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## New developments and recent results in nuclear astrophysics at Louvain-la-Neuve

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### Abstract

Nuclear astrophysics using radioactive nuclear beams is one of the major research topics in Louvain-la-Neuve. Recently, experiment aiming at the measurement of  $(\alpha, \gamma)$ , and  $(\alpha, p)$  reactions have been performed. The  $^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne}$  reaction was studied using an indirect method based on the study of the  $^{18}\text{Ne}(d, p)^{19}\text{Ne}^*$ . Preliminary results of a new analysis of this experiment are presented here.

The new mass recoil separator ARES, coupled to the new cyclotron CYCLONE-44, is now operational. The ARES project status and results of performance tests are reported here. © 2002 Elsevier Science B.V. All rights reserved.

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## 1. Indirect study of $^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne}$ reaction

The CNO cycle takes place in stellar environments where carbon is present and temperatures are of the order of  $2 \times 10^7$  K or higher. This cycle transforms hydrogen to helium by a sequence of  $(p, \gamma)$ ,  $(p, \alpha)$  reactions and  $\beta^+$  decays.

As the temperature increases to  $10^8$  K the so called hot-CNO cycles take place. These cycles include p captures by  $\beta$  unstable isotopes. The  $^{13}\text{N}(p, \gamma)^{14}\text{O}$  reaction initiates the hot-CNO cycles, while the  $^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne}(p, \gamma)^{20}\text{Na}$  reaction chain may lead to an escape from the CNO cycles and to an enhancement of the abundances of the seed isotopes for the subsequent rp-processes, which will synthesize heavier elements. The measurement of the  $^{15}\text{O}(\alpha, \gamma)^{19}\text{Ne}$  reaction cross section in the energy region of interest (roughly 500 keV), where some  $^{19}\text{Ne}$  levels are present [1], is then very important in order to understand whether this escape from CNO cycles is possible or not.

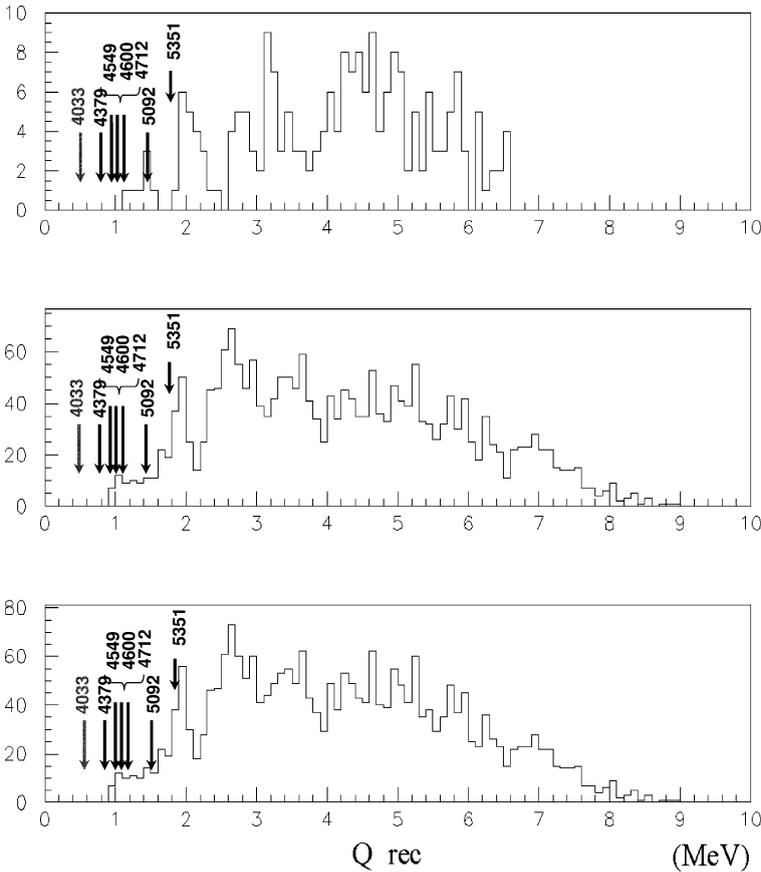


Fig. 1. Reconstructed  $^{19}\text{Ne} \rightarrow ^{15}\text{O} + \alpha$  decay  $Q$  value. The three pictures refer to three different runs performed during the experiment.

Unfortunately, in spite of a  $^{15}\text{O}$  beam being available at Louvain-la-Neuve, a direct measurement of the cross section of interest—of the order of 100 pb—presents many problems. In order to overcome some of them, it was proposed to use an indirect method: the  $^{19}\text{Ne}$  states which lie inside the Gamow window (4.033 MeV and above) can be populated via the  $^{18}\text{Ne}(d,p)^{19}\text{Ne}^*$  process and from their decay into  $^{15}\text{O} + \alpha$  one can infer information on the inverse process, namely the direct capture of  $^{15}\text{O}$  on  $\alpha$  [2,3].

The experiment was performed in three runs and different  $^{18}\text{Ne}$  beam energies (from 45 to 54 MeV) were used to bombard  $\text{CD}_2$  targets. The experimental setup was based on three Louvain–Edinburgh Detectors Arrays (LEDA). Each LEDA (fully described in [4]) is a disk shaped multistrip silicon detector with an outer radius of nearly 15 cm and a central hole with of 4 cm, divided into 8 sectors with 16 strips each, for a total of 128 strips. These detector arrays allow for an almost complete covering of the  $\phi$  azimuth angle while the distances between the three LEDAs (mounted in a coaxial geometry) to the target were such that the  $\theta$  angular regions roughly from 4 to 27 and from 125 to 155 degrees were covered.

Two different data analysis were performed. One of them is presented in another contribution to this conference [5], while the other is still in progress and very preliminary results are reported here.

In both of the two analysis, events coming from the  $^{18}\text{Ne}(d,p)^{19}\text{Ne}^* (\rightarrow ^{15}\text{O} + \alpha)$  process were selected applying proper cuts in phase space. In particular a proton tagging was applied. While events with a backward-going proton are particularly clean, theoretical calculations showed that an advantage in statistics could come from the tagging of forward going proton.

Owing to the characteristics of the available detectors, the setup was not fully optimized for this particular channel. Nonetheless, we performed an analysis of part of the data taken in the 54 MeV run using this event selection and it was possible to reconstruct spectra showing peaks due to the presence of the  $^{19}\text{Ne}$  states, as shown in Fig. 1. These preliminary results, though partial, showed that this type of analysis can give interesting information and it is presently being extended to the full data set.

## 2. Astrophysics recoil separator

Coupled to the new cyclotron CYCLONE44 [6] the Astrophysics REcoils Separator (ARES) has recently become operational at Louvain-la-Neuve. A schematic view of the apparatus is shown in Fig. 2.

ARES is conceived for studying in first instance  $(p, \gamma)$  reactions of astrophysical interest involving radioactive nuclei in inverse kinematics. These reactions lead typically to product nuclei contained in a narrow forward cone (opening  $\sim \pm 1^\circ$ ) around the beam direction. The spectrometer has to separate the beam from the reaction products within this cone [7].

In the past few month, new equipment for experimental work has been installed and performance tests have been performed. In particular, the new integrated target-scattering chamber and the ion chamber were mounted.

The target-scattering chamber comprises a target box, a detector box for monitor counters and/or a LEDA, two collimators at the entrance and at the exit of the target box and two target ladders with integrated Faraday cup. The ion chamber uses an anode–

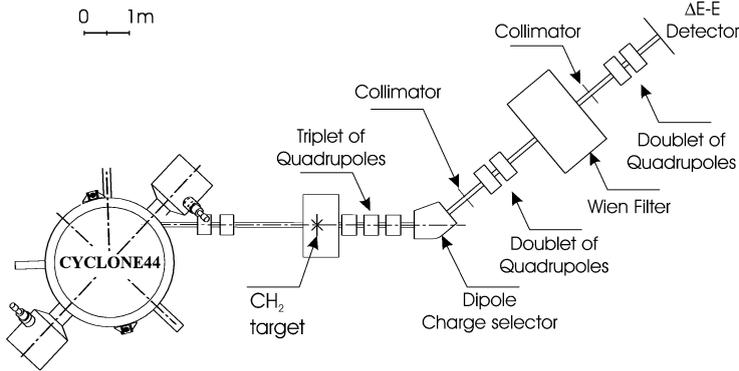


Fig. 2. CYCLONE44—ARES setup.

grid–cathode assembly for  $dE/dx$  energy loss and a  $100 \text{ mm}^2$  Si detector for  $E$  energy measurement. Tests using a three line  $\alpha$  source ( $^{239}\text{Pu}$ ,  $^{241}\text{Am}$ ,  $^{244}\text{Cm}$ ) gave an overall resolution  $\delta E < 14 \text{ keV}$  at FWHM and  $\delta E/E \sim 0.25\%$ .

The new beam line for astrophysical studies at CYCLONE44 has been completed and beams of  $^{14}\text{N}$ ,  $^{15}\text{N}$  and  $^{19}\text{F}$  were successfully transported through the optical elements of the separator with 90–100% transmission efficiency. The performances of the beam optics were as expected from beam transport calculations and Monte Carlo simulations.

A rejection factor for a 9.1 MeV  $^{14}\text{N}$  beams of  $> 10^{10}$  was obtained. The results for suppression with the  $^{19}\text{F}$  beams were worse owing to some beam instabilities that have been understood and are presently solved. We could, however, remeasure the resonant scattering to the  $J^\pi = 1^+$  resonance in  $^{20}\text{Ne}$  at  $E_{\text{cm}} = 635 \text{ keV}$ , reproducing the well-known interference between resonant and Coulomb amplitudes.

The ion chamber was tested with  $^{19}\text{F}$  beams giving an excellent  $dE/dx$  resolution. At  $\Delta E/E$  of  $\sim 20\%$ , the energy loss resolution  $\delta(\Delta E)/\Delta E = 5.1\%$  was achieved.

In order to suppress the direct beam component—including degraded energy tails—beyond the  $10^{-12}$  level, as required for nuclear astrophysics measurements, a contribution of three orders of magnitude in the suppression factor has to be obtained from the energy  $E$ , energy loss  $dE/dx$  and the time-of-flight TOF information. Tests done using a simple TOF information coming from the radio frequency of the cyclotron confirmed that at least one order of magnitude in the suppression factor is achievable from a TOF measurements. A TOF setup based on a microchannel plate and fast electronics will be installed on the ARES setup in the near future.

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