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Spectroscopic study of ^{26}Si for application to nova gamma-ray emission

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^{26}Al was the first cosmic radioactivity ever detected in the galaxy. Its nucleosynthesis in novae outbursts is still uncertain mainly due to the lack of nuclear information concerning the ^{25}Al(p,γ)^{26}Si reaction. We report here on a neutron-gamma coincidence measurement of the ^{24}Mg(^{3}He,nγ)^{26}Si reaction performed at the Orsay TANDEM facility aiming at the spectroscopic study of astrophysically important ^{26}Si states. A new level in the Gamow peak is observed at $E_X = 5.888$ MeV and the gamma-ray decay scheme of all levels below the proton threshold is confirmed.

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1. Introduction

^{26}Al has been the first cosmic radioactivity ever detected in the galaxy [1] and is characterized by a gamma-ray emission at E_γ = 1.809 MeV. This emission has been observed with many gamma-ray telescopes from high-altitude balloons or spacecraft and more recently with the INTEGRAL [2] and RHESSI [3] satellites. Its observation demonstrates that nucleosynthetic processes are currently active in our galaxy since the ^{26}Al half-life ($T_{1/2} = 7.2 \times 10^5$ yr) is very short compared to the time scale of the galactic chemical evolution ($\approx 10^{10}$ yr). Several stellar sites are thought to produce ^{26}Al such as Wolf-Rayet stars, core-collapse supernovae, asymptotic giant branch (AGB) stars and nova outbursts.

In the explosive environment of novae, ^{26}Al production and its subsequent gamma-ray emission proceed through the following reactions: ^{25}Al($\beta^+\nu$)^{25}Mg(p,γ)^{26}Al$^{g.s.}$($\beta^+\nu$)^{26}Mg*($\gamma_{1.809}$)^{26}Mg$^{g.s.}$. However, the ^{25}Al β^+-decay ($T_{1/2} = 7.2$ s) can be bypassed by proton capture on ^{25}Al and the resulting reaction sequence is: ^{25}Al(p,γ)^{26}Si($\beta^+\nu$)^{26}Al^m($\beta^+\nu$)^{26}Mg$^{g.s.}$, in which the isomeric state of ^{26}Al decays directly to the ground state of ^{26}Mg without producing the observed 1.809 MeV gamma-rays. Hence, the total amount of produced ^{26}Al$^{g.s.}$ is strongly dependent on the ^{25}Al(p,γ)^{26}Si reaction which plays a crucial role in the competition with the ^{25}Al β^+-decay.

Up to now, no direct measurement of the ^{25}Al(p,γ)^{26}Si reaction has been performed due to insufficient radioactive ^{25}Al beam intensity. Theoretical approaches with shell model calculations [4] as well as different experimental techniques were used to study proton-unbound states in ^{26}Si. These studies include multi-nucleon transfer reaction [5, 6, 7, 8, 9], as well as an in-beam gamma-ray experiment [10], β^+-decay experiment [11] and more recently one-nucleon transfer reactions [12, 13]. Moreover recent mass measurements of ^{26}Si have been done [14, 15] and we deduce a value of 5513.7 keV [15] for the proton threshold. Even if a consensus seems to have been reached concerning the spin and parity assignment of the first levels above ^{26}Si proton threshold [16], a more reliable experimental determination would still be very useful.

2. Experimental technique and set-up

In this context we performed an experimental study of the ^{24}Mg(^{3}He,n)^{26}Si*(γ)^{26}Si$_{g.s.}$ reaction. The measurement of gamma-ray transitions in coincidence with neutrons will be used to derive the decay scheme of specific ^{26}Si levels. Initial spin of the populated level could be obtained by studying the angular momentum rules of the considered gamma-ray transitions as well as the n-γ angular correlations.

The experiment was performed at the IPN Orsay 15 MV Van-de-Graaf TANDEM accelerator. The ^{3}He$^-$ beam was produced using a duoplasmatron source and was then injected into the tandem where it was accelerated and stripped. A 7.9 MeV ^{3}He beam with an intensity of 25 pnA was sent to a high purity ^{24}Mg target (99.85%) of 150 μg/cm^2 thickness produced by evaporation on a thin 0.2 mm Ta backing. Tantalum backing material was chosen since neutron as well as gamma-ray production is expected to be small for low energy ^{3}He ions. The backing thickness was adjusted to stop the beam and to limit neutron absorption.

The detection system consisted of the EDEN neutron array (NE213 organic scintillator) which was used to identify the ^{24}Mg(^{3}He,n)^{26}Si reaction and of Ge detectors to detect the gamma-rays coming from the decay of the populated levels in ^{26}Si. The neutrons were detected at forward angles with 36 EDEN modules positioned in a symmetrical way with respect to the beam axis. The EDEN array was placed at 1.75 m from the target, covering a solid angle of 370 msr corresponding to laboratory angles ranging from 0° to 35° in the reaction plane and to laboratory angles ranging from 0° to 40° above the reaction plane. Two clover and two coaxial Ge detectors were placed around the target in close geometry. One clover was positioned at 90° with respect to the beam axis while the other clover was at forward angles. Both coaxial detectors were at backward angles.

3. Analysis and Results

The EDEN detectors are cells of 20 cm diameter by 5 cm depth filled with NE213 organic liquid scintillator. They are best suited for the detection and identification of neutrons with energies between 1 and 6 MeV with a typical intrinsic efficiency of 50% at 1 MeV and 30% at 6 MeV. NE213 scintillators are both sensitive to neutrons and gamma-rays which produce scintillation light with a different decay time. Neutrons and gamma-rays are then discriminated by integrating and comparing the light output signal on two different timescales (see Fig. 1, left). The excellent discrimination down to $\approx$ 100 keVee (keV equivalent electron) for most of the detectors allows a clear identification and selection even for low energy neutrons. The neutron energy is determined by the time of flight technique where the start signal is given by the neutron (or gamma-ray) interacting in the EDEN detector ($\approx$ 1 ns intrinsic resolution) and the stop signal is given by the TANDEM pulsed time signal. The time of flight spectrum exhibits a strong peak due to prompt gamma-rays above a flat gamma-ray background (see Fig. 1, right). Neutron peaks hardly appear at larger time of flight (channels) from the prompt gamma-ray peak, but are clearly identified when neutrons are selected.

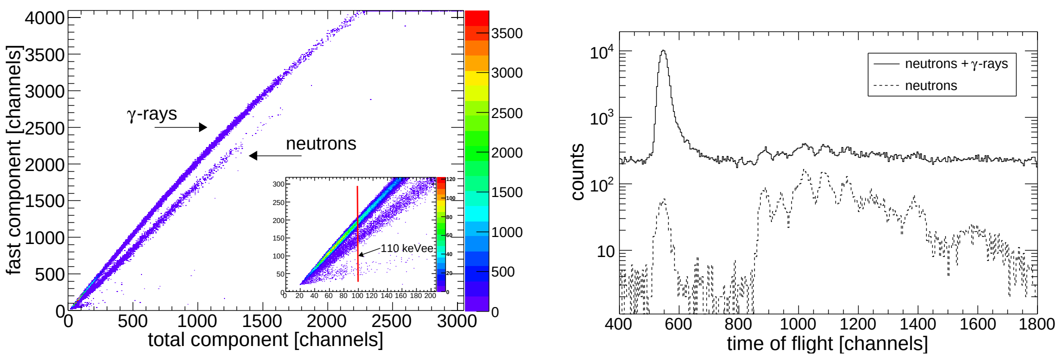

Figure 1: *Left:* Neutron and gamma-ray discrimination spectrum for one EDEN detector. The fast (total) component of the light output is integrated over 30 ns (400 ns). The inset shows the small light output region. *Right:* Time of flight spectra with respect to the TANDEM pulsed time signal for one EDEN detector. The effect of neutron selection can be observed by comparing the two spectra.

The neutron time of flight spectrum obtained for one EDEN detector is shown in Fig. 2 when a coincidence with any Ge detector is required. Apart from the presence of the prompt gamma-ray peak associated to low light outputs (see Fig. 1, left), several peaks are observed corresponding to single levels or groups of levels in ^{26}Si. All excited states below proton threshold in ^{26}Si are populated and their associated gamma-ray decay is observed confirming the decay scheme of Seweryniak et al. [10]. Identification of populated ^{26}Si levels is based on the gamma-ray transitions observed in Ge detectors when gating on individual neutron peaks. No evidence of the previously reported $E_X = 3.842$ MeV and $E_X = 4.093$ MeV levels [17] is found.

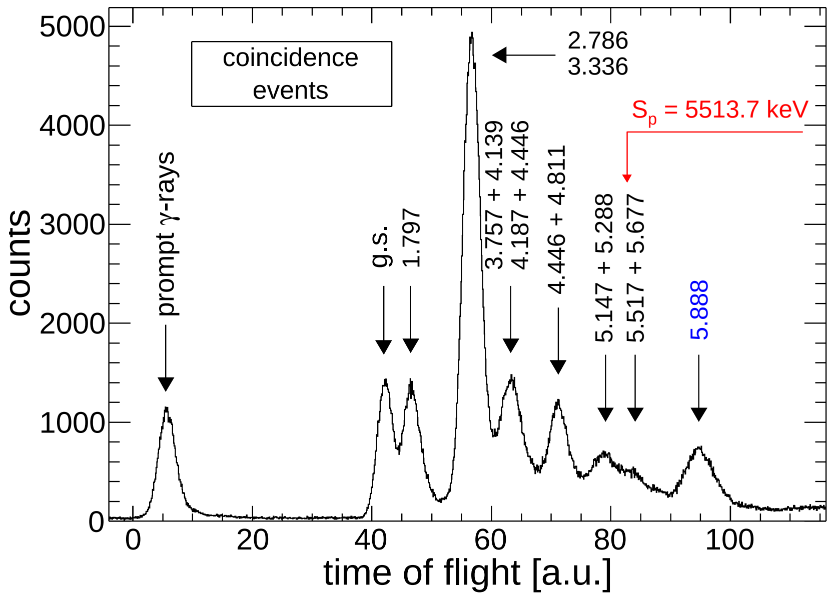

Figure 2: Time of flight for one EDEN detector in coincidence with any Ge detector when neutrons are selected. Neutron peaks associated both to levels below and above proton threshold in ^{26}Si are observed. Labels correspond to populated ^{26}Si levels energy in MeV.

Two neutron peaks close to and above the proton threshold are observed in Fig. 2. When looking at the gamma-ray spectra in coincidence with the first peak (between 80 and 90 a.u.), transitions from the E_X = 5.517 MeV level to the E_X = 4.187 MeV, 4.446 MeV, 3.757 MeV and 2.786 MeV excited states are clearly observed, as well as the transition from the E_X = 5.677 MeV level to the E_X =1.797 MeV excited state. These observations confirm the decay scheme of these two levels from Seweryniak et al. [10]. For coincidence events involving neutrons which correspond to the second peak above the proton threshold (see Fig. 2, $\sim$ 95 a.u.), the gamma-ray spectrum obtained for a coaxial detector is shown in Fig. 3. Three gamma-ray lines at 1.749 (2), 3.102 (2) and 4.091 (2) MeV are well populated and are preliminary assigned to an excited state in ^{26}Si at E_X = 5.888 (2) MeV decaying to the E_X = 4.139, 2.784 and 1.797 MeV levels, respectively. The gamma-ray decay of these intermediate levels is also observed on the same spectrum. This excited state at E_X =5.888 MeV lies in the Gamow peak region for typical temperatures achieved in classical novae. Its importance for the ^{25}Al(p,γ)^{26}Si reaction rate still need to be assessed when additional information on the spin and parity is derived.

4. Conclusions

The ^{24}Mg(^{3}He,nγ)^{26}Si reaction was studied using neutron-gamma coincidences with the goal

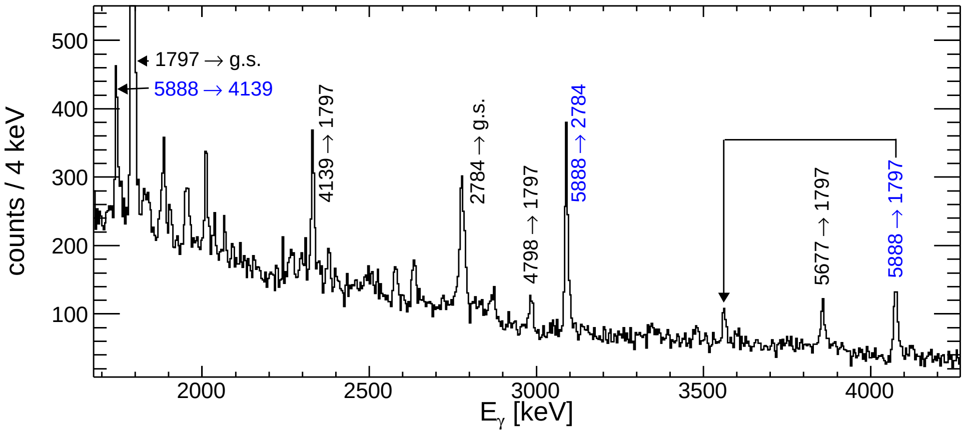

Figure 3: Energy spectrum for one coaxial detector in coincidence with the second neutron peak above proton threshold in ^{26}Si when all neutron detectors are considered. Transitions related to the $E_X(^{26}Si) =$ 5.888 MeV are labeled as well as the subsequent gamma-ray decays.

to clarify the spin and parity of states of astrophysical relevance for the ^{25}Al(p,γ)^{26}Si reaction. Peaks in the neutron time of flight spectra corresponding to single levels or groups of levels in ^{26}Si both below and above proton threshold were observed. All gamma-ray transitions from known levels below proton threshold are confi rmed. One preliminary result of this work is the observation of a state at E_X = 5.888 (2) MeV above the proton threshold. The nature and importance of this resonance is under study, as is the identifi cation of other resonances.

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