CERN-INTC-2017-067 / INTC-I-194
31/05/2017

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Study of the Pygmy Dipole Resonance using an Active Target

May 31, 2017

S. Ceruti[1], R. Raabe[1], M. Babo[1], H. De Witte[1], T. Marchi[1], O. Poleshchuk[1], A.A. Raj[1], M. Renaud[1], J. Yang[1], A. Bracco[2], F. Camera[2], F. C. L. Crespi[2], O. Wieland[2], J. Gibelin[3], M.Vandebrouck[4], Y. Blumenfeld[5], E. Khan[5]

[1]*KU Leuven, Instituut voor Kern- en Stralingsfysica, Celestijnenlaan 200D, 3001 Leuven, Belgium*

[2]*Universita degli Studi di Milano and Istituto Nazionale di Fisica nucleare sez. Milano, Milano, Italy*

[3]*LPC Caen, ENSICAEN, Universite de Caen, CNRS/IN2P3, F-14050 CAEN Cedex, France*

[4]*GANIL, CEA/DSM-CNRS/IN2P3, Bvd Henri Becquerel, 14076 Caen, France*

[5]*IPN Orsay, Universite Paris-Saclay, IN2P3-CNRS, F-91406 Orsay Cedex, France*

Spokesperson: Simone Ceruti, Riccardo Raabe (simone.ceruti@kuleuven.be, riccardo.raabe@kuleuven.be)

Contact person: L. Gaffney (liam.gaffney@cern.ch)

Abstract: In this letter of intent we propose to study the low-lying electric dipole strength in nuclei with neutron excess. The origin of this strength has been recently investigated in several theoretical and experimental works. Its presence can be explained with the existence of a collective excited state called pygmy dipole resonance. The study of this strength can be experimentally performed using hadronic or electromagnetic probes. Our proposal is to study the isoscalar electric dipole strength in long-lived nuclei using (α,α') inelastic scattering reaction in inverse kinematics. For the experiment the use of an Active Target as SpecMAT is fundamental. The proposed physics case may open the way for new experiments in the near future, when radioactive ion beams with N/Z$\gg$1 will be available.

1 Physics case

Giant Resonances (GR) are nuclear excitation modes which play a key role in the study of nuclear structure for their connection with the bulk properties of nuclear matter [1]. The IsoVector Giant Dipole Resonance (IVGDR), where protons oscillate against neutrons, is one of the strongly studied resonance in the past. This resonance exhausts the major part of the electric dipole (E1) strength and it is located at 10−20 MeV.
In nuclei with neutron excess (N>Z) few percent of the E1 strength was experimentally found below the IVGDR [2]. In particular, a concentration of $J^{\pi} = 1^{-}$ states was observed around the neutron separation energy. This experimental evidence has attracted large interest in the last few years. Indeed, the additional strength could be explained with the presence of a new collective excited state called Pygmy Dipole Resonance (PDR). Using a macroscopic approach, the pygmy dipole resonance can be represented as the oscillation of excess neutrons against the N=Z core. However, its nature is still debated [2, 3].
The interest in the PDR is not only for a better understanding of nuclear structure, but also for its possible astrophysical implications. Indeed, according to several theoretical approaches [4, 5, 6, 7], the low-energy E1 strength can provide information about the neutron skin which, in turn, can be connected to the symmetry term of the equation of state. This connection, however, is still controversial [8]. Moreover, the presence of additional strength around the neutron separation energy can affect the neutron capture rate in *r*-process calculations [9].
Particular effort is being made to investigate the isospin character of the PDR from both a theoretical and an experimental point of view [10, 11, 12, 13, 14, 15, 16, 17, 18]. The PDR exhibits both an IsoScalar (IS) and IsoVector (IV) nature and its total strength can be obtained in (γ,γ') experiments [16], since the photon scattering populates both isospin states. On the other hand, one can use an hadronic probe, as in (α,α'γ) reactions [15], to mainly populate the isoscalar part.
In Ref. [15] the nucleus ^{140}Ce was experimentally studied by using both (γ,γ') and (α,α'γ) reaction and an unexpected result was obtained: the E1 states at lower energy were excited in both reactions, while the high-energy states were only excited in the (γ,γ') reaction. Similar results were also obtained in (^{17}O,^{17}O'γ) experiments [11, 12]. These experimental observations were theoretically interpreted as follows: the low-energy E1 strength exhibits an isoscalar nature and it can be associated to the neutron skin oscillation, while the high-energy strength has an isovector nature associated to a transition towards the IVGDR [19].
In order to verify this theoretical interpretation new experimental data are necessary, especially in nuclei with large neutron excess. In particular (α,α' γ) experiments allow to determine the fraction of the isoscalar B(E1) present in the PDR, which may contain a clear signature of neutron skin oscillation.
Experiments based on the (α,α'γ) reaction can be performed at ISOLDE in inverse kinematics, using an Active Target. Several long-lived nuclei have been being identified for this LoI: ^{90}Sr ($T_{1/2}$=28.9 y), ^{194}Hg ($T_{1/2}$=444 y), ^{150}Gd ($T_{1/2}$=1.70 10^{6} y),^{148}Gd ($T_{1/2}$=71.1 y),^{146}Gd ($T_{1/2}$=48.27 d). It is worth noting that studying the Gd isotopes the evolution of PDR with N/Z may also be investigated. A beam energy of 10 MeV/u is necessary to populate the PDR states with enough cross section. In the nucleus ^{94}Sr the cross section

of PDR is expected to be of the order of 2 mb in (α,α') reaction at 10 MeV/u [20], so we can expect a similar value also in the case of ^{90}Sr.

2 Experimental method

We are planning to use (α,α') inelastic scattering reaction to populate the low-lying E1 states associated to the PDR. Since we are interested in studying unstable nuclei, the experiment has to be performed in inverse kinematics, using a He gas target. The energy of the α particles and their angular distribution are essential observables in the analysis. The maximum cross section for populating the PDR states is expected at forward center-of-mass angles, where the kinetic energy of the α particles is very small (around 1 MeV). Therefore, the scattered particles would not have enough energy to escape a solid target, as a He-implanted foil. On the other hand, such experiment can be successfully performed using an Active Target (AT) [21], where the gas is both the target and the detector. In this detector the outcoming α is detected in the gas itself. The obtained track allows to reconstruct the kinematics of the reaction and to determine the excitation energy of the incoming nucleus. In order to detect also the γ decay of the PDR states, the AT should be surrounded by γ-ray detectors. The detection in coincidence of α particles and γ rays allows to select only the γ transitions to the ground state. Thanks to the kinematic reconstruction of the reaction, the α-γ angular correlation can be used to select the multipolarity of the γ transitions. Such experimental procedure allows to select only the J^{π}=1^{-} states of the PDR of interest. The differential cross section is obtained from the γ-ray transitions and the isoscalar B(E1) is determined performing a distorted wave Born approximation (DWBA) analysis.

3 Experimental setup

SpecMAT [22] is an active target - time projection chamber surrounded by scintillation detectors. The scintillation array will be used for γ-ray spectroscopy and will be electronically synchronized with the time projection chamber (TPC). The design goal of the array is a resolution of 4% (26 keV FWHM at 662 keV) with a total photopeak efficiency of 7% at 1 MeV.
The TPC will be filled with a gas and used for tracks recording of charged particles emitted in the reaction. Interacting with the gas, charged particles will ionize it along its path. Electrons produced during the ionization will be guided by an applied homogeneous electric field and collected on a pixelated pad plane. While the two-dimensional distribution of electrons will be directly extracted from the position of fired pads, the third dimension will be reconstructed based on the electron drift time in the gas. These 3-dimensional tracks contain information about the particle, its energy and lab-angle.
The TPC and the scintillator array will be placed inside the The ISOL Solenoidal Spectrometer (ISS) at ISOLDE. A magnetic field collinear with the beam path will bend the trajectories of charged particles emitted in the reaction, providing an additional identification measuring their curvature.

Because of experimental requirements an Active Target coupled with an array of scintillation detector, as SpecMAT, will be a powerful detector for this kind of experiment. In particular, since the outcoming α's will have less than 1 MeV energy the Active Target will allow to have a small detection threshold. The pressure of the gas will be adjusted in order to find the best compromise between luminosity (higher-pressure gas) and length of the track (lower-pressure gas).
The kinetic energy of the α particles for an excitation energy of ^{90}Sr of 7 MeV is approximately 350 keV at forward angles. Using a pressure in the gas of 200 mb, for instance, the α particles travel 80 mm before being stopped in the gas.

4 Beam Time Request

The beam intensity should not exceed 10^6 pps at the entrance of the chamber, in order to not saturate the pad plane. The required beam energy to populate PDR states should be 10 MeV/u. Microscopic calculations report a cross section for populating isoscalar E1 states with (α,α') reaction equal to 2 mb in the nucleus ^{94}Sr at 10 MeV/u [20]. A similar value can be expected for ^{90}Sr as well.
Considering a 30-cm gas chamber filled by He gas at 200 mb, one can expect a count rate of around 1000 events/h for the population of the PDR. The array of scintillators will have an efficiency of 1% at 8 MeV. Therefore, requiring a γ-ray coincidence the count rate is of the order of 250 events/day.
According to these calculations, with 10-12 days of beam time we should be able to clearly observe and characterized PDR states.
However, the beam time estimation strongly depends on the nucleus that one wants to study. Specific and detailed calculations are needed for each isotope. The choice of the isotope will be done in a proposal taking into account all the possible limitations we could have in the experiment. Then, the best nucleus to be studied at ISOLDE will be chosen.

References

[1] M. N. Harakeh and A. van der Woude, *Giant Resonances, Fundamental High-Frequency Modes of Nuclear Excitation*, Oxford Science Publications, 2001.

[2] D. Savran, T. Aumann, and A. Zilges, Prog. Part. Nucl. Phys. 70, 210 (2013).

[3] A. Bracco, F.C.L. Crespi and E.G. Lanza, Eur. Phys. J. A 51, 99 (2015).

[4] J. Piekarewicz, Phys. Rev. C 73, 044325 (2006).

[5] J. Piekarewicz, Phys. Rev. C 83, 034319 (2011).

[6] A. Carbone, et al., Phys. Rev. C 81, (2010) 041301(R).

[7] X. Roca-Maza, et al., Phys. Rev. Lett. 106, 252501 (2011).

[8] P.-G. Reinhard and W. Nazarewicz, Phys. Rev. C 87, 014324 (2013).

[9] S. Goriely, Phys. Lett. B 436, 10 (1998).

[10] O. Wieland et al., Phys. Rev. Lett. 102, 092502 (2009).

[11] F.C.L. Crespi et al., Phys. Rev. Lett. 113, 012501 (2014).

[12] L. Pellegri et al., Phys. Lett. B 738, 519 (2014).

[13] P. Adrich, et al., Phys. Rev. Lett. 95, 132501 (2005) .

[14] A. Klimkiewicz, et al., Phys. Rev. C 76.051603 (2007).

[15] J. Endres, et al., Phys. Rev. C 80, 034302 (2009).

[16] K. Govaert, et al., Phys. Rev. C 57, 2229 (1998).

[17] E.G. Lanza, A. Vitturi, M.V. Andres, F. Catara, D. Gambacurta, Phys. Rev. C 84, 064602 (2011).

[18] X. Roca-Maza, G. Pozzi, M. Brenna, K. Mizuyama, G. Colo, Phys. Rev. C 85, 024601 (2012).

[19] J. Endres, et al., Phys. Rev. Lett. 105, 212503 (2010).

[20] F. Crespi, A. Bracco, et al., "SPES Letter of Intent", (2016).

[21] S. Beceiro-Novo, T. Ahn, D. Bazin, W. Mittig, Prog. Part. Nucl. Phys. 84, 124 (2015).

[22] R. Raabe, SpecMAT ERC Consolidator Grant (2014).

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	Availability	Design and manufacturing
(if relevant, name fixed ISOLDE installation: COLLAPS, CRIS, ISOLTRAP, MINIBALL + only CD, MINIBALL + T-REX, NICOLE, SSP-GLM chamber, SSP-GHM chamber, or WITCH)	☒ Existing	☒ To be used without any modification
SpecMAT	☐ 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
ISOLDE Solenoidal Spectrometer	☐ 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	[Part 1 of experiment/ equipment]	[Part 2 of experiment/ equipment]	[Part 3 of experiment/ equipment]
Thermodynamic and fluidic			
Pressure	200-400 mb		
Vacuum			
Temperature	293 K		
Heat transfer			
Thermal properties of materials			
Cryogenic fluid	[fluid], [pressure][Bar], [volume][l]		
Electrical and electromagnetic			

Electricity	field cage: Up to 10 kV, Pad plane: Up to 1 kV		
Static electricity			
Magnetic field	3 T		
Batteries	☐		
Capacitors	☐		
Ionizing radiation			
Target material	He		
Beam particle type	ions		
Beam intensity	10^6		
Beam energy	10 MeV/u		
Cooling liquids	[liquid]		
Gases	[gas]		
Calibration sources:	☐		
• Open source	☐		
• Sealed source	☐ [ISO standard]		
• Isotope	standard α and γ calibration sources		
• 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: