Nuclear astrophysics with light nuclei at GANIL

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Abstract. A short review of several experimental investigations related to astrophysical interests is presented. These experiments were performed at GANIL using radioactive beams produced by the Spiral Facility.

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INTRODUCTION

In recent years, the GANIL has seen an increasing activity in the field of astrophysical studies. Several stellar phenomena remain poorly understood (supernovae, x-ray bursts). The availability of radioactive beams has enabled new studies. The aim of this article is to present several examples of experiment performed in this field of research.

NUCLEAR ASTROPHYSICS STUDIED AT GANIL

The electron screening effect

The cross section of nuclear reactions is sometimes enhanced at sub-Coulomb energies. This effect is due to the electrons cloud surrounding the interacting nuclei and acting as a screening potential for the strong Coulomb repulsion force [1, 2]. This effect is observed at low energies in direct measurements of cross sections [3, 4] and it was confirmed by Trojan Horse indirect measurements [5] where the cross section of electron bare nucleus could be measured. Surprisingly, the measured screening effect seems to be always much larger than predicted. Up to now, there is no satisfactory explanation. A large screening effect was observed with metallic targets [6]. This strong screening effect could be due to the quasi-free electrons which are available in these materials. When nuclei are immerged in a sea of free electrons, the electrons tend to cluster around the nucleus, resulting in an effect similar to the one resulting from atomic orbital electrons (or plasma in stellar environment). Theories predict that the intensity of the quasi-free electron screening effect should depend on temperature, the electron screening increases when the temperature decreases. Several other effects of the electron screening are also predicted. The position of nuclear resonances should also be affected, as was confirmed by the observation of resonance energy shifts measured in metallic, alloy and insulator targets [7]. Electrons screening can also induce a change in the half-life of radioactive nuclei. In the case of the β decay, the half-life is roughly dictated by the law: log ft = constant. The space phase function "f" should change with the presence of the electrons,

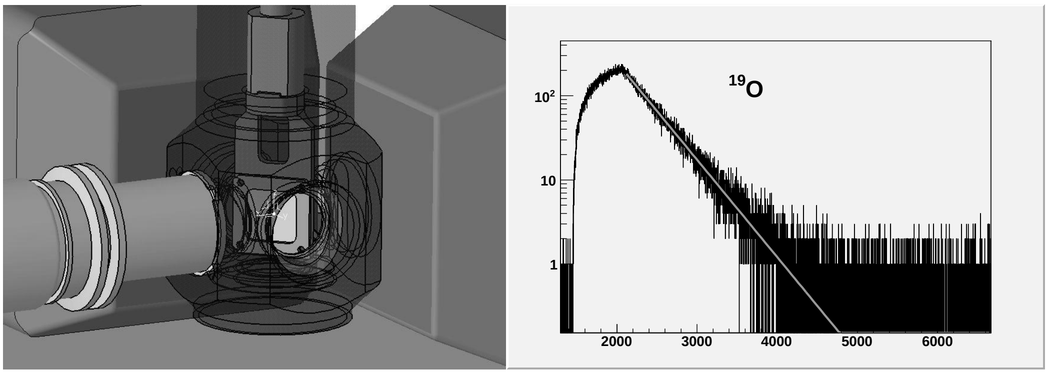

FIGURE 1. Left: Drawing of the experimental setup used to study the electron screening effect. The target is located inside a cryostat and surrounded by two EXOGAM germanium clovers detectors, one plastic and one LaBr3 scintillator (not shown here) placed in a close geometry. Rigth: A single implantation and decay curve (counts versus time in seconds) measured for ^{19}O using the plastic scintillator [12].

which induces a change in the half-life "t". It is predicted a longer half-life for the β^- decay, and a shorter one for the β^+ decay. Several experiments [8, 9] have observed a change of a few percents in the half-life of nuclei implanted in metallic material and cooled down at low temperatures. For example, the β^+ decay half-life of ^{22}Na implanted in the Pd metallic environment cooled to T = 12 K was observed to be shorter by 1.2 %. But, contradictory results were also obtained [10]. It is of high interest to investigate such effects, not only because of the possible theoretical implications but also because of the possible applications (nuclear astrophysics, nuclear fusion, waste disposal management).

Recently, an experiment was performed at GANIL by P. Ujic *et al* in order to investigate this screening effect within a superconductor material for the first time. A foil of Niobium was cooled down at different temperatures, down to 4 K. Niobium is a normal metallic conductor at room temperature, but it becomes superconductor at temperatures lower than 9.2 K. In the super-conducting phase, free-electrons couple to make quasi-bosons Cooper pairs. The effect of the Cooper-pairs was discussed by Stoppini [11], and it was predicted that a "super-screening" effect could happen. Two intense beams of radioactive ions, ^{19}O and the mirror nucleus ^{19}Ne, were produced with the Spiral Facility with more than 10^5 pps. Simulations with SRIM showed that with this intensity of the beam which induces the accumulation of lattice damages, the superconducting phase would not have been destroyed during the experiment. Ions were implanted in the foil with an energy of 4 AMeV in cycles of implantation - decay phases, each one lasting one hour. The foil was located inside a cryostat surrounded by two EXOGAM germanium clovers detectors, one plastic and one LaBr3 scintillators placed in a compact geometry (see Fig 1). Decay lifetimes were measured with a accuracy better the 0.1 %. Cycles of measurements performed at different temperatures were used in order to reduce the systematic errors. Results are still under analysis, but it is already clear that if there is any screening effect it is very small, in the limits of sensitivity of this experiment. Details and results will be published soon [12].

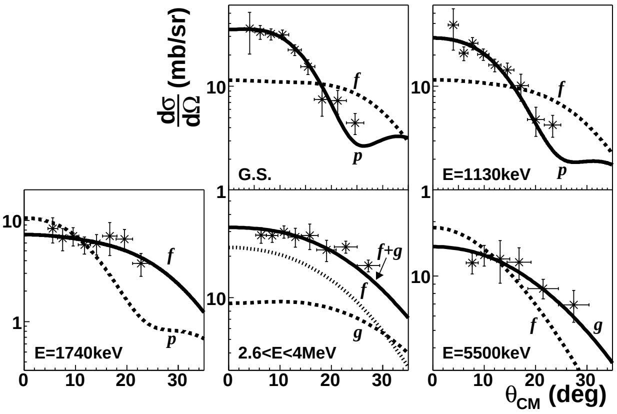

FIGURE 2. Experimental angular distributions of the protons produced in the reaction ^{46}Ar(d,p)^{47}Ar* compared to DWBA calculations [18].

R-process and the ^{48}Ca/^{46}Ca anomaly

Correlated isotopic anomalies were observed in neutron-rich isotopes found in peculiar refractory inclusions of the Allende meteorite [13]. The ^{48}Ca/^{46}Ca ratio was found to be 250, a factor of 5 larger than in the Solar System. It was concluded that these highly unusual isotopic compositions witness late-stage nucleosynthesis processes which preceded the formation of the solar nebula. A plausible astrophysical scenario to account for the overabundance of ^{48}Ca is a weak rapid neutron-capture process. The main contribution to the production of these Ca isotopes is provided by the β-decay of their progenitor isobars in the Ar isotopic chain. Therefore the determination of neutron-capture rates in the Ar isotopes is important. Knowing the β-decay half lives and neutron capture rates in the nuclei of interest, it is possible to deduce an approximative value of the neutron density which could account for the large observed isotopic ratio ^{48}Ca/^{46}Ca in the r-process. The rate of the stellar radiative neutron capture reaction ^{46}Ar(n,γ)^{47}Ar can be deduced using spectroscopic information of ^{47}Ar. This information can be obtained through the ^{46}Ar(d,p)^{47}Ar neutron pick-up reaction. This reaction was performed in inverse kinematics at GANIL with a radioactive beam of ^{46}Ar produced by the SPIRAL facility, and accelerated by the cyclotron CIME up to the energy of 10 AMeV. The beam intensity of ^{46}Ar was 2.10^4 s^{-1}, without isobaric contamination. The beam impinged a CD2 target of 380 μg cm^{-2}. The tracking of the secondary beam was achieved by a position-sensitive gas-filled detector CATS [14]. Protons were detected at backward angles (between 110 and 170 degrees) using 8 modules of the MUST array (double sided silicon stripped detectors) [15]. By measuring the energies and angles of the protons, the two-body pick-up reaction could be characterized. The transfer-like products were selected by the SPEG [16] spectrometer and identified at its dispersive focal plane through their position, energy loss and time-of-flight information. The experimental angular distributions of the proton have been compared to those obtained with DWBA calculations using the DWUCK4 code [17] to deduce the angular momentum value and spectroscopic factor of each identified level in ^{47}Ar (see Fig. 2 [18]). Then, results obtained in this experiment were used to determined the rate of the reaction ^{46}Ar(n,γ)^{47}Ar and a similar procedure was applied for ^{48}Ar(n,γ)^{49}Ar using the calculated structure of ^{49}Ar. Resonant captures are expected to be negligible because of the shell closure N=28, only direct radiative capture were taken into account [19]. It was found [20] that a neutron density of 3x10^{21} cm^{-3} is required to explain the meteoritic abundances.

P-process

An experiment was performed (spokespersons Harrisopoulos and Oliveira) in order to measure the cross section of the reaction ^{78}Kr(α,γ)^{82}Sr at low energy. The Wien Filter of the LISE spectrometer was used in order to select the compound nucleus and to reject the intense incident beam. The objective of this kind of experiment to constrain Hauser-Feshbach calculations used to calculate the thousands of reactions that are involved in a supernova explosion and the p-process. This study is described in more details in the article of P. Ujic, A. Lagoyannis *et al* in this proceeding and [12].

Novae

Stellar explosions called novae take place in stellar binary systems which are made up of two stars, a red giant and a small, hot companion called a white dwarf. Matter is torn off the red giant and falls onto the surface of the white dwarf. This stellar matter accumulates on the surface of the white dwarf, leading to an increase in its temperature and density. At some density threshold, a runaway of thermonuclear reactions is triggered producing heavier and radioactive elements [21]. It was shown that the γ-ray emission following a nova is dominated by the 511 keV line originated mainly from the β^+-decay of the radioactive nucleus ^{18}F [22]. The reaction ^{18}F(p,α)^{15}O was identified to be the most sensitive and uncertain reaction for the production of ^{18}F [23]. Despite a lot of experimental efforts [24, 25], uncertainties remain in the determination of the rate of this reaction at novae temperatures. It is possible to calculate the rate of this reaction using the properties of the resonant states in the compound nucleus ^{19}Ne. An experiment was carried out at the Centre de Recherche du Cyclotron at Louvain-la-Neuve in Belgium, as part of an international collaboration (The School of Physics and Astronomy Edinburgh UK, CRC Belgium, Horia Hulubei Nat. Inst. of Phys. and Nucl. Eng. Bucharest, LPC Caen France, CSNSM Orsay France, IPN Orsay France), in order to improve our knowledge of these properties. This experiment was based on a new experimental method developed at GANIL. The inelastic scattering reaction H(^{19}Ne, p)^{19}Ne*(p)^{18}F was measured in inverse kinematics, using a ^{19}Ne radioactive beam accelerated at 9 A·MeV with an intensity of $\approx 8 \times 10^7$ pps. Proton-proton coincidences between protons arising from the inelastic scattering reaction and protons emitted from unbound ^{19}Ne* states were used for determining energies, widths and for the first time spin values of the resonant states. Besides the remarkable agreement with the insofar known resonances, a new broad 1/2+ resonance was found at about 1.4 MeV above the reaction threshold (see Fig. 3 [26, 27]). This state was predicted by M. Dufour and P. Descouvemont [28], with predicted properties in excellent agreement with our measured

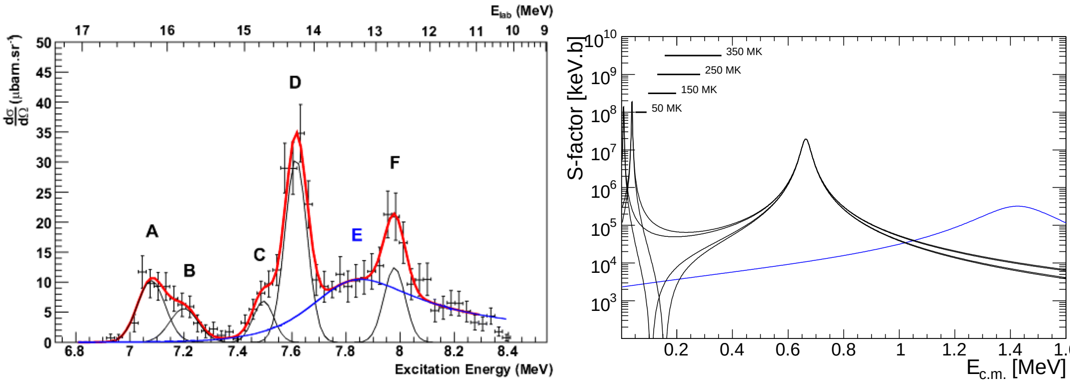

FIGURE 3. Figure. (Left): The measured differential cross section for the reaction H(^{19}Ne,p)^{19}Ne*(p)^{18}F is presented as a function of the ^{19}Ne* excitation energy. The broad peak labeled E corresponds to a state in ^{19}Ne observed for the first time. It was fitted with a Breit-Wigner shape using energy-dependent proton width. (Right): The astrophysical S-factor of the reaction ^{18}F(p,α)^{15}O is plotted as a function of the center-of-mass energy. The corresponding novae temperatures are indicated by upper marks. The contribution of the new resonance could become the major contribution to the S-factor in the range of interest, depending on interference effects between other states [26, 27].

values. The low energy tail of this resonance contributes to a significant enhancement of the ^{18}F destruction rate at novae temperatures. This reduces the chance to observe γ-ray emission of ^{18}F from a nearby nova explosion with existing telescopes.

Another experiment proposed by A. Murphy (The School of Physics and Astronomy Edinburgh UK) *et al* was performed at GANIL in order to study the states in ^{19}Ne above the proton emission threshold, and so to confirm the existence of this new 1/2+ state. The cross sections of the reactions ^{18}F(p,α)^{15}O and ^{18}F(p,p) were measured in inverse kinematics using a ^{18}F radioactive beam of Spiral. This beam was produced with an intensity of 2x10^{4} pps and a purity of 97 %, and accelerated at 4 AMeV. An important part of the work was performed in order to develop this new beam of ^{18}F at low energy and with a high purity. A stable beam of ^{18}O was also used in the same experimental conditions for calibrations. The excitation function for the elastic scattering at these low energies can be described by the Rutherford scattering, but shows "anomalies", i.e. various resonances that are related to individual states in the compound nucleus. The principle of the measurement, the so called Resonant Elastic Scattering, is described in [29, 30] and references therein. A MCP detector was placed upstream the target and was used to measure absolute time of flight. A 6 μm thick foil of gold was used to degrader the energy of the beam down to about 2.3 AMeV and a polyethylene $(CH_2)_n$ target of about 50 μm thick was used to induce the reactions. The scattered protons and emitted alpha particles were detected by a Type-W 16x16 DSSD silicon detector placed at forward angles (180° in the center of mass frame) within an total angular acceptance of about 10° (lab). Protons and alpha were identified using their energy and time-of-flight. The results of this experiment are still under analysis (Collab.: The School of Physics and Astronomy Edinburgh UK, GANIL, IPN Orsay, University of York UK, ORNL, LPC Caen). An "on-line" spectrum of the H(^{18}F,p)^{18}F reaction is shown in Fig. 4(left), it is compared with several other results obtained in different experiments. The properties

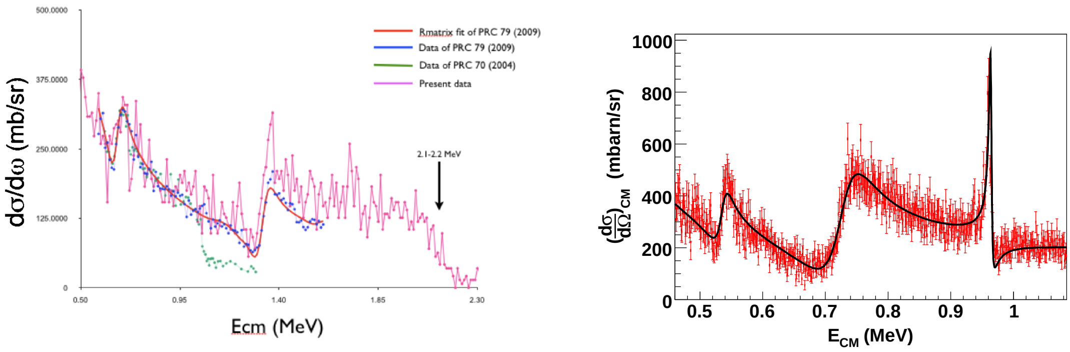

FIGURE 4. Left: Preliminary "on-line" results obtained for the excitation function of the H(^{18}F,p)^{18}F reaction. This spectrum shows structures that are related to the properties of excited states in ^{19}Ne. Our measurement is compared with other results obtained in different experiments. Right: The measured H(^{15}O,p)^{15}O resonant elastic excitation function using an ^{15}O radioactive beam. An excellent energy resolution better than 5 keV in CM was achieved. The different peaks are related to unbound states in ^{16}F.

of the excited states in ^{19}Ne will be obtained using a careful R-Matrix analysis of the excitation function constrained with the results obtained for the H(^{18}F,α)^{18}F reaction.

X-ray bursts

The proton-unbound nuclei ^{15}F and ^{16}F play an important role in X-ray bursts. These astronomical events are known to happen in close binary systems, where accretion takes place from an extended companion star on the surface of a neutron star (type I X-ray bursts). The accreted matter is compressed until it reaches sufficiently high pressure conditions to trigger a thermonuclear runaway. In these explosive events, the carbon and nitrogen elements are mainly transformed into ^{14}O and ^{15}O by successive proton captures [31]. Then, the pathway for new proton captures is hindered by the proton-unbound nuclei ^{15}F and ^{16}F. The reaction flux and the energy generation are then limited by the relatively slow β^+-decay of ^{14}O ($t_{1/2}$=71 s) and ^{15}O ($t_{1/2}$=122 s), which create waiting points. From time to time before the proton is emitted, the unbound nucleus ^{16}F can capture another proton thus producing the ^{17}Ne particle stable isotope [32]. This two-proton capture process was calculated to be significant for extreme densities (larger than 10^{11} g/cm^3), but these calculations were mainly based on predicted spectroscopic properties. The study of the low lying states of ^{16}F was the subject of an experiment performed at GANIL. The spectroscopic properties were obtained from the measurement of the H(^{15}O,p)^{15}O resonant elastic scattering excitation function using a low energy ^{15}O beam produced by the SPIRAL facility. A beam of radioactive ^{15}O nuclei was produced with a mean intensity of 10^6 pps at an energy of 1.2 A.MeV. A 31(1) μm thick polyethylene $(CH_2)_n$ target was used and the scattered protons were detected by a silicon detector placed at forward angles within an angular acceptance of

2°. Protons were identified using their energy and time-of-flight. An excellent energy resolution of 3 keV was achieved in the center of mass frame. Fig. 4 (right) shows the excitation function obtained for the H(^{15}O,p)^{15}O reaction. The measured cross section was reproduced with an R-matrix calculation using the code Anarki [33] which is seen to be in a good agreement with the data. It allowed us to extract the properties of the first three states in ^{16}F and to propose alternative reaction mechanism to bypass the ^{14}O waiting point [34, 35, 36].

OUTLOOK

The development and prospects of such experiments with astrophysical interest is performed within the group "astro@ganil". Please contact F. Oliveira (oliveira@ganil) to join discussions. Several radioactive beams are studied and should be developed (by the GANILSOL group), using the Spiral 1 facility (ex: P, S, Cl, Mg, Al, Li, Na etc.), or the Spiral 2 facility including intense light radioactive beams (^{14}O, ^{15}O, ^{8}Li etc. - Preparatory Phase Collaboration).

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