NUCLEAR ASTROPHYSICS @ GANIL

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A short review of recent nuclear astrophysics experiments performed at GANIL is given. These experiments used radioactive beams produced by the SPIRAL facility or the LISE separator.

1. Introduction

In recent years, the GANIL has seen an increasing activity in the field of nuclear astrophysical. Several stellar phenomena remain poorly understood (supernovae, x-ray bursts) and the availability of radioactive beams has lead to new studies. Several experiments are presented below. Lacking of space, the figures must be sought in the articles given in reference.

2. High-precision measurement of beta decay half-life

The cross section of nuclear reactions is sometimes enhanced at sub-Coulomb energies. It is due to the electrons cloud surrounding the nuclei and acting as a screening potential for the strong Coulomb repulsion force [1,2]. Surprisingly, the measured screening effect is most often much larger than predicted. Up to now, there is no satisfactory explanation. A large screening effect was observed with metallic targets [3]. 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 nuclei, 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. 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 Fermi function "f" change with the presence of the electrons, which induces a change in the partial half-life "t". It is predicted a longer half-life for the β^- decay, and a shorter one for the β^+ decay. Several experiments [4,5] have observed change of a few percents in the half-life of nuclei implanted in metallic materials and cooled down to low temperatures. But, contradictory results were also obtained [6].

Recently, an experiment was performed at GANIL by P. Ujic *et al* [7] in order to investigate for the first time this screening effect within a superconductor material. A foil of Niobium was cooled down to different temperatures, down to 4 K. Niobium is a normal metallic conductor at room temperature, and 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 [8], and it was predicted that a "super-screening" effect could happen. Two intense beams of radioactive ions, ^{19}O and ^{19}Ne, were produced with the SPIRAL facility with about 10^5 pps. Simulations showed that accumulation of lattice damages produced by the beam was not sufficient to destroy the superconducting phase during the experiment. Ions were implanted in the foil with 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 located in a compact geometry. Decay lifetimes were measured with an accuracy better the 0.1 %. Cycles of measurements performed at different temperatures were used in order to reduce the systematic errors. We observed that half-lives and branching ratios measured in the two phases are consistent within a 1σ error bar. This measurement casts strong doubts on the predicted strong electron screening in a superconductor. The measured difference in screening potential energy is 110(90) eV for ^{19}Ne and 400(320) eV for ^{19}O. Precise determinations of the half-lives were also obtained for ^{19}O, 26.476(9) s, and for ^{19}Ne, 17.254(5) s [7].

3. Study of $^{60}Fe(d,p)^{61}Fe$

The isotope ^{60}Fe is radioactive with a half-life of about 3 millions years. The characteristic γ-ray lines were observed in the Galaxy by spacecrafts RHESSI and INTEGRAL. The observation in meteoritic presolar grains of an excess of the daughter nuclei of ^{60}Fe, ^{60}Ni, gives constraints on the conditions of formation of the early solar system. Surprisingly, ^{60}Fe was also observed in deep-sea crust, at a depth corresponding to a contamination of the Earth 2.8 million years ago. All these facts encourage us to look at the astrophysical origin of this isotope.

The isotope ^{60}Fe is probably mainly produced in core-collapse supernova during s process. The cross-sections of the destruction reaction $^{60}Fe(n,\gamma)^{61}Fe$ is still uncertain, this motivates more studies. The total cross section of this reaction can be separated into two contributions: the direct one, involving states below the neutron separation threshold of ^{61}Fe, and the resonant ones. An experiment was performed at GANIL (F. Hammache et al) [9] in order to improve the spectroscopy of this nucleus. A radioactive beam of ^{60}Fe was produced by the fragmentation of a 55 AMeV ^{64}Ni beam and purified to 70 % purity using the LISE separator. The transfer reaction $d(^{60}Fe,p\gamma)^{61}Fe$ was measured using the detectors CATS for the beam tracking, MUST2 for the charged particles and EXOGAM for gamma. Coincidences between gamma and proton could be used to determine a new state in ^{61}Fe at the energy of 1.401 MeV. A DWBA analysis of the proton differential cross sections fits well with an angular momentum $\ell = 1$. Since the corresponding centrifugal barrier is low, this state should be taken into account in the calculation of the direct capture part of the cross section of the $^{60}Fe(n,\gamma)^{61}Fe$ reaction. This work is ongoing.

4. First direct measurement of a cross section at low energy $^{18}F(p,\alpha)^{15}O$

Stellar explosions called novae take place in stellar binary systems which are made of two stars, a red giant star and a small and hot companion star 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 [10]. The observation of γ rays from nova ejecta should provide a rather direct way to investigate the nucleosynthesis and matter ejection mechanism [11]. The γ-ray spectrum produced in novae is predicted to be maximal at energies of 511 keV and below, originating from positron annihilations. It was shown that the main contribution to positrons production is the long-lived ^{18}F radioactive nucleus (half-life 109.77 min). Therefore, the amount of radiation emitted scales with the ^{18}F content of the nova ejecta, which in turn depends strongly on its production and destruction rates.

The reaction $^{18}F(p,\alpha)^{15}O$ was identified to be the most sensitive and uncertain for the destruction of ^{18}F in novae [12]. Despite a lot of experimental efforts [13-15 and references therein], uncertainties remain in the determination of the rate of this reaction at novae temperatures. One potentially important source of uncertainty comes from interferences between three 3/2+ resonances [14,16]. M. Dufour and P. Descouvemont [17] predicted the existence of two 1/2+ states, one at 0.41 MeV below the proton emission threshold and a second broad resonance at 1.49 MeV above the threshold. If the existence and properties of these 1/2+ states were confirmed, the reaction rate at typical novae temperatures would be boosted by reactions through these states. It would follow that the importance of the interferences contribution between the 3/2+ resonances would be much reduced. Recently, J.C. Dalouzy *et al* [15] observed for the first time the second resonance at the accelerator of

Louvain La Neuve using an inelastic scattering reaction and proton-proton correlation technique, but this state was quite controversial since none of the other experiments could observe it.

A new experiment was proposed at GANIL by A. Murphy (The School of Physics and Astronomy Edinburgh UK) *et al* in order to study the excited states in ^{19}Ne located above the proton emission threshold, and so to confirm the existence of this new 1/2+ state. The cross sections of the two reactions ^{18}F(p,α)^{15}O and ^{18}F(p,p) were measured simultaneously in inverse kinematics using a ^{18}F radioactive beam produced by the SPIRAL facility and accelerated to 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. It was obtained with an intensity of $2x10^4$ pps and a purity of 97 %. A stable beam of ^{18}O was also used in the same experimental conditions for calibrations. A micro channel plate (MCP) detector was placed upstream the target and was used to measure time of flight and beam intensity. A 6 μm thick foil of gold was used to degrade the energy of the beam down to about 2.3 AMeV and a polyethylene target of about 50 μm thick was used to induce reactions. 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 a total angular acceptance of about 10° (lab). Protons and alpha particles were identified using their energy and time-of-flight. At GANIL, this is the first time that a reaction is measured directly at low energy for astrophysical interests. The results of this experiment were published recently [18]. They confirm the existence, the energy and width of the broad 1/2+ resonance.

5. Resonant Elastic Scattering reaction ^{17}Ne(p,p)^{17}Ne

X-ray bursts are astronomical events 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). These events are very similar to the novae events, except that they are more violent. In these explosive events, pathway for fast proton captures is hindered by proton-unbound nuclei, creating waiting points. Sometimes, unbound nuclei (^{16}F for example) can capture another proton producing particle stable isotope (e.g. ^{17}Ne) [19]. This exotic two-proton capture process was calculated to be significant for only extreme densities (larger than 10^{11} g/cm3). One way to investigate this reaction is to study the inverse reaction, the two-proton radioactivity.

The two-proton radioactivity of ^{19}Mg was discovered recently [20] using a tracking technique. Its lifetime was measured to be 4.0(15) ps, the Q value is 0.75(5) MeV, and the measured angular correlation between the emitted protons does not show strong di-proton correlation [21]. However, the intermediate unbound nucleus ^{18}Na is almost unknown. It was not clear if the ground state of ^{18}Na was located above or below ^{19}Mg ground state [22, 23]. It is very important to measure the properties of the ^{18}Na low lying states in order to understand the two-proton decay mechanism of ^{19}Mg and the lifetime of this nucleus. Resonant elastic scattering (RES) is a powerful method to investigate the structure of unbound nuclei. However, very few proton-rich unbound nuclei are accessible experimentally due to low beam intensities as getting closer to the proton drip-line. The unbound nucleus ^{18}Na, the intermediate nucleus in the two-proton radioactivity of ^{19}Mg, is one of the rare unbound nuclei which are accessible.

We performed the measurement of the RES reaction p(^{17}Ne,p)^{17}Ne in inverse kinematics in order to study the properties of ^{18}Na. A pure beam of radioactive $^{17}Ne^{3+}$ ions was produced by the SPIRAL facility at GANIL with a mean intensity of 10^4 pps and accelerated to 4 A.MeV. A beam of $^{17}O^{3+}$ ions was also produced in similar experimental conditions for calibration by comparison with the ^{17}O(p,^{17}O)p reaction. The beam impinged on a fixed 50μm thick polypropylene C3H6 target coupled to a second rotating 50μm thick C3H6 target. The two targets together were thick enough to stop the ^{17}Ne beam. This method, described in [24,25], enables to measure the full excitation function at once. Scattered protons were detected with a ΔE-E annular telescope of silicon detectors placed at forward angles. The telescope was composed of a thin (≈40μm) double-sided silicon strip detector coupled to a 1.5mm thick silicon detector and was covering angles from 5 to 20 degrees in laboratory reference frame. The scattered proton spectrum was polluted by beta-delayed protons emitted in the beta decay of ^{17}Ne. This nucleus decays with a lifetime of 0.109 s and a probability to emit protons of ∼90%. More than 98% of the β-delayed protons were rejected by using a 60 cm circular target (FULIS [26]) rotating at 1000 rpm. The ions were implanted in the target and moved away before they decayed. A MCP was used for time of flight and beam measurement with efficiency close to 100%. From ToF measurement and ΔE-E selection, the scattered protons were identified and the excitation function was reconstructed in the laboratory frame. The residual β-delayed protons were subtracted. The background produced by the presence of ^{12}C in the target was measured using a pure carbon target and was also subtracted. A fit of the excitation function was performed with the R-matrix code Anarχ [27]. The R-matrix calculation agrees very well with the data in most part of the excitation function. This experiment also suggests the additional presence of two very narrow states, including the ground state of ^{18}Na. These resonances are too narrow to be seen, this means their width are narrower than 1 keV. A detailed description of the experiment and results are presented in [28]. The effect of these results on the two-proton radioactivity mechanism of ^{19}Mg is also discussed in this reference.

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