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The ^{20}Ne(d,p)^{21}Ne transfer reaction in relation to the s-process abundances

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Abstract.
A study of the ^{20}Ne(d,p)^{21}Ne transfer reaction was performed using the Quadrupole Dipole Dipole Dipole (Q3D) magnetic spectrograph in Garching, Germany. The experiment probed excitation energies in ^{21}Ne ranging from 6.9 MeV to 8.5 MeV. The aim was to investigate the spectroscopic information of ^{21}Ne within the Gamow window of core helium burning in massive stars. Further information in this region will help reduce the uncertainties on the extrapolation down to Gamow window cross sections of the ^{17}O(α,γ)^{21}Ne reaction. In low metallicity stars, this reaction has a direct impact on s-process abundances by determining the fate of ^{16}O as either a neutron poison or a neutron absorber.

The experiment used a 22-MeV deuteron beam, with intensities varying from 0.5-1 μA, and an implanted target of ^{20}Ne of 7 μg/cm^2 in 40 μg/cm^2 carbon foils. Sixteen ^{21}Ne peaks have been identified in the E_x = 6.9-8.5 MeV range, of which only thirteen peaks correspond to known states. Only the previously-known E_x = 7.960 MeV state was observed within the Gamow window.

1. Introduction

Most nuclei heavier than iron are thought to be formed by exposing iron-peak seed nuclei to a source of neutrons, such that neutron-capture reactions can be initiated [1]. Neutron capture occurs either at slow rates, through a process known as the slow or s-process, or at high rates via the rapid or r-process.

Neutron capture is said to be slow when the time between two successive neutron captures is longer than the average β-decay timescale. This leads the s-process path to be located along the line of β stability. The s-process proceeds from iron-seed nuclei through most stable nuclei up to ^{209}Bi where it terminates. The s-process abundances are highly dependent on the magnitude of neutron-capture cross sections and the total neutron availability. Therefore lighter nuclei may affect the s-process abundances by either adding (neutron source), permanently removing (neutron poison) or only temporarily removing (neutron absorber) the neutrons available for the s-process.

Massive stars are responsible for one component of the s-process, known as the weak s-process, which produces nuclei with mass number between A = 70 and A = 90. The weak s-process operates in the helium core or carbon burning shell where ^{22}Ne is the main source of neutrons. ^{16}O, ^{20}Ne, ^{24}Mg and ^{25}Mg are, however, known to act as neutron poisons [2].

In low-metallicity massive stars, due to the lower abundance of heavier elements, and depending on the neutron flux, the high neutron-to-seed ratio can allow the production of isotopes beyond the Sr-Zr peak and, possibly to ^{137}Ba [3]. In this case, ^{16}O is thought to be the most dominant neutron absorber through the ^{16}O(n,γ)^{17}O reaction. Neutrons can be made available again for the s-process through the ^{17}O(α,n)^{20}Ne reaction, depending on the strength of the competing reaction channel ^{17}O(α,γ)^{21}Ne. The neutron recycling process in this instance is therefore highly dependent on the ratio of the ^{17}O(α,γ)^{21}Ne to ^{17}O(α,n)^{20}Ne reaction rate. However, despite its importance, this ratio is highly uncertain and the fate of ^{16}O as either neutron poison or neutron absorber is yet to be established. Only two theoretical predictions exist, from Caughlan and Fowler [4] and from Descouvement [5], and differ by three orders of magnitude at relevant energies.

The ^{17}O(α,n)^{20}Ne reaction has already been measured at relatively low energies and extrapolations to lower energies are available through the NACRE compilation [6] and through recent measurements by Best *et al.* in [7], for example. However, there is a lack of experimental data for the ^{17}O(α,γ)^{21}Ne reaction, for which only two recent direct measurements exist. The two measurements by Taggart *et al.* [3] and Best *et al.* [8] do not, however, cover the Gamow window which in the core helium burning is in the region of 0.3 GK which corresponds in the centre of mass to an energy range of 0.3-0.7 MeV. The uncertainties on the extrapolation of the cross sections in the Gamow window were linked to the poor knowledge of the level scheme of ^{21}Ne within the region of interest, raising the need for further spectroscopic information.

2. Experimental Method

The ^{20}Ne(d,p)^{21}Ne reaction experiment aimed to investigate and extract the ^{21}Ne level information within Gamow window located between E_x = 7.65-8.05 MeV.
The experiment took place at the Q3D magnetic spectrograph at the Maier-Leibnitz Laboratorium (MLL) of the Technische Universität München and the Ludwig-Maximilians-Universität (LMU). A 22-MeV deuteron beam between 500-1000 nA impinged on a target of ^{20}Ne implanted in ^{12}C. The nominal target area density was 7 μg/cm^2 of ^{20}Ne in 40 μg/cm^2 of ^{12}C. The experiment populated excited states of ^{21}Ne ranging from 6.9 MeV to 8.5 MeV which enabled the states around the Gamow window to be investigated. This experiment was the first ^{20}Ne(d,p)^{21}Ne measurement to be performed beyond 6-MeV in excitation energy.

The magnetic field of the three dipole magnets of the Q3D spectrograph separated the trajectories of the particles according to their magnetic rigidity. The detector used has the same features as the one described by J. Ott *et al* in [9] with the only difference being an increased active length. It is composed of two proportional gas-filled detectors followed by a scintillator. The first proportional detector provides energy loss and the second the position information. Excellent particle identification is obtained by the combination of both energy loss signals with energy collected from the scintillator.

Measurements were taken at various angles ranging from 8° to 30°. For calibration purposes ^{28}Si(d,p)^{29}Si was also measured, and for background estimation, data from the ^{12}C(d,p)^{13}C reaction was used.

3. Results and Discussion

In total, sixteen ^{21}Ne peaks were identified of which only thirteen are at energies that correspond to states reported in the literature. Table 1 summarises these results.

Table 1: Summary of identified ^{21}Ne peak energies with existing values from literature [10]. Both measured energies and uncertainties are preliminary.

Meaured Energies (keV)	Literature Energies (keV)
6960(2)	-
6977(17)	-
7032(13)	7022.6(10)
7055(13)	7042.1(5)
7239(11)	7226(5)
7330(9)	7320(5)
7485(7)	7465(10)
7558(10)	7547(10)
7955(2)	7960.3(10)
8039(12)	8062(10)
8167(15)	8154.9(6)
8301(9)	8303(10)
8328(6)	-
8349(3)	8360(10)
8437(3)	8430(10)
8520(4)	8522(3)

The observed peaks at 8328(6) keV, 6977(17) keV and 6960(2) keV are not found in the literature. All peaks were observed at most angles. For the measured energies presented in this work, it is important to underline that uncertainties due to energy determinations at different angles have been considered, energy loss effects due to the different ^{20}Ne targets employed have not been carefully considered yet. In the literature, 32 different levels exist between the 7022.6 keV and 8522 keV states and 13 could be associated to the proton peaks observed in the data. Figure 1 shows the outgoing proton spectra at 8°, 11° and 25°. As can be seen, within the Gamow window itself, only the 7960.3(10) keV peak has been observed. For most levels around that region, very little spectroscopic information is known. During the course of the experiment, although the original target thickness was known, the implanted ^{20}Ne was gradually released from the carbon foil as was seen from the ratio of ^{13}C to ^{21}Ne peak intensities. The boiling-off rate of ^{20}Ne was not monitored precisely which therefore contributes an additional uncertainty to the target thickness. Due to this fact, only the relative differential cross section at different angles may be used to infer the angular momentum and therefore the spin-parity of different states.
The results presented in this work are preliminary and analysis is ongoing.

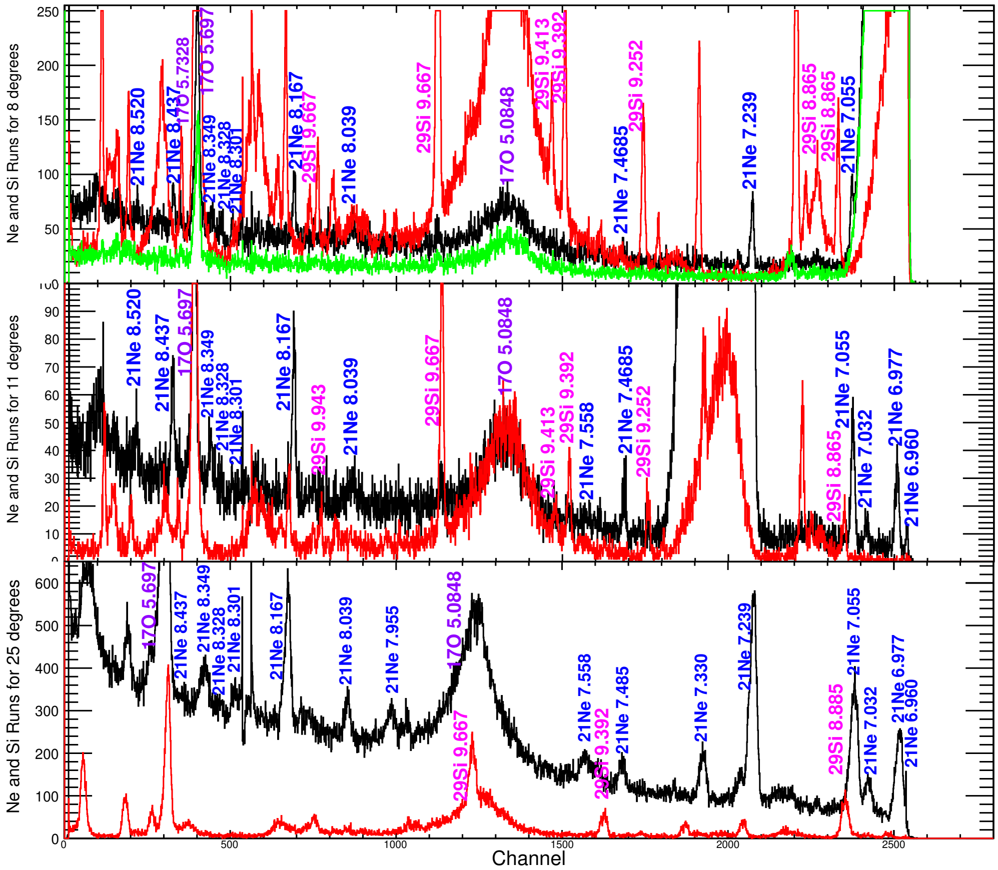

Figure 1: Excitation energy spectra at 8°, 11° and 25° respectively. This figure shows Ne runs (black), Si runs used during calibration (red) and C run at 8° only (green). Different states identified at those angles are shown. Principal contaminants, mainly ^{28}Si and ^{16}O (leading to states in ^{29}Si and ^{17}O), are also shown.

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