EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Octupole collectivity in ^{229}Pa to guide searches for physics beyond the Standard Model: Extraction rate and beam composition of ^{229}Pa and ^{228}Th

October 6 2016

G. deAngelis[1], P.A. Butler[2], Th. Storà[3], M. J. G. Borge[3], L. Razvan[3], K. Johnston[3], L. Gaffney[3], K. Hadynska-Klek[1], M. Zielinska[4], B. Blank[5] S. Lunardi[6], F. Gramegna[1], A. Goasduff[1], G. Jaworski[1], D.R. Napoli[1], G. Prete[1], M. Siciliano[1], J. Valiente Dobon[1], D. Bazzacco[6], F. Recchia[6], A. Boso, [6], P.R. John[1], S.M. Lenzi[6], R. Menegazzo[6], D. Mengoni[6], D. Testov[6], B. Melon[7], A. Nannini[7], C. Fahlander[8], R. Orlandi[9], P. Reiter[10], D. Rosiak[10], M. Seidlitz[10], N. Warr[10], T. Kroell[11], C. Chenrich, [11], T.D. Goodacre[12], B. Marsh[12], M. Rocchini[7], E. Sahin[13], G. Benzoni[14], D. Santonocito[15], C. Corradi[1], S. Szilner[16], M. Scheck[17], T. Marchi[18], A. Gottardo[19]

1 INFN Laboratori Nazionali di Legnaro, viale dell'Università 2 I 35020 Legnaro, Italy
2 Oliver Lodge Laboratory, University of Liverpool, Liverpool L69 7ZE, UK
3 Experimental Physics Department, CERN, CH-1211 Geneva 23, Switzerland
4 DRF IRFU CEA, Saclay, France
5 CENG Bordeaux, France
6 INFN and Dipartimento di Fisica e Astronomia, Università di Padova, Padova, Italy
7 INFN sezione di Firenze, Firenze, Italy
8 Department of Physics, Lund University, Lund, Sweden
9 Japan Atomic Energy Agency, Tokay, Japan
10 Institut fuer Kernphysik, Universitaet zu Koeln, Koeln, Germany
11Institut fuer Kernphysik, Technische Universitaet Darmstadt, Darmstadt, Germany
12 Engineering Department, CERN, CH-1211 Geneva 23, Switzerland
13 University of Oslo, Oslo, Norway
14 INFN Sezione di Milano e Dipartimento di Fisica dell'Università, Milano, Italy
15 INFN LNS, Catania, Italy
16 University of Zagreb, Croatia
17 School of engineering and computing, University of west Scotland, Paisley, UK
18 University of Leuven, Leuven Belgium
19 IPNO, Orsay, France

Spokesperson(s): Giacomo de Angelis (giacomo.deangelis@lnl.infn.it)
Local contact: Karl Johnston (karl.johnston@cern.ch) Liam Gaffbey (liam.gaffney@cern.ch)

Abstract

The determination of electric dipole moments (EDM), which violate parity and time-reversal invariance, is one of the crucial steps to pinpoint physics beyond the Standard Model. At present the most sensitive EDM search is performed on ^{199}Hg and the upper limits already constrain various extension of the Standard Model.

Nuclear structure can strongly amplify the sensitivity of EDM measurements, in particular the occurrence of octupole correlations in nuclei lead to considerably larger Schiff moments enhancing atomic EDM. One of the most promising cases is the ^{229}Pa nucleus. Due to the expected octupole collectivity and being an odd nucleus an enhancement factor of the order of 10^3 has been calculated with respect to Hg nuclei.
The final aim of the research envisaged in this LOI is a characterization of the octupole collectivity of ^{229}Pa and of the "core" nucleus ^{228}Th. The octupole collectivity of ^{229}Pa and ^{228}Th can be determined via Coulomb excitation. **Such measurements are only possible at the HIE-ISOLDE facility due to its unique performances able to post-accelerate radioactive nuclei of such heavy mass.**
Because ^{229}Pa and ^{228}Th have never been extracted at ISOLDE, prior to this it is necessary to know the extraction rate from UCx and ThO_2 targets.

The specific aim of this Letter of Intent is to provide an estimate for the beam intensity of ^{229}Pa and ^{228}Th at ISOLDE in order to collect the necessary information for a future proposal concerning the measurement of the octupole collectivity in such nuclei.

For providing this information we are requesting 2 shifts of beam time of mass A=229 and 228 using UCx and ThO_2 targets.

Requested shifts: [2] shifts
Beamline: []

Beam A=229 and 228 from UCx and ThO_2 target

1 Motivation

The search for physics beyond the Standard Model (SM) is presently a major issue. Despite its spectacular success, it is recognized that the SM could be incomplete and could eventually be incorporated into a more fundamental framework. As an example the excess of matter over antimatter in the Universe indicates the presence of baryon-number-violating interactions and most likely of new sources of charge conjugation-parity (CP) violation.

The existence of a finite permanent electric dipole moment (EDM) of a particle or an atom would violate time-reversal symmetry (T), and would also imply violation of the combined charge conjugation and parity symmetry (CP) through the CPT theorem [1,2,3]. EDMs are suppressed in the SM of particle physics, lying many orders of magnitude below current experimental sensitivity. Additional sources of CP violation are needed to account for baryogenesis and many theories beyond the SM, such as supersymmetry [4,5], predict EDMs within experimental reach.

Experimental searches for EDMs have so far yielded no results. The most significant limits have been set on the EDM of the neutron [6], the electron [7] and on the ^{199}Hg atom [8], leading to tight constraints on extensions of the SM [5].

The most sensitive EDM search to date is performed on the Hg nuclei providing for d (^{199}Hg) < ($0.49 \pm 1.29_{stat} \pm 0.76_{syst}$) x$10^{-29}$ *e* cm [8]. This value has been used to set new constrains on CP violation in physics beyond the standard model but an enhancement of about three orders of magnitude would be necessary to probe the prediction of the SM.

CP violation in atomic nuclei is conventionally parameterized by the Schiff moment S, the lowest order CP violating nuclear moment unscreened by the electron cloud. Schiff showed that any neutral system of electrically charged, point-like constituents interacting only electrostatically have no net EDM [9].

Nuclear structure can strongly amplify the sensitivity of nuclear EDM measurements. In particular the occurrence of octupole correlations in nuclei lead to closely spaced parity doublets and considerably larger Schiff moments (proportional to the difference between the mean square radius of the nuclear dipole moment distribution and the nuclear charge distribution). The EDM of atoms is induced by the interaction of the electrons with the nuclear Schiff moment. Because a CP-violating Schiff moment induces a contribution to the atomic EDM, a large enhancement due to the octupole effects translates into an improved sensitivity to an atomic EDM when compared to atomic systems having nuclei without this deformation. Enhancements factor of 10^2-10^3 have been calculated for nuclei with octupole deformation [10,11] or soft octupole vibrations [12]. Actinides atoms as Ra and Pa are among the best candidate in the search for atomic EDM.

Prior to the long-term program required for such (atomic) measurements, it is critical to identify the best candidates. In particular the EDM of Pa is calculated to exceed the EDM of Ra by a factor 40 [13] and may become a prime candidate for an EDM measurement in the future. A particularly promising case is ^{229}Pa. Condition for that is the high octupole collectivity of the nucleus. Being an odd system the direct determination of the octupole strength is certainly difficult but an estimation can be obtained by the neighbour even-even nucleus ^{228}Th. Since ^{229}Pa can be seen as a proton coupled to the ^{228}Th core, the octupole collectivity of those two nuclei can be assumed to be similar (or enhanced in the odd-mass system due to the polarization). The octupole collectivity of ^{228}Th can be determined via a Coulomb excitation reaction through the B(E3) strength of the 0^+ to 3^- state of the octupole band.

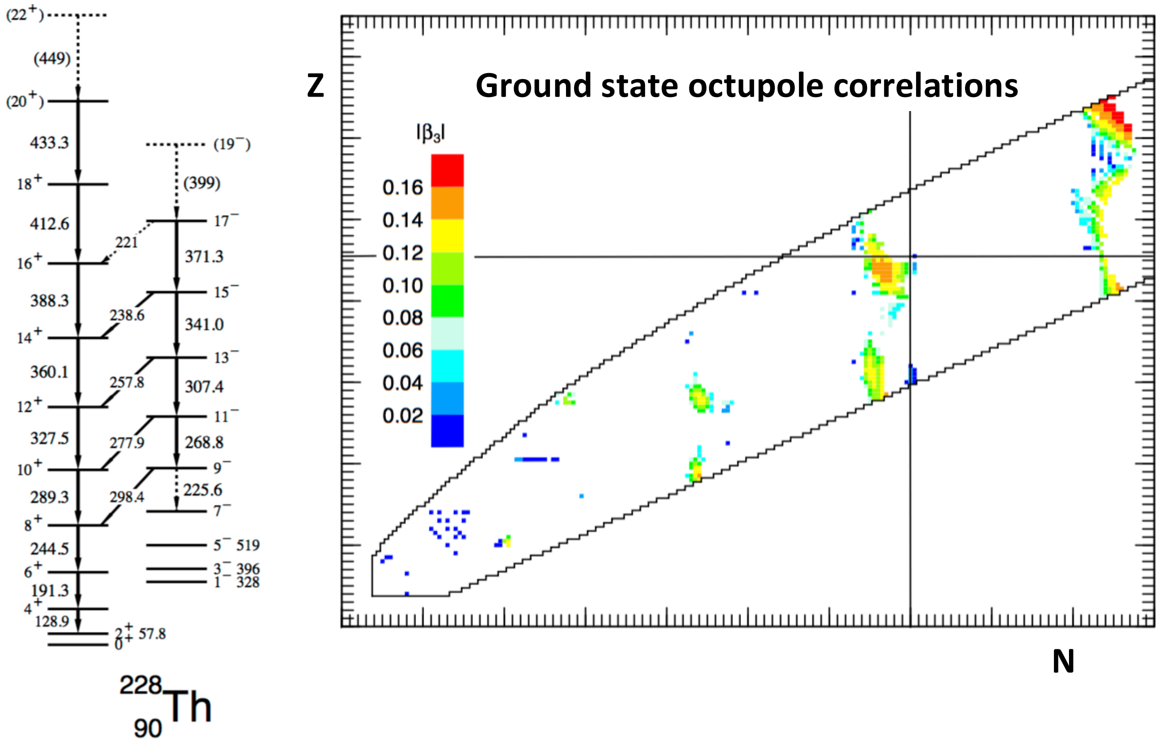

Fig. 1 (Left) Partial level scheme of ^{228}Th showing the g.s. and octupole bands from ref. [14]. Details of the low spin decay can be found in ref. [15]. (Right) Regions of octupole correlations in the Finite Range Droplet Model from ref. [16]. The location of ^{229}Pa is shown.

Figure 1 (left) shows the partial level scheme of ^{228}Th comprising the g.s and octupole bands from ref. [14]. Details of the low spin decay in particular for the 3^- and 1^- states can be found in ref. [15]. On the right calculated β_3 values are reported as a function of N and Z (Finite Range Droplet Model). The location of the ^{229}Pa is also shown. The level scheme of ^{228}Th shows the typical structure of an octupole correlated nucleus. Octupole collectivity can be determined through the measurement of the population of the 3^- state via low energy Coulomb excitation extracted by the experimental determination of the gamma decay of the level. Gamma rays should be detected using the MINIBALL array and the particles in coincidence by the CD silicon detector. Such a measurement is only possible due to the unique characteristics of the HIE-ISOLDE facility able to extract and post-accelerate radioactive ions of such an heavy mass. Since ^{229}Pa and ^{228}Th have never been extracted at ISOLDE, prior to that it is necessary to perform an extraction test from an UCx and ThO_2 targets.

The purpose of this Letter of Intent is therefore to provide an estimate for the beam intensity of ^{228}Th and ^{229}Pa aiming to a possible future proposal concerning the measurement of the octupole collectivity via Coulomb excitation using the HIE-ISOLDE accelerator.

The knowledge of this transition rate is essential for guiding EDM searches on actinide atoms.

2. Extraction scheme

We plan to extract mass A=228 and 229 activity from a UCx (1 shift) and ThO_2 (1 shift) targets doing a collection for building a secondary source of mass A=228 (for later extraction of ^{228}Th). Due to the refractory behaviour of the Th atoms main contributions will come from ^{228}Pa ($t_{1/2}$ = 22 h), ^{228}Ac ($t_{1/2}$ = 6.15 h), ^{228}Ra ($t_{1/2}$ = 5.75 a) and ^{228}Fr ($t_{1/2}$ = 38 s) all nuclei decaying into ^{228}Th. Due to the long half-life of ^{228}Th ($t_{1/2}$ = 1.9116 a) and of ^{228}Ra after about a day the secondary source will be only composed of this two elements. ^{228}Th will be then selected (in a second stage) from the secondary source using laser ionization (a laser ionization scheme has been developed). In any case for a Coulomb excitation measurement the contamination of ^{228}Ra will not be a problem due to the different de-exciting gamma rays. Assuming for the Coulomb-excitation measurement a minimum rate of 10^5 pps, we estimate for the full collection (therefore not part of this LOI) a minimum total number of implanted atoms in the secondary source of 10^{12}. This can be achieved by implantation of a beam of ^{228}Ac at 10^7pps for 18 shifts. Beams of ^{226}Ac of more than 10^7pps have been measured at ISAC, TRIUMF from UCx targets and Rhenium surface ion sources. It is proposed to implant the beam into foils of 20 µm tungsten or tantalum.

According to the Swiss ordinance on radioprotection ORaP, the limit of authorization (LA) for ^{228}Th is 200Bq and for ^{228}Ra is 3kBq; A source of less than 100LA (100xLA is the limit for a class C laboratory like ISOLDE) is required with negligible dose rate. The release from foils and the Thorium RILIS scheme can be tested subsequently. Other components of the implanted target would need to be investigated.

Diffusion properties of Thorium in tungsten are known. From these parameters, it is expected to release Thorium by increasing the temperature of the foils up to 2000 C, as classically done with ISOLDE target and ion source units.

Summarising with this LOI we intend therefore to test the extraction rate of ^{229}Pa and ^{228}Th using the described collection scheme. This knowledge will allow to verify the feasibility of further measurements. The requested number of shifts will be needed for testing the extraction of ^{229}Pa and the proposed scheme for ^{228}Th from UCx (1 shift) and from ThO_2 (1 shift).

Summary of requested shifts:

A=228 and 229 1 shift (UCx target).

A=228 and 229 1 shift (ThO_2 target).

References:

[1] I.P. Khriplovich and S.K. Lamoreaux, CP violation without strangeness (Springer, Berlin 1997).

[2] P.G.H. Sandars, Contemp. Phys. 42, 97 (2001)

[3] M. Pospelov and A. Ritz, Ann. Phys. (N.Y.) 318, 119 (2005)

[4] S.M. Barr, Int. J. Mod. Phys. A 8 209 (1993)

[5] K.A. Olive et al. Phys. Rev. D 72 075001 (2005)

[6] C.A. Backer et al., Phys. Rev. Lett. 97, 131801 (2006)

[7] B.C. Regan et al. Phys. Rev. Lett. 88, 071805 (2002)

[8] W.C. Griffith et al., Phys. Rev. Lett. 102, 101601 (2009)

[9] L.I. Schiff, Phys. Rev. 132, 2194 (1963)

[10] N. Auerbach et al., Phys. Rev. Lett. 76, 4316 (1996)

[11] V. Spevak, N. Auerbach, V.V. Flambaum, Phys. Rev. C 56, 1357 (1997)

[12] V.V. Flambaum and V.G. Zelevinsky Phys. Rev. C 68, 035502 (2003)

[13] V.V. Flambaum Phys. Rev. A 77, 024501 (2008)

[14] J.F.C. Cocks et al., Nucl. Phys. A 645, 61 (1999)

[15] J. Dalmasso et al., Phys. Rev. C 36, 2510 (1987)

[16] P. Moeller et al., Nucl. Data Tables 59, 185 (1995)

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 Choose an item.	Availability	Design and manufacturing
	☒ Existing	☐ To be used without any modification
[Part 1 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
[Part 2 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 [MINIBALL + only CD, MINIBALL + T-REX] installation.

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	[pressure][Bar], [volume][l]		
Vacuum			
Temperature	[temperature] [K]		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
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 (1-300MHz)			
Chemical			
Toxic	[chemical agent], [quantity]		
Harmful	[chemical agent], [quantity]		
CMR (carcinogens, mutagens and substances toxic to reproduction)	[chemical agent], [quantity]		
Corrosive	[chemical agent], [quantity]		
Irritant	[chemical agent], [quantity]		
Flammable	[chemical agent], [quantity]		
Oxidizing	[chemical agent], [quantity]		
Explosiveness	[chemical agent], [quantity]		
Asphyxiant	[chemical agent], [quantity]		
Dangerous for the	[chemical agent], [quantity]		

environment			
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]		

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)*

… kW