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2016 J. Phys.: Conf. Ser. 665 012018

Nuclear Physics in Astrophysics VI (NPA6) IOP Publishing
Journal of Physics: Conference Series **665** (2016) 012018 doi:10.1088/1742-6596/665/1/012018

Study of the ^{26}Al(n,p)^{26}Mg and ^{26}Al(n,α)^{23}Na reactions using the ^{27}Al(p,p')^{27}Al inelastic scattering reaction

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Abstract. ^{26}Al was the first cosmic radioactivity ever detected in the galaxy as well as one of the first extinct radioactivity observed in refractory phases of meteorites. Its nucleosynthesis in massive stars is still uncertain mainly due to the lack of nuclear information concerning the ^{26}Al(n,p)^{26}Mg and ^{26}Al(n,α)^{23}Na reactions. We report on a single and coincidence measurement of the ^{27}Al(p,p')^{27}Al(p)^{26}Mg and ^{27}Al(p,p')^{27}Al(α)^{23}Na reactions performed at the Orsay TANDEM facility aiming at the spectroscopy study of ^{27}Al above the neutron threshold. Fourteen states are observed for the first time within 350 keV above the ^{26}Al+n threshold.

1. Introduction

^{26}Al is a radioisotope produced in a variety of stellar sites such as massive stars (Wolf-Rayet phase and core-collapse supernovae), asymptotic giant branch (AGB) stars and nova outbursts. It β^+ decays ($T_{1/2} = 7.2 \times 10^5$ yr) to the first excited state of ^{26}Mg which then de-excites to its ground state emitting a characteristic gamma-ray line at $E_\gamma = 1.809$ MeV. The induced gamma-ray emission and ^{26}Mg excesses are observed since the late 70's thanks to gamma-ray [1] and meteoritic [2] observations, respectively. For example, these observations can give insight of the massive star forming conditions as well as of the astrophysical context of the Solar System formation.

Production of ^{26}Al in massive stars occurs at different stages of their evolution which includes core hydrogen burning, neon/carbon convective shell burning as well as explosive neon burning. For a typical 20 $M_\odot$ massive star the largest contribution to the ^{26}Al yield comes from the explosive phase [3]. Sensitivity studies [3, 4] have shown that this yield depends strongly on the ^{26}Al(n,p)^{26}Mg and ^{26}Al(n,α)^{23}Na reactions.

For typical temperatures achieved during explosive burning ($\approx$ 2.3 GK) the relevant energy range above the ^{26}Al+n threshold goes up to $\approx$ 500 keV. Unfortunately very little experimental data are available in this energy range. Indeed neutron induced measurements on ^{26}Al above the thermal energy are scarce [5, 6, 7]. In this work we investigate ^{27}Al spectroscopy up to 350 keV above the ^{26}Al+n threshold by means of the ^{27}Al(p,p')^{27}Al* reaction.

2. Experimental method and set-up

The ^{27}Al spectroscopy above ^{26}Al+n threshold (S_n = 13.057 MeV) has been investigated with a high-precision study of the proton inelastic scattering off ^{27}Al. High-resolution particle spectroscopy was used to derive the energy of the levels of interest. Their decay modes were studied performing the coincidence measurement of the ^{27}Al(p,p')^{27}Al(p)^{26}Mg and ^{27}Al(p,p')^{27}Al(α)^{23}Na reactions.

The ^{27}Al(p,p')^{27}Al* reaction was studied at the Tandem-Alto facility in Orsay, using a 18-MeV proton beam of about 300 nA. The beam impinged a self-supporting ^{27}Al target with a thickness of 89 μg/cm^2 and the light reaction products were momentum analysed with an Enge Split-Pole magnetic spectrometer. The focal-plane detection system includes a position sensitive gas chamber, a ΔE proportional gas counter and an plastic scintillator. The energy loss and position informations were used to identify the inelastic protons from other light particles. A resolution (FWHM) in the laboratory frame of 22 keV and 12 keV was obtained for excitation energies of 4.5 MeV and 13 MeV, respectively.

In case of the Split-Pole inclusive measurement ^{27}Al levels from the ground state up to about 14 MeV were studied by changing the magnetic field four times. Measurements were performed at spectrometer angles of 10°, 40° and 45°. In case of the coincidence measurement the inelastic protons were detected with the magnetic spectrometer positioned at an angle of 40°. The decaying protons and alpha-particles were detected using three Double-Sided Silicon Strip Detectors (DSSSD) of 5×5 cm^2 with 16 channels on each side (W1 model from Micron Semiconductor Ltd.). While two DSSSDs had a thickness of 300 μm the third one had a thickness of 1 mm. The DSSSDs were placed at about 10 cm from the target at backward angles in the laboratory to avoid high counting rate from elastic scattering. They covered about 6% of the 4π steradians. The beam intensity was reduced down to 100 nA for this measurement.

3. Split-Pole inclusive measurement

A careful focal-plane calibration was performed using the low-excitation energy exposure where well-known isolated states are strongly populated. Eleven ^{27}Al states across the whole focal plane were used to obtain a relation between the radius of curvature ρ and the focal-plane position. The one-degree polynomial function describing the previous relation was used for all other magnetic field settings. Proton energy losses in the target were taken into account.

Proton focal-plane spectrum obtained with the ^{27}Al target is shown in Fig. 1 for a spectrometer angle of 40°. The spectrum covers an energy region about 350 keV above the ^{26}Al+n threshold. The main proton peak observed at $B\rho \approx 0.308$ T.m. corresponds to the 12.710-MeV ^{12}C state. The proton focal-plane spectrum obtained at 45° (not shown here) was used to check that the proton peaks were following the mass-kinematic displacement associated to the ^{27}Al(p,p')^{27}Al* reaction. This confirmed that all observed proton peaks in Fig. 1 correspond to ^{27}Al states.

Deconvolution of the proton spectrum after background subtraction is superimposed to the data in Fig. 1. While our results are in excellent agreement with the ^{23}Na(α,γ)^{27}Al measurement

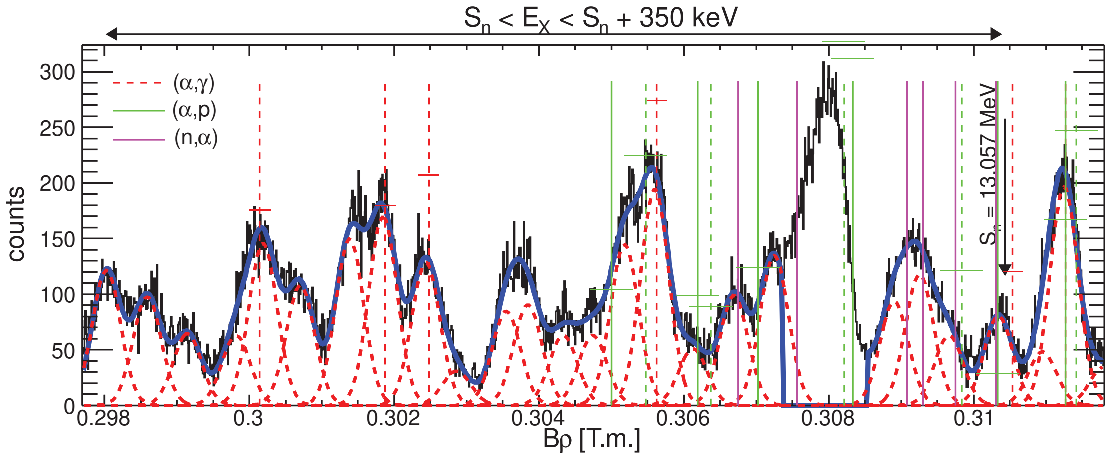

Figure 1. (Color on-line) Proton rigidity spectrum at spectrometer angle of 40°. The spectrum deconvolution is shown after background subtraction. Vertical lines represent the levels that have been observed in previous experiments (see text). The energy uncertainty of each level is represented by an horizontal line.

Table 1. Energies for new ^{27}Al states above the ^{26}Al+n threhsold. Uncertainty is about 4-5 keV. Experimental rigidity associated to each state is also given.

E_X (keV)	$B\rho$ (T.m.)	E_X (keV)	$B\rho$ (T.m.)	E_X (keV)	$B\rho$ (T.m.)
13104	0.3089	13249	0.3038	13363	0.2998
13152	0.3072	13258	0.3035	13381	0.2992
13211	0.3052	13277	0.3029	13397	0.2986
13224	0.3047	13319	0.3014	13412	0.2980
13235	0.3043	13338	0.3007		

of de Voigt et al. [8], they agree marginaly with the ^{23}Na(α,p$_{0,1}$)^{26}Mg measurements of Whitmire et al. [9]. Recently, neutron resonances have been populated using the ^{26}Al(n,α)^{26}Mg reaction [7], confirming the energies of neutron resonances obtained from direct ^{26}Al+n measurements [5] and time-reverse measurements [10, 11]. All these neutron resonances were observed in the present data. Excitation energies were extracted with an uncertainty of about 4-5 keV. The excitation energies for the new observed levels are listed in Table 1.

4. Coincidence measurement

For the coincidence measurement the Split-Pole spectrometer was set to an angle of 40° and covered excitation energies in ^{27}Al in the vicinity of the ^{26}Al+n threshold. The DSSSDs placed in the reaction chamber were used to record the energy and time information of the decaying protons and alpha-particles. Their energy resolution was about 20 keV. The DSSSDs signal was used as a stop for the time-of-flight measurement while the start signal was given by the Split-Pole plastic scintillator. After time-of-flight selection and after ensuring that the two sides of the DSSSDs measure the same energy deposit, the Split-Pole position information is plotted as a function of the DSSSD energy (see Fig. 2). Proton decays to the ground state and first excited state of ^{26}Mg are clearly observed. At lower DSSSD energies two loci are observed which could correspond to alpha-decay to ground state and first excited state of ^{23}Na as well as proton decay to the second excited state of ^{26}Mg. This measurement confirms that the ^{26}Al(n,p)^{26}Mg is dominated by the (n,p_1) component. Extraction of the proton and alpha branching ratio is in progress.

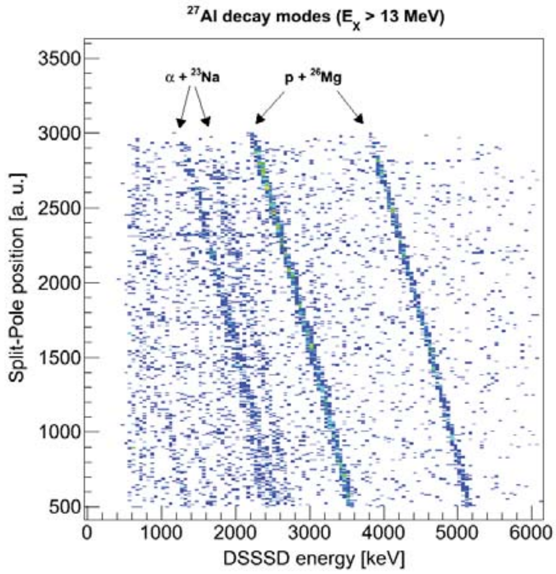

Figure 2. Split-Pole position information as a function of the energy deposit of one DSSSD. The Split-Pole spectrometer covers excitation energies in ^{27}Al in the vicinity of the ^{26}Al+n threshold.

5. Conclusions

A high-resolution coincidence measurement of the ^{27}Al(p,p')^{27}Al(p)^{26}Mg and ^{27}Al(p,p')^{27}Al(α)^{23}Na reactions has been performed at the Tandem-Alto facility using the Enge Split-Pole spectrometer coupled to a DSSSDs array. The energy range up to 350 keV above the ^{26}Al+n threshold was covered and 14 new states were observed. The coincidence measurement confirms that the ^{26}Al(n,p)^{26}Mg reaction rate is dominated by the (n,p_1) component. The branching ratio extraction is in progress.

Acknowledgments

The continued support of the staff of the Tandem-Alto facility as well as the target laboratory staff is gratefully acknowledged. UK personnel acknowledge the support of the Science and Technology Funding Council. This work has been supported by the European Community FP7 - Capacities-Integrated Infrastructure Initiative- contract ENSAR n° 262010 and the french-spanish AIC-D-2011-0820 project.

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