EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Letter of Intent to the ISOLDE and Neutron Time-of-Flight Experiments Committee for experiments with HIE-ISOLDE

Direct measurements in the rp-process with active-target detectors

M. Caamaño[1*], J. Benlliure[1], D. Cortina[1], H. Álvarez-Pol[1], H. Savajols[2], P. Roussel-Chomaz[2], J. Pancin[2], F. Rejmund[2], B. Fernández-Domínguez[2], R. Raabe[3], T. Roger[3], J. Gibelin[4], W. Mittig[5], D. Suzuki[5], A. Moro[6].

* Spokesperson. **1**. U. de Santiago de Compostela, Santiago de Compostela, Spain. **2**: GANIL, Caen, France. **3**: U. of Leuven, Leuven, Belgium. **4**: LPC, Caen, France. **5**: NSCL, East Lansing, U.S.A. **6**: U. de Sevilla, Sevilla, Spain.

Abstract: We propose to start a new scientific program that would contribute to the characterization of the stellar *rp-process* path, with active-target detectors. This will be done with the study of different reaction channels involving a series of neutron-deficient beams available in HIE-Isolde. The program includes mass and direct proton-capture cross-section measurements for those beams and neighboring nuclei.

Introduction:

Among the known sources of nucleosysnthesis, type I X-ray bursts play an important role housing the so-called *rp-process* [1,2]. In these binary systems, the accretion of matter in a neutron star from an expanded companion can start a burst that consists in a series of rapid proton captures that compete with *β*-decay in the same nucleus. If the capture is fast enough, the proton drip line is reached and the process is stuck until *β*-decay or two-proton capture allow bypassing these so-called *waiting points*. Their characteristics determine the final abundance and the X-ray light curve observed.

In order to understand the process and its contribution to galactic nucleosynthesis, the underlying nuclear characteristics must be well defined. Nuclear masses of the isotopes involved, as well as proton-capture rates, are very sensitive parameters of the models that describe the rp-process [3]. The involved nuclei are naturally close to the proton drip-line and short-lived, which, along with the associated low production rates, make them difficult to handle in laboratory and force the relevant measurements to be performed with indirect methods in the most of the cases. In this proposal, we intend to use the advantages of active-target detection, along with available neutron-deficient beams, to attempt direct measurements of the relevant reactions and characteristics of the nuclei involved in the rp-process.

Physics case:

The ***aim of the present letter*** is to start a program of measurements of direct proton-capture rates and masses in rp-process relevant nuclei as they become available in HIE-Isolde. Among these measurements, we expect the proton-capture rate of ^{56}Ni, ^{60}Zn, ^{72}Kr, and ^{76}Sr; and the masses of ^{71}Kr, ^{73}Rb and ^{77}Y. The case of ^{72}Kr and ^{73}Rb is particularly interesting: the proton-unbound character of ^{73}Rb was recently discussed [4,5] and it may have important implications in the way ^{72}Kr act as a waiting point.

We propose to use ^{56}Ni, ^{60}Zn, ^{72}Kr, and ^{76}Sr beams and a C_4H_{10} gas target to study, simultaneously, X+p and X+^{12}C transfer and fusion channels. In addition, measurements of elastic cross-sections with ^{12}C and proton would be used to determine the associated optical potentials, feeding the theoretical descriptions of direct reactions in this region. The reaction energy will be scanned from the beam energy available (closest to 10 MeV/u) down to 0 MeV, or the corresponding limit of detection, by stopping the beam in the reaction target. The active-target setup will detect simultaneously the following reaction channels:

1a)   **Elastic scattering with ^{12}C and proton** will serve as references and, in addition, will allow the calculation of the associated optical potentials.

1b)   **Resonant elastic scattering** with proton, forming $^{A+1}$Z+1 resonances (as it may be the case in ^{73}Rb [4]), would be explored by measuring the excitation energy distribution.

2) **Inelastic cross-sections** allow an approximation to the spectroscopy of studied systems.
3) **Proton transfer with ^{12}C** will be used to measure the $^{A+1}Z+1$ mass. It also serves as indirect measurement of proton-capture rate.
4) **Neutron transfer with ^{12}C** will be used to measure the ^{A-1}Z mass.
5) **Direct proton-capture** cross-section will be determined.

Experimental Setup:

The experimental setup will be based on an active-target detector. We consider two detectors to use: ACTAR [6], a new detector with improved performances, is currently being developed and is expected to be operational by 2013. Should it be ready and available, it would be preferred. A second choice is the detector MAYA, developed and built at GANIL [7], and already fully operational. The characteristics of the proposed measurements make them feasible in either detector. In this letter, we focus on the detector MAYA since the experience accumulated allows to perform realistic estimates.

MAYA is especially well suited to study direct reactions in low-energy ranges. Its 3D tracking provides a unique tool to determine complete angular distributions and the energy of each reaction, even in a thick-target setup. This is of great importance when evaluating the differential cross-section respect to both angle and energy of reaction. The detector also possesses an extremely low detection threshold, and an angular coverage of almost 4π, that permit to work with very low counting rate. Different observables, including masses, are accurately determined with this complete reconstruction of reaction kinematics [8-10], even with extremely low statistics [11].

In addition, a Micro-channel Plate Detector (or a similar detector) will be used for monitor the beam position and intensity. Both detectors occupy an effective volume of around 1 m^3 in the beam line, with additional space to place the associated electronics, with no relevant shielding.

Beam Requirements:

The beam characteristics are the main reason to perform this experiment in HIE-Isolde:

- ^{56}Ni, ^{60}Zn, ^{72}Kr, and ^{76}Sr beams with energies close to 10 MeV/u, and intensities higher than 1000 pps for two weeks (or a total of ~1.5×10^9 impinging projectiles), are required.

- The energy resolution is relatively important, especially in the fusion reactions. An energy spread below 1 % would be within the optimal conditions.

- A pure beam is desirable for the present experiment. However, a moderate presence of contaminants (<10 %) is not necessarily a problem: As long as the contaminant species are known, a selection can be performed thereafter during the data analysis.

- To keep the beam well centred and as parallel to the amplification wires as possible is only an essential working condition in those cases where the beam is masked and, therefore, not observed in the detector. In such conditions, a beam spot smaller than 0.25 cm^2, with a divergence of at most 8 mrad, and an emittance smaller than 10π mm*mrad are required.

- The time structure of the beam is an extremely important issue for the detector. Being it a gas detector, the drift time and the signal readout put limits to the highest intensity. With an efficient beam rejection, MAYA is limited to 10^5 pps. The time structure defined by EBIS allows having a maximum rate of 100 Hz and a pulse length of 500 μs [12]. This structure produces a factor 20 between the average and the instantaneous intensity: the required 1000 pps for the present proposal would be $2\cdot10^4$ pps within each EBIS pulse. Therefore, the required time structure would be linked to a minimum average intensity of 1000 pps and a maximum instantaneous intensity of 10^5 pps.

Experiment:

We propose to use ^{56}Ni, ^{60}Zn, ^{72}Kr, and ^{76}Sr beams at the available energy closest to 10 MeV/u impinging on a C_4H_{10} gas target. The complete reaction reconstruction will be done with the active-target detector. The beam monitor detector will be used to monitor the incident beam to trigger the acquisition. MAYA will be filled with different pressures from 100 to 400 mbar, assuring a wider kinematical coverage. In the case of ACTAR these pressures may vary depending on its dimensions.

The beam projectiles will react with the atoms in the gas with an energy ranging between the initial value and virtually 0 MeV (stopping point inside the gas). The angle and range of the recoil products from binary reactions will be detected inside the active target. Information on the scattered

(beam-like) products will consist in their range inside the gas, since their angles will be too small to be determined with the tracking reconstruction. The recoil products detected at forward angles in the ancillary detectors (which is the main case for protons) will be identified by E-ΔE, and their angle will be measured by the tracking reconstruction. This information will be used to identify each channel by means of their different kinematics, as a function of the reaction point (equivalent to reaction energy).

On the other hand, the direct proton-capture will leave a single trace inside the detector without any deviation angle. In this case, the identification of the channel will be done with the relation between the total range (reaction point + range of $^{A+1}Z+1$ system) and the total energy deposited, measured with the pads and the amplification wires in the case of MAYA.

Count rate estimates:

With a C_4H_{10} gas target and ^{56}Ni, ^{60}Zn, ^{72}Kr, and ^{76}Sr beams at 10 MeV/u, the equivalent thickness is ~1.3×10^{21} protons/cm^2 and ~5.2×10^{20} ^{12}C/cm^2. In counts per mb of cross-section and number of incident projectiles (n_p), these are ~8.7×10^{-7} counts/(mb*n_p) with H, and ~3.5×10^{-7} counts/(mb*n_p) with ^{12}C. The efficiency and acceptance of MAYA have been already taken into account in this calculation (the kinematical coverage may be further, but slightly, reduced in some channels due to recoils escaping the gas volume).

Estimations of the cross-sections obtained with FRESCO [13] and NON-SMOKER [14] codes are listed in the following. They are evaluated as a function of the energy, which is also a function of the position and, therefore, of the thickness. The final results integrate these dependencies. Elastic channels are considered for angles where the cross-section is expected to deviate from Rutherford scattering. The listed cross-sections are average values for the different beams over the energy range. They are displayed for reference:

	Reaction	Average cross-section	Total counts for $n_p=1.5\times10^9$
1a)	**Elastic scattering**	> 1 b	> 5×10^5
1b)+2)	**Resonant + Inelastic**	~ mb	~ 10^3
3)	**Proton transfer**	~ 1 mb	~ 500
4)	**Neutron transfer**	~ 10^{-2} mb	~ 5
5)	**Proton capture**	~ 5 μb	~ 10

Safety:

The active volume of MAYA (~3×10^4 cm^3) will be filled with isobutane C_4H_{10} at pressures between 100 and 400 mbar. In the case of ACTAR, the pressures might be lower due to its larger dimensions.

References:

1 R. Wallace and S. Woosley, Astrophys. J. Suppl. Ser. **45** (1981) 389
2 HIE-ISOLDE: The scientific opportunities (CERN Report 2007-08)
3 H. Schatz, Int. J. Mass Spectrom. **251** (2006) 293
4 D. G. Jenkins, Phys. Rev. C **78** (2009) 012801
5 D. Rodríguez *et al.*, Phys. Rev. Lett. **93** (2004) 161104
6 R. Raabe and the ACTAR collaboration, "ACTAR: An Active Target detector for the study of extremely exotic nuclei". Available at https://perswww.kuleuven.be/~u0004046/actar.pdf
7 C.E. Demonchy *et al.*, Nucl. Inst. and Meth. A **583** (2007) 341
8 C. Monrozeau *et al.*, Phys. Rev. Lett. **100** (2008) 042501
9 I. Tanihata *et al.*, Phys. Rev. Lett. **100** (2008) 192502
10 T. Roger *et al.*, Phys. Rev. C **79** (2009) 031603
11 M. Caamaño *et al.*, Phys. Rev. Lett. **99** (2007) 062502
12 http://hie-isolde.web.cern.ch/HIE-ISOLDE/HIE-ISOLDE_site/Hie-linacsite/Beam_Specifications.html (may 2010)
13 A. Moro (private communication)
14 http://nucastro.org/nonsmoker.html (may 2010)