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Abstract. In this work the astrophysical ^{26}Si(p,γ)^{27}P reaction is studied using the Coulomb dissociation technique. We performed a ^{27}P Coulomb Dissociation experiment at GSI, Darmstadt (28 May-5 June 2007) using the ALADIN-LAND setup which allows complete-kinematic studies. A secondary ^{27}P beam at 498 AMeV impinging a 515mg/cm^2 Pb target was used. The relative energy of the outgoing system (^{26}Si+p) is measured obtaining the resonant states of the ^{27}P. Preliminary results show four resonant states measured at 0.36±0.07, 0.88±0.09, 1.5±0.2, 2.3±0.3 MeV and evidence of a higher state at around 3.1 MeV. The preliminary total cross section obtained for relative energies between 0 and 3 MeV has been measured and yields 55±7 mb.

1. Introduction

Nuclear Physics inputs are of great importance in the building of a coherent picture of the production and evolution of the constituents of the Universe. In particular, the production and evolution of stars is an important topic throughout the history of the science. The success of the theories by Eddington (1920) [1] and Hans Bethe (1939) [2] explaining nuclear fusion processes involved in stars lead to the development of nucleosynthesis theories as a key part of the understanding of the Universe.

The famous review paper by Burbidge, Fowler and Hoyle in 1957 [3] proposed the stars as the seat of the origin of the elements as previously suggested in 1946 by Hoyle [4]. Previous theories assumed that nuclides were built in a primordial fireball (for which there was no evidence) at the beginning of the Universe. Those models were very attractive for the scientific community and managed to explain many observable features. However, they failed in the explanation of

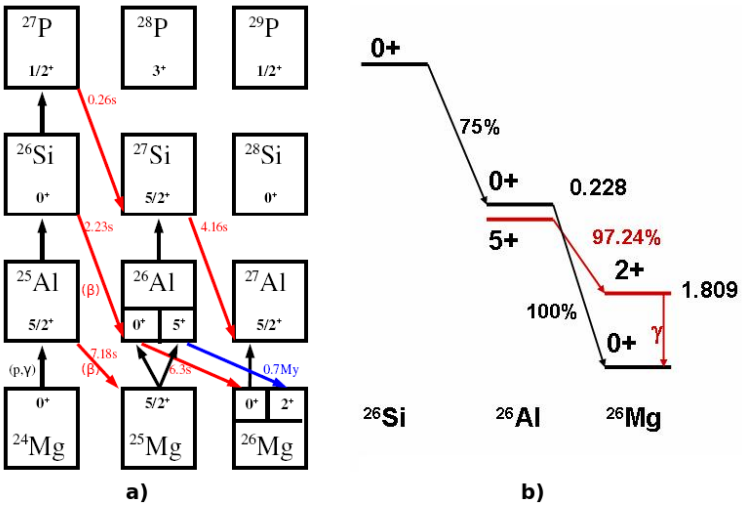

Figure 1. The left figure shows a subset of the nuclide chart showing the ions involved in the production of ^{26}Al, including the reaction of interest ^{26}Si(p,γ)^{27}P. The right part shows the decay scheme for the ^{26}Al to ^{26}Mg, showing the involved levels and the 1.809 MeV γ line

the observational fact that not all the stars exhibit the same surface composition. Primordial theories explained the distribution of material in a cosmic scale as spatially uniform and independent of time, and thus the composition should be uniform. However, the variation of the universal abundance distribution of the elements, requires their distribution after the formation by ejecting material in several phases of the evolution of the stars (red giants, supernovae, novae...). This fact supports the stellar synthesis theories.
In particular, in this work we are interested in the proton rich side of the nuclide chart, whose nuclei evolve mainly due to the rapid proton capture process (rp-process). This process consists of consecutive proton captures producing heavier nuclei.
Particularly, we are interested in the region of formation of ^{26}Al. The measurement of populations of this element in stellar scenarios served as a proof of the ongoing nucleosynthesis in stars. This nucleus has a life time of 1.05×10^6 years, much shorter than the age of the Universe. Thus, the detection of this nucleus is a direct evidence of nucleosynthesis as an ongoing process. Nucleosynthesis of ^{26}Al is complicated by the presence of a short-lived ^{26}Al$_m$ (τ 9.15 s) spin isomer. The only way to synthesise the long- lived ^{26}Al$_g$ isotope in nova explosions is through proton capture reactions on ^{25}Mg, which can yield both the ^{26}Al ground and isomeric states [5].
A subset of the nuclide chart with the ions involved in this process is shown in figure 1.
The isomeric state decays predominantly to the ground state of ^{26}Mg, while the ground state decays to the first excited of ^{26}Mg giving the γ -ray of 1.809 MeV, (the one detected in galactic measurements). The β -decay of ^{26}Si mainly populates the ^{26}Al(g.s.), and the production of the ^{26}Si comes from the competition of the β -decay ^{25}Al and the reaction ^{25}Al(p,γ)^{26}Si that is destructed in the ^{26}Si(p,γ)^{27}P. This reaction is the small part of the puzzle which is addressed in this work.

2. Coulomb Dissociation technique

The Coulomb dissociation technique [6] [7] is proposed as a very suitable method for the investigation of electromagnetic transitions between a bound state of two particles and resonant states at small relative energies between the interacting particles. In this method, the nuclear Coulomb field is used as a source for the photodisintegration process, so instead of the direct

(p,γ), the time reverse reaction (γ,p) is measured. The Coulomb field of the target serves as a source of virtual photons, and thus induces the breakup reaction. The number of equivalent photons can be calculated theoretically [8] [9], so the experimental measurement of the Coulomb breakup can be used to obtain the corresponding γ-induced cross section and, by using the detailed balance theorem, the related direct (p,γ) reaction cross section.

3. Experiment S223 at GSI

The experiment was performed at the German laboratory Hemholtzzentrum fur Schwerionenforschung (GSI) located in Darmstadt, in particular in the ALADIN-LAND experimental setup. A ^{36}Ar primary beam was accelerated and produced a secondary ^{27}P beam at 498 AMeV by nuclear fragmentation on a Be target. This secondary beam was selected in-flight in the Fragment Separator (FRS) [10] [11] [12].

After the selection of the secondary beam in the FRS, the exotic nuclei are transmitted to the ALADIN-LAND setup in Cave C, that comprises the following parts:

(i) Along the path to the ALADIN-LAND reaction target the incoming species are tracked and identified with the help of the secondary beam tracking detectors.
(ii) The target area comprises a target chamber that contains a target wheel and a microstrip-silicon detector located just behind it. The Crystal Ball detector surrounds the target and guarantees the detection of gamma-rays originated in the reaction.
(iii) Then A Large Area DIpole magNet (ALADIN) separates the species produced in the reaction according to their magnetic rigidities, in particular in this experiment we are interested in protons and heavy fragments (mainly ^{26}Si).
(iv) After ALADIN we can distinguish two branches: one that allows the tracking of the protons, composed by two drift chambers (DCH) and a ToF wall (TFW); and another branch for the heavy fragments with two fiber chambers (GFI) and a smaller ToF wall (NTF).

This ensemble of detectors allows the kinematically complete measurement of the reaction of interest.

4. Experimental results

The relative energy spectrum is a very convenient observable which helps to study the resonant states of the incoming nucleus and the different electromagnetic decay modes. This spectrum is constructed from the measured momenta as follows:

$$E^* = \sqrt{\sum_i m_i^2 + \sum_{i \neq j} \gamma_i \gamma_j m_i m_j \left(1 - \beta_i \beta_j \cos \vartheta_{ij}\right)} + E_\gamma - m_{proj} \tag{1}$$

where $m_{i,j}$ are the masses of the outgoing fragments, $\gamma_{i,j}$ the Lorentz factor, $\beta_{i,j}$ their velocity in terms of the speed of light, ϑ_{ij} the relative angle between both fragments, E_γ the excitation energy of the projectile and m_{proj} the mass of the projectile.

Figure 2 shows the preliminary histogram obtained for our measured data after the selection of the reaction channel.
A first view of the spectrum clearly shows the evidence of the existence of resonant states that are actually predicted by the theoretical model of S. Typel [13] and measured in a previous Coulomb Dissociation experiment in RIKEN at much lower energy (57 AMeV) [14] [15] [16]

A preliminary scheme of the measured excited states in this experiment is represented in figure 3 in comparison with the previous measurements of RIKEN [14] [15] [16], Caggiano et al

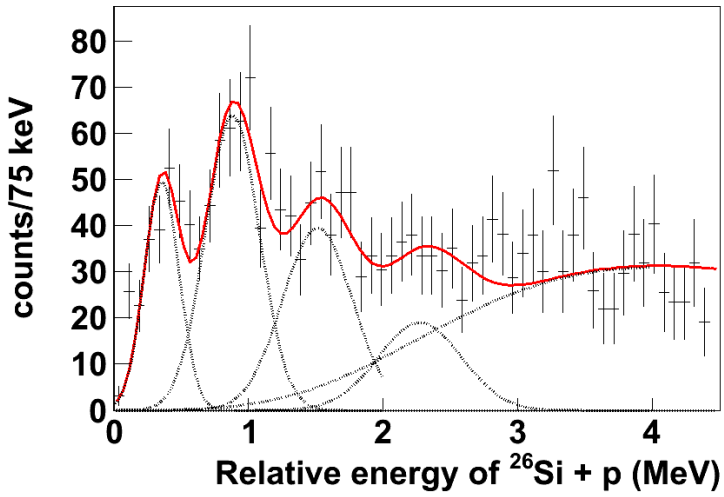

Figure 2. Preliminary relative energy spectrum corrected by efficiency. Gaussians are fitted to the resonant states. The direct capture component is fit to the theoretical prediction of S. Typel for the E1 component cross section

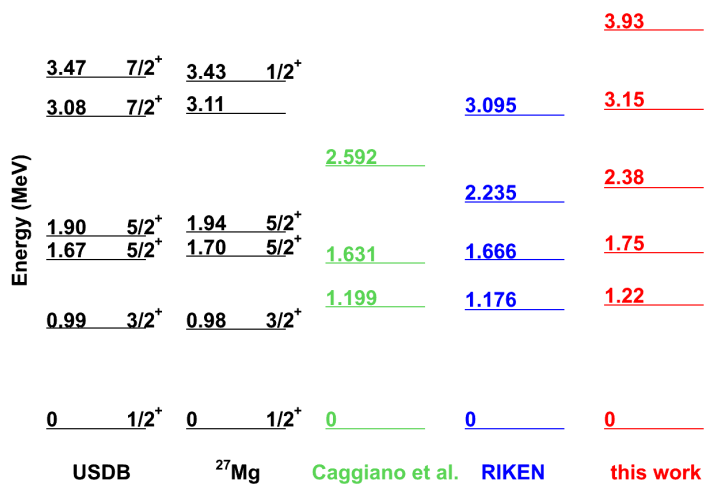

Figure 3. Preliminary level scheme for the ^{27}P excited states measured in this experiment, compared to the previous measurements in RIKEN [14][15][16], the mirror nucleus ^{27}Mg, USDB calculations [17] and ANC extrapolation [18]

[18] and also to theoretical USDB expectations and the comparison to the mirror nucleus states (^{27}Mg). Our measurements show good agreement with the others within the resolution.

The preliminary total cross section for the Coulomb dissociation was evaluated and amounts 55± 7 mb for relative energies smaller than 3 MeV. The considered error sources are the statistical errors and the contribution from the efficiency calculation.
S. Typel's calculation [13] predicted a value of 98 mb for energies up to 3 MeV which does not reproduce the experimental result accurately even though the order of magnitude is correct.

Further analysis will allow to calculate the partial cross section for the different resonant states and direct capture component

5. Conclusions

The reaction ^{26}Si(p,γ)^{27}P was studied by using the virtual photon theory in a Coulomb Dissociation experiment in inverse kinematics and preliminary results are shown. The relative energy spectrum of the outgoing particles was obtained, showing the resonant states of the ^{27}P. Four states are reported at energies 1.22±0.07, 1.75±0.09, 2.4±0.3, 3.1±0.4 MeV and evidence of a resonant state at around 3.9±0.4 MeV. All of them are in good agreement with previous measurements in RIKEN within the resolution. The fourth state was first evidenced in the RIKEN experiment with low statistics; with our measurement we find evidence of the higher state at 3.9±0.4 MeV.
The total cross section for energies up to 3 MeV is 55±7 mb about 1.8 times smaller than the theoretical prediction [13].

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