Light ion induced nuclear reactions close to the Coulomb barrier

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Abstract. The aim of our study is to determine excitation functions for the formation of different reaction products with light ions near the Coulomb barrier and to compare the results with computations according to different reaction mechanisms (compound reactions, direct reactions). In the present study results from experiments with a beam of $^9$Be on a thin Aluminum target below and around the Coulomb barrier are presented. The formation of several reaction products was determined by the characteristic gamma emissions from these nuclei. Excitation functions of the reactions $^{27}$Al($^9$Be,$^8$Be→2α)$^{28}$Al, $^{27}$Al($^9$Be,2n)$^{34}$Cl, $^{27}$Al($^9$Be,pn)$^{34}$S and $^{27}$Al($^9$Be,α2n)$^{30}$P with lab energies between 5 and 14 MeV have been determined.

1. Introduction
Many important astrophysical cross-sections cannot be measured directly. Thus, it is necessary to understand the mechanism of these nuclear reactions to estimate the excitation functions by model calculations. The aim of our study is to determine excitation functions for the formation of different reaction products with light ions near the Coulomb barrier and to compare the results with computations according to different reaction mechanisms (compound reactions, direct reactions). In the present study results from experiments with a Beryllium beam on a thin Aluminum target below and around the Coulomb barrier are presented. Although this reaction has no direct astrophysical relevance it was investigated because it is representative for other weakly bound light ion induced reactions. The target material was chosen because it has only one stable isotope and can easily be produced in thin foils. The projectile is the first in a series of light ions. In a next step reactions with $^6$Li and $^7$Li are studied. A beam of $^9$Be ions with energies between 5 and 14 MeV was produced at the VERA tandem accelerator. The formation of several reaction products was determined by the characteristic gamma emissions from these nuclei. For this purpose an HPGe-detector was installed close to the target. A new scheme to calibrate the particle energy coming from the tandem accelerator has been established to minimize the contribution of the beam energy to the final uncertainty of the excitation function. In the following sections first the experimental setup will be described in detail. Afterwards results from the most important reaction channels will be presented.

2. Experimental Setup
Aluminum foils (0.542±0.006 mg/cm²) were irradiated by $^9$Be ions with energies between 5 and 14 MeV [1] at the VERA tandem accelerator AMS (accelerator mass spectrometry) facility [2].
Negatively charged BeO⁻ ions were extracted from a cesium sputter ion source using beryllium oxide as target material. The mass separated beam was injected into the tandem accelerator where the negatively charged molecules break up and the resulting beryllium atoms were stripped in the terminal of the tandem to positive ions. With an analyzing magnet after the tandem \(^{9}\text{Be}^{2+}\) or \(^{9}\text{Be}^{3+}\) was selected, depending on the desired particle energy. The desired ion beam was subsequently directed onto the target. The number of particles impinging on the target was measured by using the target itself as a Faraday cup. In front of the target an additional Faraday cup with a central hole as an aperture was mounted. The diameter of the aperture was slightly smaller than the target to ensure that the whole cross section of the beam hits the target. During the experiment the beam never hits the aperture cup which demonstrated the stability of the accelerator. Both Faraday cups were equipped with a suppressor electrode biased at -100 V to prevent the loss of secondary electrons produced by the bombardment of \(^{9}\text{Be}\) ions. The target Faraday cup was calibrated against a calibrated cup of the VERA facility. The particles were stopped immediately behind the aluminum foil by a tantalum plate. Foil and tantalum plate were electrically connected and formed the central part of the Faraday cup. The \(^{9}\text{Be}\) currents on target were 0.5 to 100 nA depending on particle energy and charge state.

The formation of several reaction products was determined by characteristic gamma emissions using a HPGe-detector (ORTEC® GAMMA-X, 25% rel. efficiency) perpendicular to the beam line — about 5 cm away from the target. The pre-amplifier output was processed with an ORTEC® 571 analogue amplifier and digitized by a 16k Canberra 8713 analogue-to-digital converter. The stability of the electronics was checked by a precision pulse generator (ORTEC® model 419) fed into the preamplifier. The events were collected with a FAST ComTec MPA-3 multiparameter multichannel analyzer equipped with a real-time-clock option. The detector efficiency was determined by several calibration sources at the target position. Background spectra were taken with the beam off and with beam on but without the target mounted.

The \(^{9}\text{Be}\) current impinging on the target was measured in intervals of 15 s. The gamma ray pulse height information was stored together with a time stamp supplied by the real-time-clock in list mode. Data acquisition was started with the start of the beam hitting a new target and was stopped 30 minutes after the beam shut-down. This allows detecting and distinguishing prompt gamma ray emission and gamma rays from the decay of radioactive reaction products.

![Figure 1](image.png)

**Figure 1.** Typical count rate of gamma-ray emission from a radioactive reaction product (1779 keV from \(^{28}\text{Al}\)) with a constant ion current. The ion beam was shut-down after 1200 s.
Obviously, the $^9\text{Be}$ ions are slowed down when penetrating the Al target. To account for this the Monte Carlo code SRIM [4] was used to calculate the mean energy for the nuclear reaction for a given ion energy at the target surface.

2.1. Beam Energy Calibration

At VERA the terminal voltage of the tandem is stabilized by corona discharge controlled by a generating voltmeter. The stability is below 300 V\text{rms}. In most AMS applications the absolute value of the particle energy is of minor importance. However, for the determination of the cross section of nuclear reactions a precise knowledge of the projectile energy is essential. Therefore a procedure for calibrating the terminal voltage measured by the generating voltmeter had to be established to minimize the energy uncertainty contribution to the overall uncertainty of the measured excitation functions. Previous attempts to calibrate the particle energy by using the sharp resonance energy of the reaction $^3\text{F}(\alpha, \gamma)^{16}\text{O}$ at ~16.5 MeV rendered ineffective because of the uncertainty of the known resonance energy (~2.5%) and the difficulty to scan the particle energy continuously over the resonance.

In a different approach an ion-implanted-silicon charged-particle detector (ORTEC® BU-016-150-100) was used. To calibrate this detector $^{216}\text{Po}$ from the decay of $^{228}\text{Th}$ was electrostatically collected on the surface of a sample holder. This was subsequently used as an alpha source with sharp alpha energies between 6 and 8 MeV. The sample holder was brought into the vacuum system and positioned in front of the charged particle detector. In a second step helium gas was introduced into the sputter ion source to produce a beam of He$^+$ [3]. The helium ions were subsequently stripped to positive ions in the terminal of the tandem accelerator. He$^{2+}$ beams of up to 8 MeV were selected and were further impinging on the calibrated charged particle detector. The pulse height deficit can be neglected as we used the same particle species for calibration of the detector and for measuring the beam energy. The energy loss of the helium particles in the stripper (O$_2$, 80 cm long, 9.7 mTorr pressure) was calculated using the computer code SRIM [4]. This leads to an energy correction in the order of 1.5 keV.

![Figure 2. Decay scheme of $^{28}\text{Al}$ [5].](image)

![Figure 3. $^{27}\text{Al}(^9\text{Be},^8\text{Be}\rightarrow 2\alpha)^{28}\text{Al}$ excitation function as a function of lab energy. The solid line denotes the result of the theoretical calculations mentioned in the conclusions.](image)

3. Results

The binding energy of the $1p_{3/2}$ neutron in $^9\text{Be}$ is the lowest binding energy of a neutron in a stable nuclide. Therefore, the reaction $^{27}\text{Al}(^9\text{Be},^8\text{Be}\rightarrow 2\alpha)^{28}\text{Al}$ can be expected to occur with a high probability since a neutron transfer mechanism can be expected. Figure 2 shows the decay scheme of
The measurement of the 1779 keV line in $^{28}$Si allows the determination of the $^{27}$Al($^9$Be,2$\alpha$)$^{28}$Al excitation function. A much more complicated decay scheme shows $^{34}$Cl, the end product of the reaction $^{27}$Al($^9$Be,2n)$^{34}$Cl. The ground state of $^{34}$Cl has a half-life of $\sim$1.5 s and decays directly to the ground state of $^{34}$S. The cross section for the formation of the ground state is determined by the measurement of the prompt $\gamma$-transitions from the three lowest levels. Transitions from higher levels to the ground state could not be observed. The isomeric state of $^{34}$Cl, with the much longer half-life of 32 min compared to the ground state, decays by electron capture and positron emission to excited states of $^{34}$S (figure 4). The cross section for the formation of the isomeric state was determined by the measurement of $\gamma$-transitions in $^{34}$S following the $\beta^+$/EC decay of $^{34m}$Cl. The same $\gamma$-transitions in $^{34}$S occur promptly after the emission of a neutron and a proton from the compound nucleus $^{36}$Cl and are used to determine the cross section for $^{27}$Al($^9$Be,pn)$^{34}$S. The excitation functions for the reactions leading to $^{34}$Cl and $^{34}$S are shown in figure 5.

![Figure 4](image_url)

**Figure 4.** Decay scheme of $^{34m}$Cl [5].

![Figure 5](image_url)

**Figure 5.** $^{27}$Al($^9$Be,2n)$^{34}$Cl and $^{27}$Al($^9$Be,pn)$^{34}$S excitation functions as a function of lab energy. The solid and the dashed line denotes the result of the theoretical calculations mentioned in the conclusions.
Further problems concern reaction products like $^{30}\text{P}$ with 99.94% positron emission to the ground state of $^{30}\text{Si}$. The reaction leading to $^{30}\text{P}$ is $^{27}\text{Al}(^{9}\text{Be},\alpha 2n)^{30}\text{P}$. Here, only the 511 keV annihilation line of the emitted positrons can be used for the cross section determination. The annihilation does not occur inside the target volume but in the material surrounding the target. Therefore, the detector efficiency was corrected for the distributed emission points of the two simultaneously emitted 511 keV photons within the masses surrounding the target. The excitation function for the production of $^{30}\text{P}$ is shown in figure 6. The uncertainties in the cross sections of $^{30}\text{P}$ production are larger than for the other reactions due to the efficiency correction of the 511 keV annihilation line.

![Figure 6](image.png)

**Figure 6.** Excitation function of the production of $^{30}\text{P}$ as a function of lab energy. The solid line denotes the result of the theoretical calculations mentioned in the conclusions.

4. Conclusions

Preliminary calculations were based on a statistical model (nuclear reaction model code EMPIRE, version 2.19 Lodi [6]). The total fusion cross sections were derived from the Nuclear Reactions Video knowledge base [7] and used as input for the EMPIRE calculations. These result in a production cross section for $^{28}\text{Al}$ significantly lower than observed. G.V. Marti et al. [8] suggested that the observed difference in the reaction cross section and the total fusion cross section near and above the Coulomb barrier is dominated by noncapture breakup reactions (elastic breakup, EBU). Our results near and below the Coulomb barrier however indicate that transfer reactions with capture of the fragments are important. This is seen in the high production cross section for $^{28}\text{Al}$ (around 100 mb at 12 MeV $E_{\text{lab}}$) and the cross section for $^{30}\text{P}$ production, which is significantly larger than predicted by statistical models. A possible mechanism for the latter reaction could be capture of an alpha fragment followed by emission of a neutron. It is well known, that the reaction $^{27}\text{Al}(\alpha,\text{n})^{30}\text{P}$, induced by natural $\alpha$ particles was used in the historic Nobel-prize winning work of F. Joliot and I. Joliot-Curie for the first production of new radioactive elements.

The sum of all observed reaction cross sections is below the total fusion cross sections (compound nucleus) for the relevant energies determined by G.V. Marti et al. [8]. This is not surprising, because a number of reaction products formed via a compound nucleus reaction could not be observed in our experiments because of a lack of characteristic gamma-ray emissions of the reaction products. Examples of possible, but not observed reactions are: $^{27}\text{Al}(^{9}\text{Be},p)^{32}\text{S}$, $^{27}\text{Al}(^{9}\text{Be},\alpha)^{32}\text{P}$, $^{27}\text{Al}(^{9}\text{Be},2\text{pn})^{33}\text{P}$, $^{27}\text{Al}(^{9}\text{Be},\alpha p)^{31}\text{Si}$. The discrepancy between the statistical model and the observed cross section for the production of $^{34}\text{Cl}$ and $^{34}\text{S}$, which are expected to proceed via complete fusion, may be explained by missed gamma-rays leading directly to the ground states. While the cross sections for production of
$^{28}$Al and $^{30}$P are much larger than calculated the production cross section for $^{34}$S and $^{34}$Cl are even somewhat smaller than the statistical model predictions.

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