pressure (max) through chamber	
Electrical and electromagnetic			
Electricity	[voltage] [V], [current][A]		
Static electricity			
Magnetic field	[magnetic field] [T]		
Batteries	☐		

Capacitors	☐		
Ionizing radiation			
Target material [material]			
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope			
• Activity			
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]: 0.5 kW