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EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Committee

The application of ISS to measure E3 transition strengths in rare-earth and EDM candidate nuclei.

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Abstract

We propose to use the ISOLDE Solenoidal Spectrometer, incorporating an advanced silicon array, to measure E3 transition strengths in a selected stable or long-lived rare-earth nucleus, with N~ 88. This will be a proof-of-principle experiment to test whether the technique can be applied to heavier odd-mass nuclei such as ^{225}Ra that are candidates for highly-sensitive EDM searches.

Scientific case

The only observable that should provide unambiguous and direct evidence for enhanced octupole correlations is the electric octupole (E3) moment, because it is generated by coherent contributions arising from the quadrupole-octupole shape and should be quite insensitive to single-particle effects. It has been demonstrated by our collaboration [Gaf13] that radioactive beams of heavy nuclei with A ~ 220, provided by REX-ISOLDE, can be successfully accelerated with sufficient intensity to measure both even- and odd-order electric-multipole matrix elements with an accuracy of 10% or better, showing clear evidence that ^{224}Ra is octupole deformed while ^{220}Rn has characteristics of an octupole vibrator. These measurements have tested various theoretical approaches that, while in agreement for the transition electric quadrupole moments, give divergent predictions for the E3 moments. In addition, knowledge of the octupole collectivity is important for the interpretation of limits obtained in searches for CP-violating permanent atomic electric-dipole moments (EDM). The sensitivity of such searches is increased, through enhancement of the Schiff moment, by factors of 100-1000 for odd-A nuclei having sizeable octupole moments and low-lying parity doublets.

A major goal would be to measure E3 moments in odd-mass Rn and Ra isotopes directly. This will enable the dependence of the Schiff moment on any CP-violating nuclear forces to be determined and enable the results of new EDM searches (e.g. [Par15]) using octupole Rn and Ra atoms to be interpreted. In principle this can be done by measuring γ-ray and conversion electrons. However, we believe that the density of states near the ground state in these nuclei will make such measurements extremely difficult. Instead, an alternative approach [But15] would be to measure the population of the states directly using (d,d'), provided that sufficient energy resolution can be achieved in the charged-particle spectrometer, see Fig. 1. Indeed, such measurements have been made for states in ^{226}Ra using a single-gap magnetic spectrometer [Tho90]. Our measurements would employ the ISOLDE Solenoidal Spectrometer (ISS), for which a FWHM final state resolution of ~ 20-30 keV FWHM should be achievable. This will exploit the advanced Si array, 500mm in length and having a detector strip pitch of 1 mm along the beam axis and 2 mm orthogonal to it currently being constructed within the UK ISOL-SRS project. The array is due to be shipped in stages to CERN from November 2019. The estimate of the energy resolution also assumes that the energy spread of the radioactive beam from HIE-ISOLDE is reduced to 0.1% through de-bunching and phase-rotation. Even better resolution, comparable to that expected using cooled beams from a storage ring, can be achieved, at the expense of beam intensity, by collimating the beam.

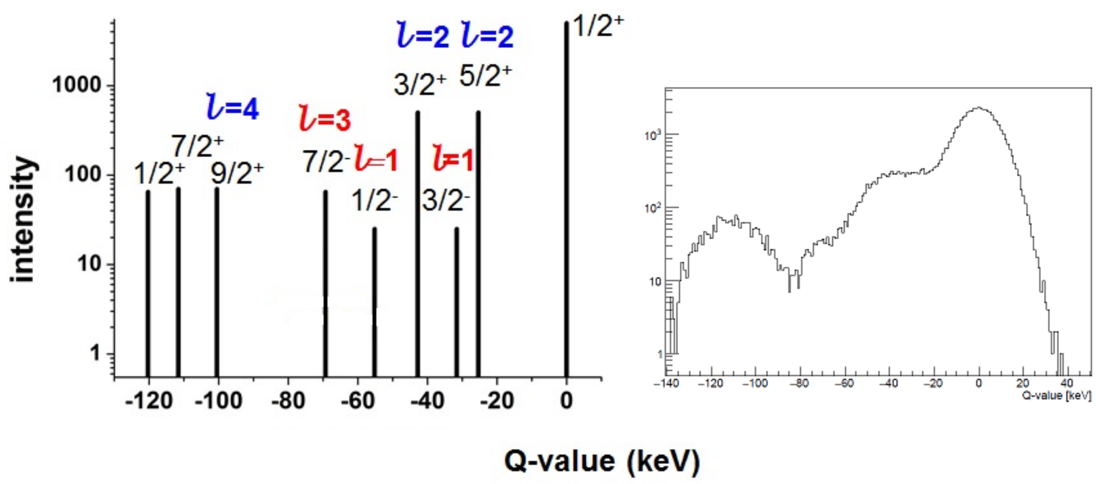

Figure 1 Expected spectrum of states in ^{225}Ra populated by the (d,d') reaction at a bombarding energy of 10 MeV.A. The relative intensity of the low-lying states, labelled by their spin, parity and l-transfer, is given in the left-hand figure. The right-hand figure has folded in the detector response, assuming a FWHM resolution of 20keV. See [But15].

We propose to test this approach by measuring E2 and E3 transition strengths in selected rare-earth nuclei with N~88. Fig. 2, an updated version of that presented in [But16], summarises our knowledge on E3 strengths in this region. These include the recent results on ^{144,146}Ba [Buc16, Buc17], whereby a largely American collaboration carried out measurements at ANL using CARIBU +GRETINA. We would choose one example from rare-earth (RE) isotopes ^{146,148}Nd, ^{148,150}Sm and ^{150,152}Gd, which are stable or (^{150}Gd) very long-lived. Most of these isotopes have been studied using numerous probes including (d,d') and heavy-ion Coulomb excitation.

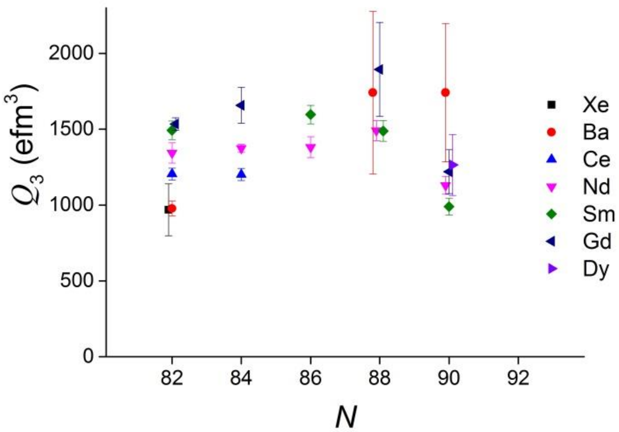

Figure 2 The systematics of measured E3 intrinsic moments Q_3 for $3^- \rightarrow 0^+$ transitions in the lanthanide region [But16].

The RE(d,d') reaction will be carried out in inverse kinematics at ~9-10 MeV.A using the ISS spectrometer to analyse the outgoing deuterons. We would run at an intensity of ~10^5 ions per second. An ionisation detector will be used downstream to detect the beam and recoils, in order to provide a time reference for the light particle identification (PID) and to suppress events from compound-nucleus reactions involving the carbon in the deuterated polyethylene target. The PID for the light particles, which makes use of the cyclotron period in the magnetic field of ISS, will suppress the (d,t) and (d,^{3}He) channels. The (d,α) channel cannot be removed in this way, but as the kinematics are quite different from (d,d') events from the two channels can be easily distinguished in the analysis.

Angular distributions for deuterons, following excitation of the 2^+_1 and 3^-_1 states via ^{146}Nd(d,d') at 10 MeV.A, are shown in Fig. 3. In this experiment we can measure the cross-section for the population of the 3^-_1 state. In this way we can extract β_3^2, which is the square of the deformation length. This quantity relates the experimental cross-section to the DWBA cross-section; the value of B(E3;$0^+ \rightarrow 3^-$) is proportional to β_3^2. We assume an integrated cross section of 2 mb for the c.m. angular range 20° -40°, as determined using the finite-range DWBA code PTOLEMY. Under these conditions, we expect 30 counts per day in the peak for a target thickness of 20 μg/cm^2. Our estimate for running time is 5 days, which should result in a 8% statistical uncertainty in the value of B(E3). This can be compared with the 60-70% error in B(E3) in ^{144,146}Ba [Buc16,Buc17]. This is also comparable to the ~10% systematic uncertainty in determining the absolute cross-section. However, the main aim of the measurement is to determine the Q-value resolution, in order to assess whether this technique can be applied to odd-A Rn and Ra isotopes.

In addition to the aforementioned beam(s), accelerated stable noble-gas beams will be required from HIE-ISOLDE at different stages of ISS commissioning. These will be used to commission the advanced ISS silicon array (including electronics and array alignment) during LS2. Stable isotopes of Ne, Ar, Kr or Xe will be used for this purpose. It is envisaged that at least a week is required for commissioning the new array plus a day of stable beam for calibration before data-taking experiments. These noble-gas beams do not require the production target and can be produced directly from the EBIS.

We should note that there are number of related experiments at ISOLDE and elsewhere, see appendix 1.

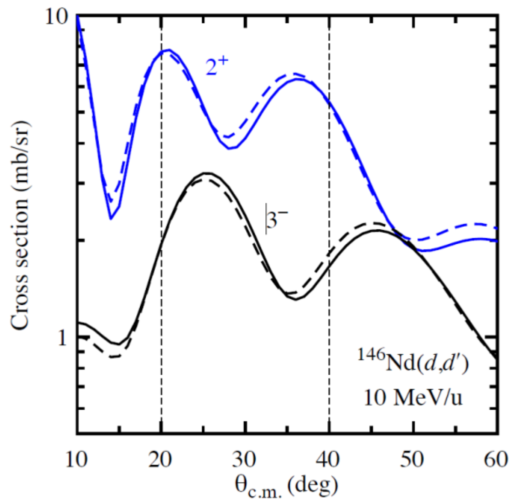

Figure 3 Angular distributions for 2^+_1 and 3^-_1 states in ^{146}Nd calculated using PTOLEMY. The assumed value of β_λ was 0.15 for λ = 2,3. Taken from ATLAS #1619 (see appendix 1).

References:

[Gaf13] Gaffney L P et al. 2013 Nature **497** 199

[Par15] Parker RH et al. 2015 Phys. Rev. Lett. **114** 233002

[Dob05] Dobaczewski J and Engel J 2005 Phys. Rev. Lett. **94** 232502

[But15] Butler PA 2015 JPS Conf. Proc **6** 010017 (ARIS 2014)

[Tho90] Thorsteinsen et al. 1990 Phys. Scripta **42** 141

[But16] Butler PA 2016 J.Phys.G. **43** 073002

[Buc16] Bucher B et al. 2016 Phys. Rev. Lett. **116** 112503

[Buc17] Bucher B et al. 2017 Phys. Rev. Lett. **118** 152504

Appendix 1: Related experiments

ISOLDE #552 "Measurement of octupole collectivity in Rn and Ra nuclei using Coulomb excitation" (Butler et al.) is yet to be scheduled. It will use MINIBALL+CD (+SPEDE in some cases) to study ^{221,222,224,226}Rn and ^{222,226,228}Ra. The participants of this experiment have a strong overlap with our collaboration.

ISOLDE #553 "Measurements of B(E3,$0^+ \rightarrow 3^-$) strength in the octupole correlated nuclei ^{142,144}Ba using Coulomb excitation" (Scheck et al.) is scheduled to run in July 2017. It will use MINIBALL +CD for these measurements. The participants of this experiment have a strong overlap with our collaboration.

ISOLDE #618 "Two-phonon octupole collectivity in the doubly-magic nucleus ^{146}Gd" (de Angelis et al.) plans to use MINIBALL + CD to determine the double octupole E3 strength ($6^+ \rightarrow 3^-$) in ^{146}Gd via Coulomb excitation.

ISOLDE I-158 "Are ^{221}Rn and ^{223}Rn good candidates to search for an atomic EDM?" (Scheck et al.). This LoI requests beam development of pure ^{221,223}At beams in order to study low lying parity doublets in the Rn isotopes following beta decay. The participants of this experiment have a strong overlap with our collaboration.

ISOLDE I-173 "Octupole collectivity in ^{229}Pa to guide searches for physics beyond the Standard Model…" (de Angelis et al.). This LoI aims to provide an estimate for the beam intensity of ^{229}Pa and ^{228}Th at in order to collect the necessary information for a future proposal

ATLAS #1531 "Octupole strength in ^{225}Ra: Providing nuclear structure information for an EDM search" (Janssens et al.). This proposes to use GRETINA + CHICO2 to measure the intensity of E1 transitions between the $K=1/2^{\pm}$ bands in ^{225}Ra. The scheduling of this experiment awaits the development of a 3mCi source of ^{225}Ra ($T_{1/2}$=15 days).

ATLAS #1619 "The (d,d') reaction on ^{146}Nd" (Kay et al.) involves our collaboration and will use HELIOS to test the same technique as described here. In this case the expected resolution is ~100 keV, sufficient to resolve the 3^- state from its neighbours in ^{146}Nd but ultimately insufficient for resolve states in ^{225}Ra.

ATLAS #1709 "Octupole correlations in neutron-rich nuclei: Coulomb Excitations of odd-A…" (Macchiavelli et al.) has been approved beam time to study ^{143}Ba using CARIBU, GRETINA, CHICO2.

ALTO N-SI-69 "Measurement of octupole collectivity in Nd, Sm and Gd nuclei using Coulomb excitation" (Zielińska et al.) took beam in January 2015. This experiment, which involves our collaboration, used the MINORCA Ge array to measure B(E3)s in ^{146}Nd and ^{148}Sm; the data are being analysed.

Appendix 2

DESCRIPTION OF THE PROPOSED EXPERIMENT

The experimental setup comprises:

	Availability	Design and manufacturing
ISOLDE Solenoidal Spectrometer	☒ Existing	☒ To be used without any modification
Advanced silicon array constructed within ISOL-SRS project	☐ 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
Fast ionisation detector	☐ 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

Additional hazards:

Hazards	*[Part 1 of the experiment/equipment]*	*[Part 2 of the experiment/equipment]*	*[Part 3 of the experiment/equipment]*
Thermodynamic and fluidic			
Pressure			
Vacuum			
Temperature			
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	LHe]		
Electrical and electromagnetic			
Electricity			
Static electricity			
Magnetic field	2.5 [T]		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material			
Beam particle type (e, p, ions, etc)			
Beam intensity			
Beam energy			
Cooling liquids	Liquid N2		
Gases			
Calibration sources:	☐		
• Open source	☐		

• Sealed source	☐		
• Isotope			
• Activity			
Use of activated material:			
• Description	☐		
• Dose rate on contact and in 10 cm distance			
• Isotope			
• Activity			
Non-ionizing radiation			
Laser			
UV light			
Microwaves (300MHz-30 GHz)			
Radiofrequency (1-300MHz)			
Chemical			
Toxic			
Harmful			
CMR (carcinogens, mutagens and substances toxic to reproduction)			
Corrosive			
Irritant			
Flammable	Isobutane or tetrafluoromethane		
Oxidizing			
Explosiveness			
Asphyxiant			
Dangerous for the environment			
Mechanical			
Physical impact or mechanical energy (moving parts)			
Mechanical properties (Sharp, rough, slippery)			
Vibration			
Vehicles and Means of Transport			
Noise			
Frequency			
Intensity			
Physical			
Confined spaces			
High workplaces			
Access to high workplaces			
Obstructions in passageways			
Manual handling			
Poor ergonomics			

0.1 Hazard identification

3.2 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)*