EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

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

Upgrade and scientific programme of *LUCRECIA*, the Total Absorption Spectrometer at ISOLDE

Jan - 8th - 2020

E. Nácher[1], A. Algora[1], B. Rubio[1], J.L. Taín[1], W. Gelletly[2], L.M. Fraile[3], J. Agramunt[1], G. de Angelis[4], A. Beloeuvre[6], J. Benito[3], M.J.G. Borge[5], J.A. Briz[5], M. Estienne[6], M. Fallot[6], A. Fijalkowska[7], V. Guadilla[6,7], E. Ganioglu[8], Z. Janas[7], A. Jungclaus[5], M. Karny[7], R. Kean[6], R. Lică[9], C. Mazzocchi[7], F. Molina[10], A.I. Morales[1], N. Orce[11], S.E.A. Orrigo[1], A. Perea[5], A. Porta[6], M. Pfutzner[7], Z. Podolyak[2], A. Porta[6], M. Stepaniuk[7], O. Tengblad[5] and J.M. Udías[3]

1 Instituto de Física Corpuscular, CSIC - Universidad de Valencia, E-46071 Valencia, Spain
2 Department of Physics, University of Surrey, GU2 7XH Guildford, United Kingdom
3 Grupo de Física Nuclear and IPARCOS, Universidad Complutense de Madrid, E-28040 Madrid, Spain
4 INFN, Laboratori Nazionali di Legnaro, Legnaro, Italy
5 Instituto de Estructura de la Materia, CSIC, E-28006 Madrid, Spain
6 Subatech, IMT-Atlantique, Université de Nantes, CNRS-IN2P3, F-44307 Nantes, France
7 Faculty of Physics, University of Warsaw, PL-02-093 Warsaw, Poland
8 Department of Physics, Istanbul University, 34134 Istanbul, Turkey
9 ISOLDE-EP, CERN, CH-1211 Geneva 23, Switzerland
10 Comisión Chilena de Energía Nuclear, Casilla 188-D, Santiago, Chile
11 Department of Physics and Astronomy, University of the Western Cape, P/BX17, ZA-7535, South Africa

Spokesperson(s): E. Nácher (Enrique.Nacher@csic.es)
A. Algora (A.Algora@ific.uv.es)
B. Rubio (B.Rubio@ific.uv.es)

Local contact: R. Lică (Razvan.Lica@cern.ch)

CERN-INTC-2020-007 / INTC-I-210
08/01/2020

Abstract

Here we present the planned upgrade of *LUCRECIA*, the Total Absorption Spectrometer at ISOLDE. After 20 years of fruitful experiments, we plan to continue during the period 2021-2025 with an ambitious scientific programme. In this LOI we discuss the future physics programme and the status of the collaboration. This research programme will have large synergies with the ISOLDE Decay Station and other setups in the hall. To accomplish our goals, a major intervention on the tape transport system and associated vacuum support will be implemented in the short-term future.

The Total Absorption Spectrometer *LUCRECIA* at ISOLDE

LUCRECIA, a Total Absorption Spectrometer (TAS) setup, is in operation at ISOLDE since 2001. It is comprised of a main NaI(Tl) crystal, for the detection of gamma-ray cascades produced after beta decay, a plastic detector for beta particles and a HPGe telescope detector for high-resolution X and gamma-ray spectroscopy.

The TAS method is based on the detection of the energy of the entire gamma-ray cascade that follows beta decay, rather than the detection of individual gamma rays, with the aim of avoiding the systematic error referred to as Pandemonium effect [HAR]. For such a purpose, large inorganic scintillator crystals, NaI(Tl) in this case, are used to create a detector with a high detection efficiency and an acceptable energy resolution for gamma rays. *LUCRECIA*, at ISOLDE, is a large NaI(Tl) single crystal with cylindrical shape of both, diameter and length, equal to 38 cm. Ideally, the information on the beta intensity distribution could be extracted directly from the measured beta-delayed gamma-ray spectrum if the scintillator had a 100% full-peak efficiency for gamma detection and infinitely good gamma-ray energy resolution. However, this is never the case and this leads to a complex problem in the analysis of the TAS spectra. These difficulties have been assessed in [TAI07], where solutions to the analysis problem are outlined.

A typical experiment with *LUCRECIA* implies, among other things, the implantation of the radioactive samples from the ISOLDE separator onto an aluminized Mylar tape that moves periodically to remove the activity of the daughters of the isotopes of interest.

This setup has been used over the last 10 years and has produced five Ph. D theses and the corresponding contributions to conferences and publications [POI04, NAC04, EST11, PER13, BRI15]. The authors of this letter have the intention to propose to the INTC several new experiments in the next period with an improved setup that includes a better and more efficient tape transport system for radioactive samples.

Scientific Program

In December 2019, the authors of this letter have celebrated a Collaboration Workshop in Valencia to discuss future plans with regards to beta decay studies with the Total Absorption Spectroscopy technique, focusing mainly on future plans at ISOLDE. As a result of this meeting we have agreed on several topics that we would like to exploit at this unique facility. In the following we outline some of the cases of interest that we plan to propose in the next INTC meetings in June 2020 and February 2021.

The region around ^{132}Sn

The study of the beta decay of nuclei in the south east of ^{132}Sn is particularly interesting. First of all, these studies can provide unique nuclear structure information on the properties of nuclei close to the doubly magic nucleus ^{132}Sn and the stability of the magic numbers as we depart from the core. On the other hand, the Q-beta values are high and one hopes to have access to a large fraction of the total GT strength if nuclei sufficiently far from the stability are reached. Moreover, these nuclei are key cases for our understanding of the astrophysical r-process. Because most of the GT strength is expected at high excitation energy, this region of nuclei is especially suited for the TAS technique. However, there are two circumstances that make these measurements challenging. One is the presence of beta-decaying isomers and the other is the competition between beta-delayed gamma decay and beta-delayed neutron emission. This is the reason why we will start our studies in this region with cases such as ^{133}In where enough experimental information on these two points exists [PIE19] and where we can test our analysis approach. In addition, studying the beta decay of neutron-rich In and Sn isotopes could provide access to low-lying collective modes such as the Pygmy Dipole Resonance (PDR). Finally, with the TAS it will be possible to quantify the gamma decay of neutron unbound states in 133Sn which already has been observed in [VAQ17] and [PIE19].

Light mirror nuclei

Possible isospin asymmetries have been discussed in the sd shell and often interpreted as a consequence of neutron halo effects on the neutron rich side. However, to which degree these asymmetries are real or the consequence of incomplete experimental data is still unclear. The advantage in the sd shell is that one can compare not only mirror nuclei but also the two mirror processes beta-plus and beta-minus. This comparison is not exempt of difficulties. In the beta-plus side because of the beta-delayed multiparticle emissions, in the beta minus because of the possible Pandemonium effect. We plan to revise the beta minus side of some of these cases with LUCRECIA and put on solid grounds this side of the picture. One good candidate is the pair of nuclei ^{27}S and ^{27}Na, where the decay of ^{27}S is also important in terms of Nova and X-ray burst modelling. In this case, the beta-intensity distribution in the decay of ^{27}Na is suspected to suffer from Pandemonium effect [JAN17, SUN19].

X-Ray bursts and rp-process: $^{68\text{-}70}Se$

Nucleosynthesis in Type I X-ray bursts eventually proceeds through the rp-process near the proton drip-line. In particular, several N=Z nuclei such as ^{64}Ge and ^{68}Se act as waiting points in the nuclear flow. Theoretical calculations have shown that, in these scenarios, continuum electron capture rates, as well as decay from excited states, might play an important role, in particular around the waiting point nuclei and their N=Z+1 neighbours [SAR09] [NAB12]. Within the IS570 experiment, the light Ge isotopes were measured in May-2016, and results will be presented soon. We plan to propose the measurement of the light Se isotopes, already contemplated in the last proposal [NAC12], to allow for a detailed analysis of their contribution to the EC-decay rates in X-Ray burst explosions. This will provide a benchmark for testing models under terrestrial conditions that can be used later for predictions in stellar conditions. These studies will require complementary measurements at the IDS setup and complete the study on waiting-point nuclei intended in the IS570 experiment [NAC12].

Shape coexistence in the Pb/Hg regions: odd-Hg

Hg isotopes have attracted considerable attention in relation to shape effects and shape coexistence (see [MAR18] and [BRE14]). They show an odd-even staggering in the variations of nuclear radii that is unique in the nuclide chart. In this framework, we have recently finished the analysis of the total absorption study of ^{186}Hg, which marks the beginning of the shape staggering. The apparently contradictory decay data can be interpreted assuming mixing in the ground state of ^{186}Hg. With this assumption, a nice description of the beta strength has been obtained recently [GAN20]. We plan to continue along this line of research by studying the odd isotopes around the staggering, where beta decay can offer an additional insight on the evolution of the shape in this interesting region of the nuclide chart. The availability of RILIS for selective ionization in narrow band mode provides the means to investigate separately the decay of the high and low spin beta-decaying isomers, which is unique worldwide to ISOLDE. This data will allow us to further test theoretical models. Some of the planned studies will require complementary measurements at the IDS setup.

Neutron-deficient Tm isotopes

The observation of the proton decay fine structure provides a unique access to the composition of the wave function of the initial state. The study of the fine structure of the ^{145}Tm proton decay proves that the wave function of the initial state has a 3% component of proton in the $f_{7/2}$ orbital [KAR90]. If this $f_{7/2}$ component exists in the wave function of the ground state of all neutron-deficient Tm isotopes, the beta decay of this component should be sensitive to the N=82 crossing. In this context, we propose the study of the beta decay of the odd-even ^{149,151,153,155}Tm. Furthermore, the beta decays of ^{152,156}Tm have been measured with the TAS technique in the past [NAC04, NAC15]. We propose to complete this set of measurements with ^{154}Tm to map the increase in the width of the Gamow-Teller main resonance as we move from spherical to deformed nuclei. Target-Ion-Source development for neutron-deficient Tm beams at ISOLDE is therefore requested.

Low-lying collectivity studies from beta decay data.

In recent years the possibility of exciting low-lying collective excitations in the beta decay has been explored both theoretically and experimentally [PER14, SCH16, GOT17]. The main idea here is to examine whether gamma-ray spectroscopy following beta decay from mother nuclei with low ground-state spin can be exploited as a probe for the Pygmy dipole resonance [SCH16]. These studies require looking into decays with high Q values. Experimentally, one study has been performed until now using high-resolution and $LaBr_3$ detectors [GOT17]. The Pandemonium effect could affect such measurements since collective modes decay preferentially through one or two very energetic gamma-rays. Exploiting the TAS technique for those studies can represent a great advantage, since the technique has already shown the potential of detecting gamma emission from states above the neutron separation energy in several cases (see e.g. [TAI15, VAL17, SPY16, GUA19]). These recent studies have shown the existence of gamma de-excitation that competes with neutron emission above the S_n value. The study of the gamma competition above S_n and Pigmy resonance studies can have large astrophysical impact. As part of the future programme, we plan to propose the measurement of $^{80\text{-}84}$Ga isotopes at ISOLDE using the *LUCRECIA* setup.

First-forbidden beta transitions and the competition of beta-delayed gamma-decay and neutron emission around ^{78}Ni.

Beta-decay transitions play an important role in explosive scenarios leading to r-process nucleosynthesis. Beta-decay properties are typically calculated by only considering allowed transitions. Nonetheless first-forbidden transitions become very significant for medium mass and heavy nuclei, both due to phase space and nuclear structure reasons. The role of first-forbidden transitions has been highlighted in the beta decay of neutron-rich nuclei around N=82. The neutron-rich nuclei above ^{78}Ni are also very interesting from this point of view.
The TAS technique is ideal to detect gamma-ray cascades and locate beta-decay feeding to (allowed) high-lying states, which otherwise is misidentified as population of lower-lying states via first-forbidden transitions. One of the most favourable cases in this region is the ^{81}Zn → ^{81}Ga decay [PAZ20], for which the yield and beam purity of ^{81}Zn at ISOLDE is unparalleled. In addition, beta-decay populates neutron-unbound states. In spite of the strength of the electromagnetic interaction in comparison to the strong force, they may decay by high-energy gamma-ray cascades that can be detected with high efficiency employing the ISOLDE TAS. The gamma-ray emission above the neutron separation energy has an impact on the analogous radiative capture cross sections on very neutron-rich nuclei, which are key elements in reaction network calculations for the r-process.

Part of this programme involves nuclei with half-lives of the order of few seconds and even shorter. This requires direct implantation at the centre of the crystal and time cycles of the tape-transport system in the range of 2-5 seconds. To accomplish these requirements, we need to upgrade our setup as we will explain in the next section.

Upgrade and required space

The old tape transport system, that has been used until the last experiment in May-2016, relies on a device that was used originally in the Mass Separator setup at GSI. It makes use of a differential pumping system that presently limits the half-lives of the beta decaying isotopes that can be studied at the *LUCRECIA* TAS station. We are presently refurbishing a tape station that was used earlier at ISOLDE, from now on referred to as "new". As part of this process, new continuous motors with internal encoder have been acquired and the development of a new control system is underway. This system will work in vacuum, connected to the ISOLDE beam line, and will address the technical limitations that we were facing with the old system. A new turbo-molecular pump has been recently acquired and coupled to this new system.

Our plan is to finish the electronic controllers, software development and vacuum system during the first half of 2020. According to this schedule we should transport the system to ISOLDE not later than June 2020. Since we are keeping the same path for the tape inside the spectrometer as in the old system, no major mechanical developments are needed and, therefore, between June 2020 and October 2020 we will couple the new system and perform all the necessary tests to be ready for beam by the end of 2020. To optimize the use of the space in the hall, at this stage we might ask for help and mechanical support for the integration and new alignment of the final section of the beam pipe. In Fig. 1 we have marked an area labelled "TAPE" around the *LUCRECIA* shielding to hold the tape transport system structure.

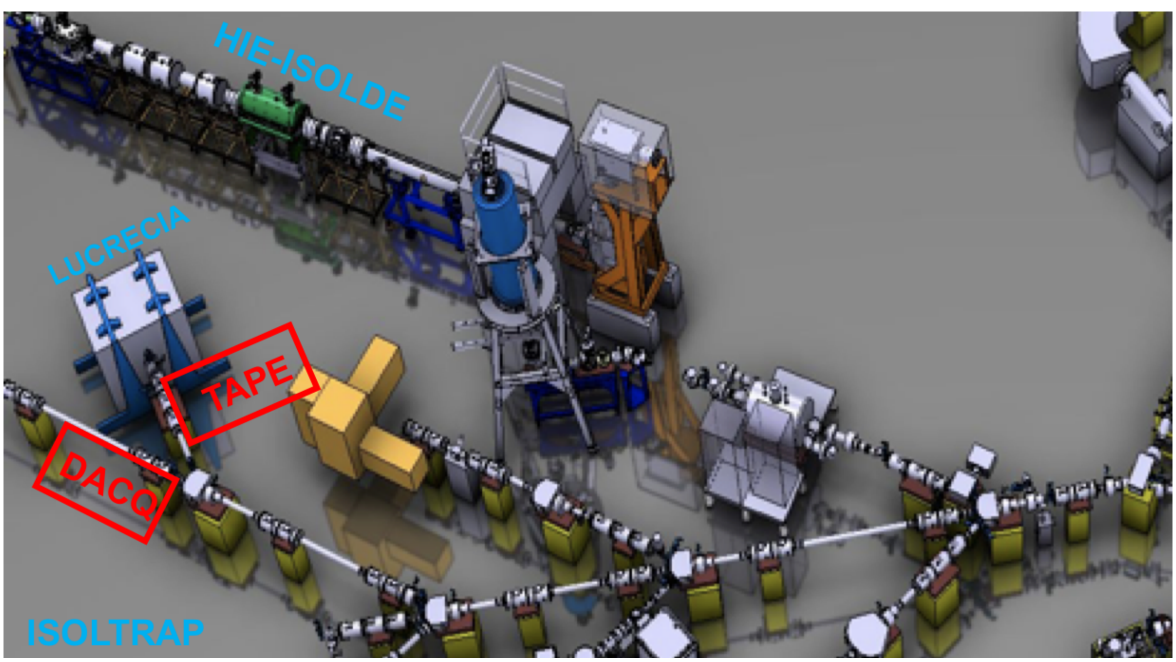

Figure 1. Areas (red, not to scale) that will be occupied by the new tape transport system and the permanent data acquisition system.

This area (not to scale in the figure) must be at least 1.5 x 2 m^2 to allow for access and manipulation of the system. In the new configuration, it will extend ~1 m beyond the open shielding. All in all, we require the same space that we are presently occupying with the old system.
Apart from the tape transport system, we plan to install a permanent data acquisition system (dacq) based on VME digitizers from Struck Innovative Systeme GmbH. This dacq will require 2 NIM crates and 1 VME crate. This, plus a PC to control the dacq, will be placed in the area marked as "DACQ" in Fig. 1, or, alternatively, at the other side of the wall behind the shielding. The required space for this dacq is again roughly 1.5 x 2 m^2 to allow for the access and manipulation of the system. We also require access to any of the data acquisition rooms in building 518 for remote control of the experiments.

References:

[BRE14] N. Bree et al., Phys. Rev. Lett. 112 (2014) 162701
[BRI15] J.A. Briz et al., Phys. Rev. C 92 (2015) 054326
[EST11] E. Estevez et al., Phys. Rev. C 84 (2011) 034304
[GAN20] E. Ganioglu, A. Algora, P. Sarriguren et al., in preparation
[GOT17] A. Gottardo et al., Physics Letters B 772 (2017) 359
[GUA19] V. Guadilla et al. Phys. Rev. C 100 (2019) 044305
[HAR77] J.C. Hardy et al, Phys. Lett., 71B (1977) 307
[JAN17] L. Janiak et al. Phys. Rev. C 95 (2017) 034315
[KAR90] M. Karny et al., Phys. Rev. Lett. 90 (2003) 012502
[MAR18] B.A. Marsh et al., Nat. Phys. 14 (2018) 1163
[NAB12] Jameel-Un Nabi, Astrophys. Space Sci. 339 (2012) 305
[NAC03] E. Nacher et al., GSI Scientific Report 2002 (2003) 8
[NAC04] E. Nacher et al., Phys. Rev. Lett. 92 (2004) 232501
[NAC12] E. Nacher et al., Proposal to the INTC: CERN-INTC-2013-009 / INTC-P-374
[NAC16] E. Nacher et al., Phys. Rev. C93 (2016) 014308
[PAZ20] V. Paziy et al., submitted to Phys. Rev. C
[PER13] A.B. Perez-Cerdan et al., Phys. Rev. C 88 (2013) 014324
[PER14] S. Peru, M. Martini, Eur. Phys. J. A (2014) 50
[PIE19] M. Piersa et al., Phys. Rev. C99 (2019) 024304
[POI04] E. Poirier et al., Phys. Rev. C 69 (2004) 034307
[SAR09] P. Sarriguren, Phys. Lett. B 680 (2009) 438
[SCH16] M. Scheck et al. Phys. Rev. Lett. 116 (2016) 132501
[SPY16] A. Spyrou et al., Phys. Rev. Lett. 117 (2016) 142701
[SUN19] L. J. Sun et al., Phys. Rev. C99 (2019) 064312
[TAI07] J. L. Taín et al., Nucl. Inst. and Methods A 571 (2007) 728
[TAI15] J. L. Tain et al., Physical Review Letters 115 (2015) 062502
[VAL17] E. Valencia et al. Physical Review C 95 (2017) 024320
[VAQ17] V. Vaquero et al., Phys. Rev. Lett. 118 (2017) 202502