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Low-energy radioactive ion beam induced nuclear reactions

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Abstract. Low-energy post-accelerated radioactive ion beams have been used to study nuclear reactions addressing important nuclear structure and nuclear astrophysics questions. A high-granularity, large-solid-angle silicon strip detector array has been used to account for the low reaction products' yields. First experiments using a ^{6}He beam on thin ^{12}C targets show the feasibility of direct reaction studies with good angular resolution and a detection limit in access of 0.1 mb sr^{-1} cross sections. The measurement of the six α-decay channel in a ^{13}N-induced reaction on a ^{11}B target shows the capabilities of this experimental technique even for sophisticated reaction studies. The study of stellar properties in ground-based experiments, in particular break-out reactions from the hot-CNO, i.e. ^{15}O$(\alpha,\gamma)^{19}$Ne, can be pursued using these beams. Experiments are being performed to study these reactions by measurement of d(^{18}Ne, p)^{19}Ne$^*(\alpha)^{15}$O and $\alpha(^{18}$Ne, p), which might provide an alternative breakout route.

1. Motivation

The advent of post-accelerated radioactive ion beams (RIBs) having intensities in access of 10^6 ions s^{-1} at the cyclotron laboratory at Louvain-la-Neuve has enabled the study of nuclear reactions induced by these projectiles. Both important nuclear structure and nuclear astrophysics questions can be addressed in this way due to a high-granularity, large-solid-angle silicon strip detector array, i.e. the Louvain Edinburgh Detector Array (LEDA) [1], which is especially suited for the limited reaction products' yields encountered with these beams.

The measurement of ^{6}He-induced direct reactions on ^{12}C targets at $E_{\mathrm{lab}} = 5.9$ MeV may serve as an example for the possibilities of the LEDA set-up and the experimental conditions encountered. The interest in studying the ^{6}He nucleus is connected to the low binding energy of its p-shell neutrons, which leads to peculiarities in their density distribution known as the 'neutron-halo' feature. ^{6}He is regarded as the benchmark nucleus for the theoretical understanding of these peculiarities [2]. Most important is the weak binding of the valence orbitals in this drip line nucleus. The large radial extension of the wavefunctions implies an extremely narrow structure in momentum space. Thus, reactions with small momentum transfer and vanishing Q-value are favoured, which on stable targets can be realized via the transfer into excited states. As a consequence, transfer cross sections obtain their maximum at low incident energies for which the momentum transfer is small. This experiment will be discussed in section 3. The high-multiplicity capabilities of this experimental set-up will be demonstrated in a brief account on a ^{13}N-induced reaction on a ^{11}B target at $E_{\mathrm{lab}} = 45$ MeV. Originally, the experiment aimed at the study of the proton transfer reaction. Surprisingly, it also yielded information on the six α compound nucleus decay channel (see section 4).

In recent years, the direct study of stellar properties in ground-based laboratories has become more and more attractive, due to the availability of RIBs, for example ^{18}Ne. During explosive hydrogen burning in stars the seed nuclei C, N and O may leak out of the energy generating CNO cycle to produce the heavier elements and isotopes. The main inhibition to such heavy-element production is the long mean lifetime of the ^{15}O(α, γ)^{19}Ne reaction. A direct measurement of the ^{15}O(α, γ) reaction is extremely difficult, so indirect methods could yield some information. Such a method is provided by the ^{18}Ne-induced neutron pick-up reaction on a deuterium target. The population of a level of interest in ^{19}Ne can be tagged by the recoiling proton. For this measurement it is necessary that the three-particle channel be measured with a high-granularity, large-solid-angle set-up. A first test experiment will be discussed in section 5.

In high temperature and density environments it is possible that other reactions could pave the way for a significant leakout from the hot-CNO cycle. In particular, reactions with ^{18}Ne could provide such leakage through the ^{18}Ne(α, p) and ^{18}Ne(2p, γ) channels, although for the 2p reaction abnormally high densities would be required. At present there is little definitive information concerning these key reactions. The ^{18}Ne(α, p) reaction has been studied recently using a gaseous helium target. The reaction has been scanned for centre-of-mass energies from 1.8 to 3.0 MeV. Several proton energy groups have been observed and this will be discussed in section 6.

2. Production of post-accelerated radioactive ion beams

The subsequently discussed experiments have been performed at the RIB facility at Louvain-la-Neuve, Belgium. The short-lived projectiles have been created via proton-induced reactions on a composite target consisting of carbon and lithium fluoride. The protons, accelerated by a first cyclotron up to 30 MeV energy and currents of around 0.2 mA, produce, for example, ^{18}Ne via the (p, 2n) reaction. The gaseous activity is transferred into an electron cyclotron resonance (ECR) source. The extracted ions, for example, in the 3^+ charge state, is then mass separated in a 90° analysing magnet before being injected into a second cyclotron. The post-accelerated beam is subsequently delivered to the target position of the experimental set-up.

3. Typical experimental conditions: ^{6}He + ^{12}C scattering

A typical set-up is shown in figure 1. The energy and timing resolutions were determined using a post-accelerated secondary ^{6}He beam of 5.9 MeV and 2×10^{6} ions s^{-1} that has been scattered on gold and carbon targets of 180 μg cm^{-2} and 50 μg cm^{-2}, respectively. The energy resolution in the beam has been 0.8% full width half maximum. The beam showed less than 20 ppm contamination of ^{12}C ions which had the same rigidity as the ^{6}He beam. The reaction products were measured in two LEDA-type [1] silicon strip detector arrays (see figure 1) covering two different angular ranges from 7 to 14° and from 20 to 70° in the

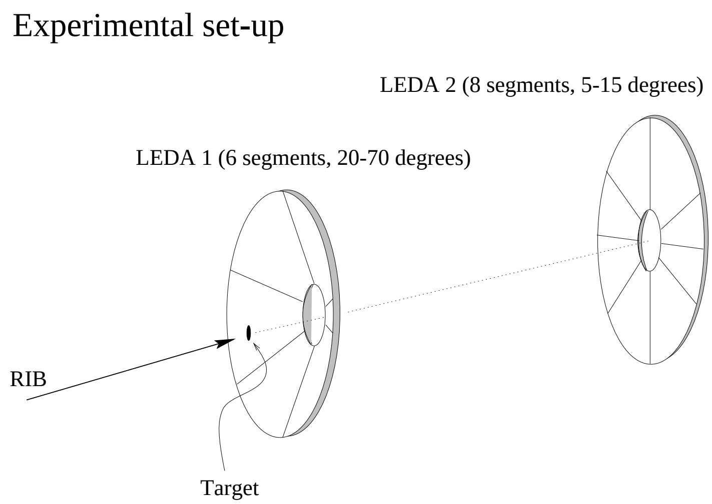

Figure 1. Schematic drawing of the Louvain Edinburgh Detector Array.

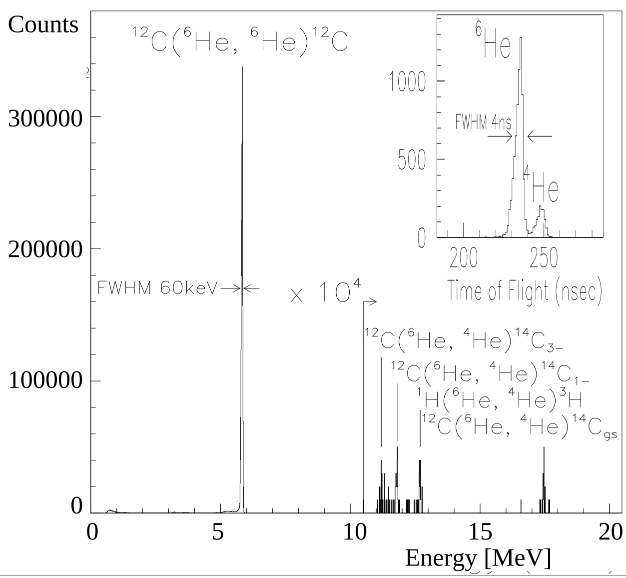

Figure 2. ^{6}He + ^{12}C spectrum at $E_{\text{lab}} = 5.9$ MeV and $\Theta_{\text{lab}} = 7$ degrees. The timing spectrum is given in the inset.

laboratory, respectively. Both the energy and the time of flight with respect to the cyclotron frequency were measured for each reaction product. Figure 2 shows the prominent elastic scattering peak measured at 7°. The energy resolution is 60 keV and is mainly due to the longitudinal emittance of the beam. In the inset the timing spectrum acquired from all angles is shown. The timing resolution of 4 ns is sufficient to discriminate ^{6}He from ^{4}He reaction products.

The energy spectrum given in figure 2 has been magnified for energies higher than 10 MeV. The two neutron transfer reaction products originating from the carbon and a

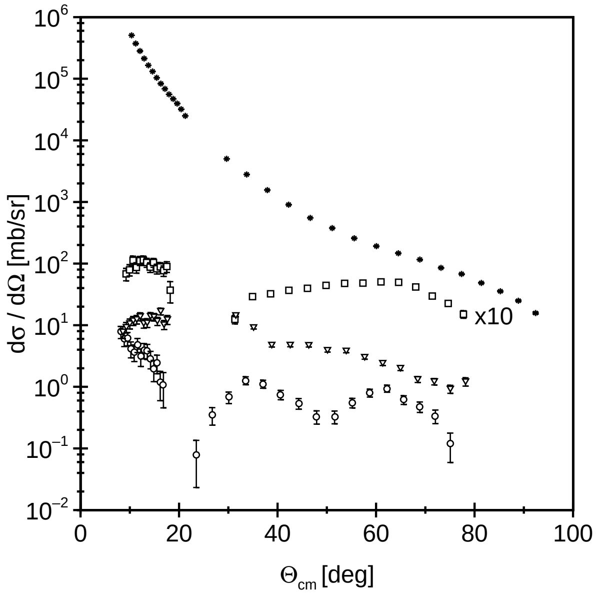

Figure 3. Angular distributions for the ^{6}He + ^{12}C reaction. Given are the elastic cross sections (stars), as well as the ^{12}C(^{6}He, ^{4}He)^{14}C$_{gs}$ (circles), ^{12}C(^{6}He, ^{4}He)^{14}C$_{1-,6.098\ \mathrm{MeV}}$ (squares, $10 \times d\sigma/d\Omega$), ^{12}C(^{6}He, ^{4}He)^{14}C$_{3-,6.728\ \mathrm{MeV}}$ (triangles) two-neutron transfer cross sections.

hydrogen contamination are clearly visible. In figure 3 the angular distributions obtained in this measurement are shown. Clearly, cross sections down to 0.1 mb sr^{-1} can be measured in such an experiment. The angular resolution is about 1° in the forward hemisphere and is limited by the transversal beam emittance. The solid angles have been calibrated using the scattering on the gold target, assuming pure Rutherford scattering.

4. Multiplicity capabilities: ^{13}N + ^{11}B fusion reaction

During the last decade considerable effort has been put into the study of peculiar excited states in ^{24}Mg [3]. The population of this compound nucleus via RIB induced reactions opens a new line of approach. The high granularity of the LEDA set-up means that high-multiplicity events have become accessible in such experiments, for example ^{11}B(^{13}N, 6α), and that sophisticated correlations can be studied. This is demonstrated by figure 4, which shows a total energy spectrum of the 6α-channel on a Q-value scale. The beam intensity applied was 10^{8} ions s^{-1} and the target had a thickness of 0.8 mg cm^{-2}. The peak position is in agreement with the calculated total energy taking the different energy losses that are encountered in this reaction into account.

5. Hot-CNO break-out reactions

5.1. The $^{19}Ne^{*} \rightarrow {}^{15}O + \alpha$ reaction

For states which have a very small α-branching ratio, for example $\approx 10^{-4}$, for the first scattering resonance in the ^{15}O + α reaction at 504 keV corresponding to a compound state in ^{19}Ne at 4.033 MeV, $\omega\gamma \approx \omega\Gamma_{\alpha}$. The study of α-decays of excited states in ^{19}Ne above

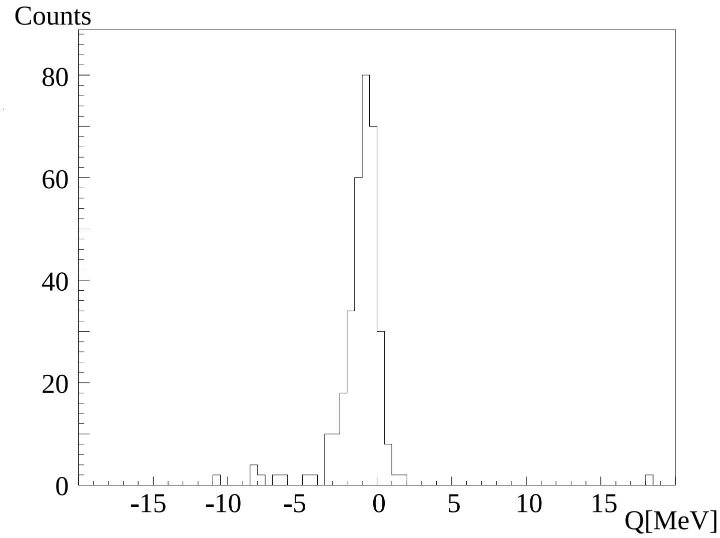

Figure 4. $Q_{\rm val}$ spectrum for the ^{11}B(^{13}N, 6α) reaction at $E_{\rm inc} = 45$ MeV.

the ^{15}O $+ \alpha$ threshold at 3.529 MeV can give information concerning $\omega\gamma$ and, therefore, details of the reaction rate for the helium burning of ^{15}O.

A test experiment using the d(^{18}Ne, ^{19}Ne*)p reaction has been performed at 45 MeV incident energy and a beam intensity of 10^5 ions s^{-1}. The CD$_2$ target used was 0.7 mg cm^{-2} thick. Three LEDA-type silicon strip detector arrays have been carefully positioned around the target to measure the particles that are produced in this reaction and subsequent particle decays of the excited states in ^{19}Ne. A total of 276 strips have been used and both energy and time of flight with respect to the cyclotron frequency have been recorded for each strip. The maximum yield of the reaction protons will be in the backward hemisphere.

The left-hand side of figure 5 shows a preliminary proton spectrum obtained between 160° and 170°, filtered by the condition that the event multiplicity is three, which is consistent with the d(^{18}Ne, p)^{19}Ne$^*(\alpha)^{15}$O reaction path. However, due to the intense β^+ background, events of the type d(^{18}Ne, p)^{19}Ne$^*(\gamma)^{19}$Ne are also present in the spectrum. A total energy filter using a cut-off below 35 MeV removes most of the events above 2.5 MeV as expected, since events of the (p, ^{19}Ne, β^+) reaction are removed and the α-branching ratio becomes very small for $E_x(^{19}\mathrm{Ne}) < 4.5$ MeV.

This preliminary experiment shows the yield that can be obtained in such an approach. Feasible improvements including target thickness, solid angle and beam intensity will lead to an experimental situation in excess of the quality of information obtained in an earlier experiment using the ^{19}F(^{3}He, t)^{19}Ne* reaction [4]. However, a beam intensity of 10^7 ions s^{-1} would be required to obtain new information on the α-branching ratio of the 4.033 MeV state.

5.2. The ^{18}Ne(α, p) reaction

This reaction offers an alternative breakout route from the hot-CNO cycle at higher temperatures and densities than the previous reaction. In this experiment a helium gas target at a pressure of 0.5 bar was separated from the beam line vacuum by a nickel window of 2 mg cm^{-2} thickness. A three-silicon-detector telescope—each detector a double-sided

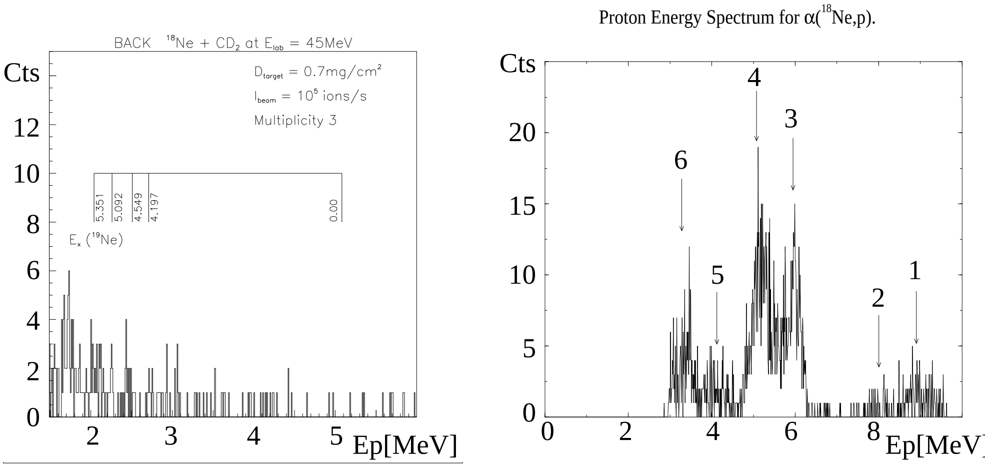

Figure 5. Proton energy spectra from the d(^{18}Ne, p)^{19}Ne* reaction (left) and the ^{18}Ne(α, p) reaction (right).

silicon strip array having thicknesses 0.06 mm, 0.3 mm and 0.5 mm, respectively—housed at 0° inside the gas was used to discriminate elastically scattered protons or helium nuclei as well as β-particles from the interesting reaction protons. The trajectory of each proton can be reconstructed in the off-line analysis thanks to the 'quasi-pixellization' warranted by the double-sided silicon strip detectors.

A nickel foil selected to stop the beam particles was mounted in front of the telescope. The distance between the window and the telescope was adjustable to allow for the scanning of different energy ranges in the compound nucleus. The distance was selected so that resonant reactions between the helium and the ^{18}Ne beam of $E_{\rm lab} = 30$ MeV could be detected at $E_{\rm cm} = 1.8$–3 MeV. The data were normalized by using Rutherford scattering measured by monitor detectors mounted upstream from the entrance window.

The right-hand side of figure 5 shows the proton energy spectra obtained with the helium gas. Peaks 4 and 6 are also present in the spectrum measured without gas. Hence, these two peaks are due to proton contaminations most likely in the nickel foils. The other four peaks, which correspond to levels being excited in the compound state, indicate that at least two resonance states are present in the energy range 2.5–3 MeV. The upper level decays to the 3.455 MeV and 0.331 MeV level in ^{21}Na, while the lower level decays to the 1.716 MeV and ground state of ^{21}Na, respectively.

6. Conclusions

The available post-accelerated, low-energy RIB at Louvain-la-Neuve have enabled us to study nuclear reactions for nuclear physics and nuclear astrophysics investigations. High-granularity, large-solid-angle silicon strip detector arrays, for example LEDA, are essential, due to low yields and the necessity to suppress large backgrounds. For such large arrays it has proved essential to have good energy and particle identification. The ^{12}C(^{6}He, ^{4}He)^{14}C* reaction has been measured for the first time. High granularity means that high-multiplicity events have become accessible in such experiments, for example ^{11}B(^{13}N, 6α). For the first time complex compound nucleus decay modes have been observed in a RIB experiment. The investigation of key reactions of the hot-CNO break-out via RIB induced reactions using *direct*, for example ^{18}Ne(α, p), methods has yielded completely new information on the reaction pathway. By exploiting an *indirect* approach, i.e. ^{18}Ne(d, p)^{19}Ne*, first results demonstrate the feasibility of a new way to obtain information concerning the ^{15}O(α, γ) reaction.

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