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Coulomb dissociation of ^{27}P: a reaction of astrophysical interest

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The ground-state decay of ^{26}Al(0^+) ($T_{1/2}$=1.05$\times$ 10^6) has a shorter life-time than the Universe. The presence of this element in the Galaxy was measured via γ-ray spectroscopy, showing that the nucleosynthesis of this element is an ongoing process in stars. The proton-capture reaction ^{26}Si(p,γ)^{27}P competes with the production of ^{26}Al(0^+) by β-decay. Coulomb dissociation of ^{27}P has been suggested as an indirect method to measure radiative-proton capture when the direct reaction is not feasible. Such an experiment was performed at GSI with a secondary ^{27}P beam produced by fragmenting a ^{36}Ar primary beam at 500 *A* MeV. Two main observables are preliminarily presented in this work: the reaction cross section and the relative-energy spectrum of the outgoing fragments

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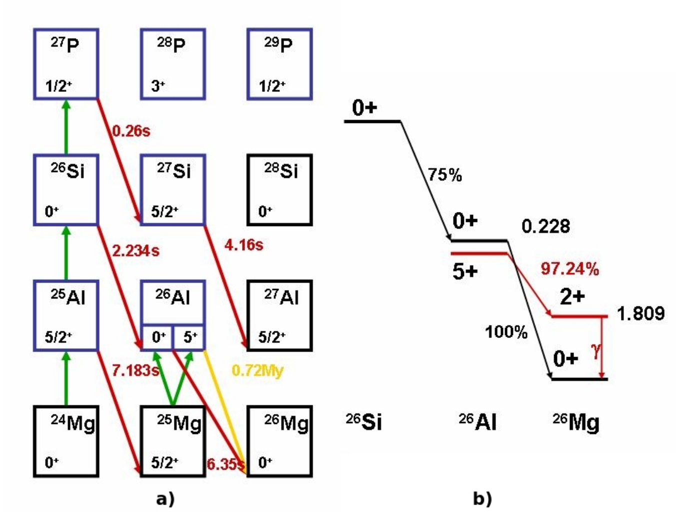

Figure 1: Decay scheme of the different isotopes around ^{26}Al

1. Motivation

Satellite-born measurements of γ-rays [1] from the Galaxy confirmed the idea of presently ongoing nucleosynthesis processes in stars. The first evidence [2] was the measurement of the γ-ray line from the de-excitation of ^{26}Mg produced by the β-decay of ^{26}Al (Fig.1a). ^{26}Al has a $J^{\pi} = 0^{+}$ isomer and a $J^{\pi} = 5^{+}$ ground state. The first one decays fast to the ground state of ^{26}Mg, whereas the ground state decays with a half-life of 1.05×10^{6} years to the first excited state of ^{26}Mg giving a γ-ray of 1.809 MeV. Since this half-life is much shorter than the age of the Universe, the detection of such a long-lived β-delayed γ-radiation was taken as clear evidence for ongoing production. The relative population of these two states in ^{26}Al is, among others, controlled by the competition between the β-decay of ^{26}Si and the reaction ^{26}Si(p,γ)^{27}P which takes flux out of the β-decay channel.

2. Coulomb dissociation technique

The direct proton-capture reaction (p,γ) is in general extremely difficult to measure in the lab due to the low intensities of low-energy radioactive beams and the small cross sections, in particular at low relative energies which correspond to the astrophysical scenario. The particular case of the ^{26}Si(p,γ)^{27}P reaction under typical nova conditions occurs at a mean center-of-mass energy of 300 keV; in this energy regime the cross section is of the order of nb.

Coulomb dissociation (CD, see Ref. [3]) has been proposed as an alternative, indirect method, studying the time-reversed reaction ^{27}P(γ,p)^{26}Si. In this method, the Coulomb field of a high-Z target nucleus is used as an intense source of virtual photons electromagnetically disintegrating the projectile. Thus, in our case, the ^{27}P beam impinges on a thick ^{208}Pb target. The ^{27}P is excited via the absorption of a virtual photon to a particle-unbound state which decays into p+^{26}Si. One advantage is that CD has a much larger cross section (in the order of mb) than radiative proton capture. This is because the phase volume for (γ,p) is much larger than for (p,γ). Since at high

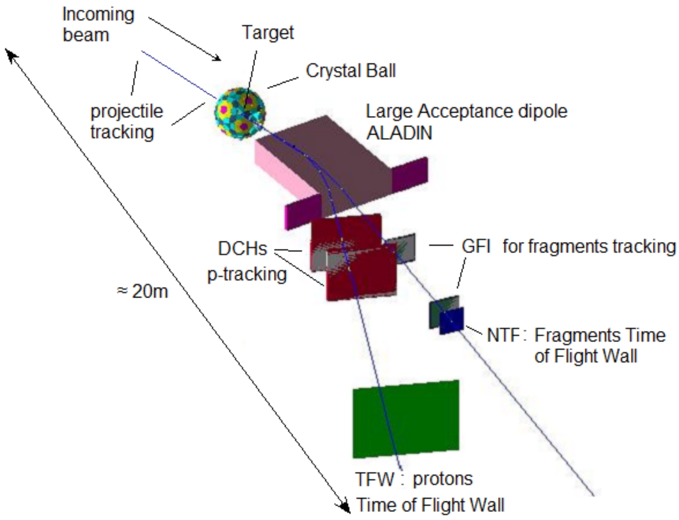

Figure 2: Experimental setup

energies also the virtual-photon intensity [4] is large and it is possible to use a thick target, one can easily compensate for the low beam intensities.

3. Experiment S223 at GSI

The experiment [5] was performed using the ALADIN-LAND setup [6] at GSI with a ^{36}Ar primary beam at 500 *A* MeV. A secondary beam of ^{27}P was produced by projectile fragmentation and separated in-flight in the FRS [7]. The ALADIN-LAND setup allows to measure reactions in full kinematics. After the Coulomb dissociation of ^{27}P in a thick Pb target, both outgoing fragments, protons and ^{26}Si, enter the large-acceptance magnet (ALADIN) and are deflected differently according to their rigidities. A set of detectors located after the magnet allows to track and identify protons and fragments on an event-by-event basis (Fig.2). The highest angle branch corresponds to the identification of the protons and consists of 2 large area (1×0.8 m^2) drift chambers (DCH) which track position and angle and a time-of-flight wall based on plastic scintillator paddles. The second branch intends to track the heavy fragments and consists of 2 large area ($0.5\ \times0.5$m^2) fiber detectors (GFI) for position and angular measurement and a time-of-flight wall which allows charge and mass identification.

The measurement with a lead target gives information about the Coulomb dissociation, but it also contains nuclear contributions. In order to disentangle those, data were also taken with a carbon target which only has nuclear contributions. Together with an empty-target measurement, the pure electromagnetic contribution can be extracted.

4. Preliminary results

The calibration and analysis of the 2000 electronic channels of the experiment allow the preliminar determination of two main observables: the cross section of the Coulomb dissociation reaction and the relative energy spectra for the outgoing fragments. Further inspection of those will

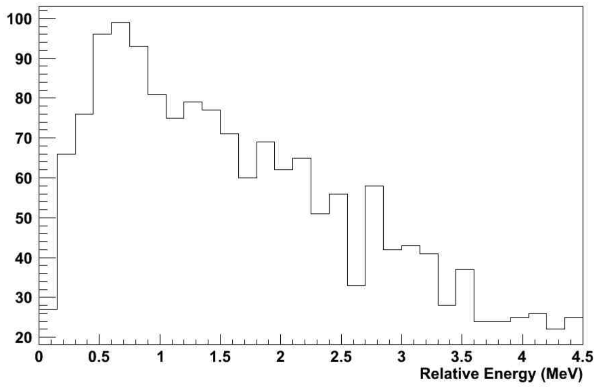

Figure 3: Relative energy in MeV of the outgoing fragments: ^{26}Si and p. The y axis shows number of counts per bin

provide astrophysical information that may help to better understand the production of ^{26}Al in stars.

The invariant mass of a multi-particle final state can be expressed as:

$$M = \sqrt{\left(\sum_i E_i\right)^2 - \left(\sum_i \vec{P}_i\right)^2} = E_{decay} + \sum_i m_i \tag{4.1}$$

where E_i is the total energy, $\vec{P}_i$ the momentum vector and m_i the rest mass of the different i-th reaction products in natural units (c=1). E_{decay} is the excitation energy above the particle threshold, and identical to the relative energy between two decay particles in case of a two body decay. This relative energy is also identical to the center-of-mass energy in the (p,γ) reaction, thus, the relative energy can be extracted from the invariant mass:

$$E_{rel} = M - (m_1 + m_2) = \frac{T_1 T_2 \left(\frac{\vec{p}_1}{T_1} - \frac{\vec{p}_2}{T_2}\right)^2}{\sqrt{(m_1+m_2)^2 + T_1 T_2 \left(\frac{\vec{p}_1}{T_1} - \frac{\vec{p}_2}{T_2}\right)^2} + (m_1 + m_2)} \tag{4.2}$$

where T_i the kinetic energy of the products.
The relative energy can be obtained by measuring the kinetic energies and momentum vectors of the outgoing fragments. In Fig. 3 a relative-energy spectrum for ^{26}Si and proton is shown. Further studies and comparison with the known data for this reaction [8, 9] will help in better understanding the astrophysical implications of this reaction.

To estimate the total cross section of the Coulomb dissociation reaction the nuclear contribution as well as the background must be subtracted; for this purpose measurements with a carbon and an empty target were performed. A first approximation to the cross section can be calculated as it follows:

$$\sigma_{CD} = p_{Pb}\frac{M_{Pb}}{d_{Pb}N_{Av}} - p_C \alpha \frac{M_C}{d_C N_{Av}} - p_{empty}\left(\frac{M_{Pb}}{d_{Pb}N_{Av}} - \alpha \frac{M_c}{d_C N_{Av}}\right) \tag{4.3}$$

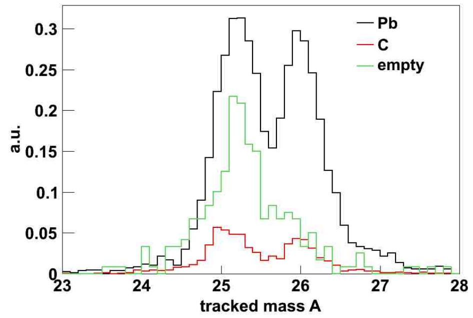

Figure 4: Masses of the silicon fragments after tracking, for the 3 different targets

where p_i is the ratio of the number of selected events for that target versus the total number of incoming ^{27}P, d_i the thickness of the target, N_{Av} is the Avogadro number and $\alpha = \frac{1+aA_{Pb}^{1/3}}{1+aA_{C}^{1/3}}$ is the scaling factor based on a semiempirical model [10] which relates the nuclear contribution cross section for a Pb target as compared to the one measured with a carbon target. Parameter $a = 0.14$ and $\alpha = 1.385$. Fig.4 shows the tracked masses of the selected Si ions produced after the Coulomb breakup of the incoming ^{27}P. Only Si events measured in the heavy ion branch in coincidence with a proton in the proton branch and in coincidence with a proton and ^{27}P incoming beam are shown. Scaled contributions for the different targets are represented. With this data, the preliminar total cross section obtained is $\approx 100 \pm 5$ mb, taking into account detection and geometrical efficiency. The value is in the order of the theoretical expectations (98.7 mb) [11]. Further studies of the different excited-state contributions in the relative energy (fig.3) can give information of the cross section of the different resonances (M1+E2 is the main one according to [9]).

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