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$^{18}F(\alpha,p)^{21}Ne$ reaction as an alternative neutron source for r-process in Supernovae

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The reaction rate of ^{18}F(α,p)^{21}Ne has been studied in the inverse kinematics using a radioactive ^{18}F beam and in the time-reverse reaction ^{21}Ne(p,α)^{18}F using the off-line counting activation method. They have been measured in the energy range of the relevant Gamow window. Experimental results will be discussed and compared with the results of Hauser-Feshbach calculations and previous measurements.

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1. Introduction

Recent observations of the abundance distribution of heavy elements in metal poor old stars suggest an indication of the existence of more than one r-process site [1,2], suggesting a different site for the synthesis of light r-process nuclei. This led to a reexamination of previously proposed models for r-process sites which originally did not provide sufficient neutron flux for the production of the very heavy elements. One of these models is the r-process nucleosynthesis in the supernova shock traveling through the He-rich shell of the pre-supernova star [3]. In this scenario, the ^{14}N from preceding CNO burning is converted to ^{18}F, via the reaction $^{14}N(\alpha,\gamma)^{18}F$ [4] and subsequent β^+-decay forms ^{18}O, which produces neutrons by $^{18}O(\alpha,n)$ or $^{18}O(\alpha,\gamma)^{22}Ne(\alpha,n)$. The statistical model predicted that the reaction of $^{18}F(\alpha,p)^{21}Ne$ can compete with the β^+-decay at high helium density and temperatures in the shock front [see fig. 1]. Since $^{21}Ne(\alpha,n)$ has a positive Q-value, it has been identified as a stronger neutron source than $^{22}Ne(\alpha,n)$.

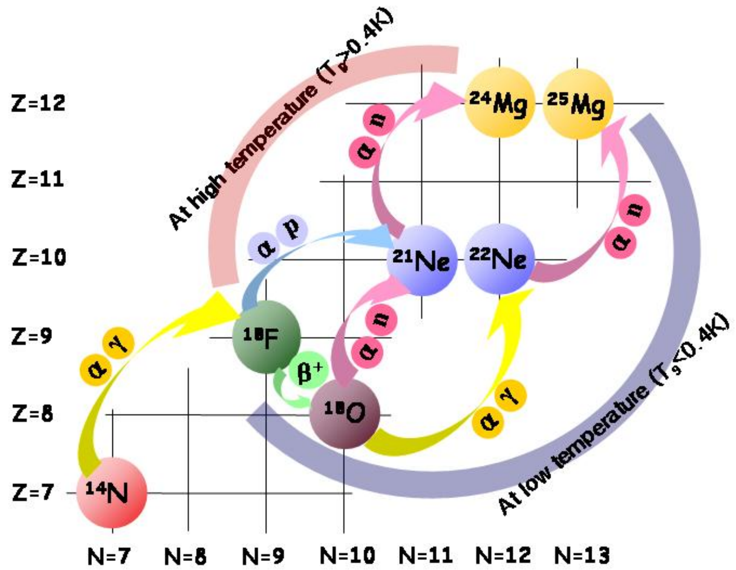

Figure 1. The nuclear network at the helium-rich region in pre-supernova.

Because no published data on the $^{18}F(\alpha,p)^{21}Ne$ reaction are available, we have measured the $^{18}F(\alpha,p)^{21}Ne$ reaction using a radioactive ^{18}F beam with a helium gas cell, and in addition the total cross section of the inverse reaction $^{21}Ne(p,\alpha)^{18}F$ using an activation method with an implanted ^{21}Ne target.

2. $^{18}F(\alpha,p)^{21}Ne$ study

The experiment was performed at the Radioactive Ion Beam (RIB) facility at Louvain-La-Neuve [5]. A ^{18}F beam of energy 23MeV in the 2+ charge state was used, with an average intensity of 5×10^6 pps. A gaseous helium target at a pressure of 250mbar and two SSD's (Silicon Strip Detectors) with thicknesses of 45μm and 300μm were used to measure ΔE and E of protons from (α,p) reactions[6], respectively. Due to the extended gas target and the strip detectors[see fig.2], the excitation function could be acquired at one beam energy from 1.4MeV to 2.3MeV in the c.m. system.

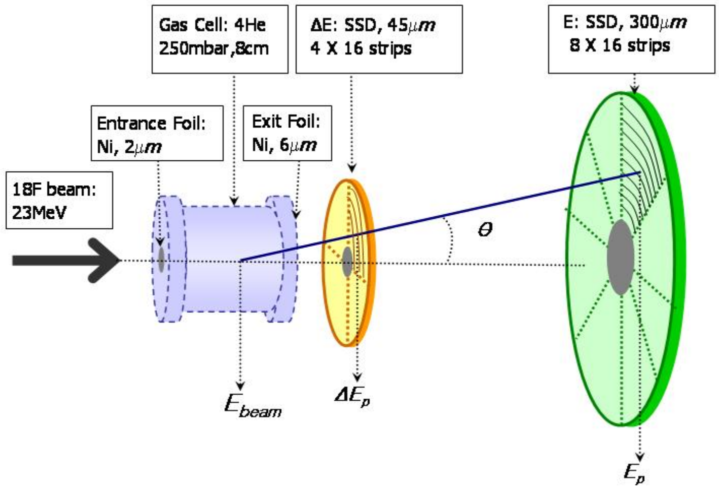

Figure 2. Schematic view of gas cell and detectors.

The use of the ΔE-E telescope technique allows the identification of protons and the strip number of each detector gives the angular information to calculate the Q-values of ^{21}Ne through the 2-body kinematics equation. From this information, we can obtain the ratio of the cross sections for the 1st excited state transition (p_1) relative to the ground state transition (p_0) in ^{21}Ne. This will provide a correction factor for $^{21}Ne(p,\alpha)^{18}F$ reaction for which the p_1–channel can not be measured directly. Final analysis of this correction factor is in progress along with Monte Carlo simulations.

3. ^{21}Ne(p,α)^{18}F study

The experiment was performed at the KN and FN accelerators at the Nuclear Structure Laboratory at the University of Notre Dame in an energy range of 2.5 MeV to 3.5 MeV with p-beam currents of 2-30 μA. The targets were made by implantation of ^{21}Ne (0.27% natural abundance). The backings were thick gold layers on copper disks to reduce background reactions and to have good thermal conductivity for efficient cooling. Implantation was done with 2 different energies, 150 keV and 400 keV, to achieve a homogenous ^{21}Ne distribution. This was monitored using the 768 keV resonance in the $^{21}Ne(p,\gamma)$ reaction [7]. During the activation experiment, the ^{18}F activity was measured by counting 511 keV annihilation γ rays in coincidence. The detection system consisted of two Ge clover detectors mounted face to face [8] with an absolute coincidence counting efficiency of 2.63%, which was measured with a weak ^{22}Na source.

The preliminary total cross section [see Fig.3] shows a good agreement with the current data (solid square) and the previous spectroscopy data (Bochum), corrected for the target thickness of ~23 keV. Contrary to the previous study the current data show no existence of a resonance in ^{21}Ne(p,α)^{18}F at an energy of 2.91 MeV in the lab system [9], which is equivalent as 2.78 MeV in the c.m. system in Fig.3. The upper limits reflect a resonance in ^{18}O(p,n)^{18}F [10], which can also contribute to the ^{18}F activity above the threshold of 2.57 MeV. Since the existence of a thin oxygen layer on the target surface is unavoidable, it is necessary to subtract the yield of ^{18}O(p,n)^{18}F from ^{21}Ne(p,α)^{18}F, especially below 3 MeV, when both yields are comparable.

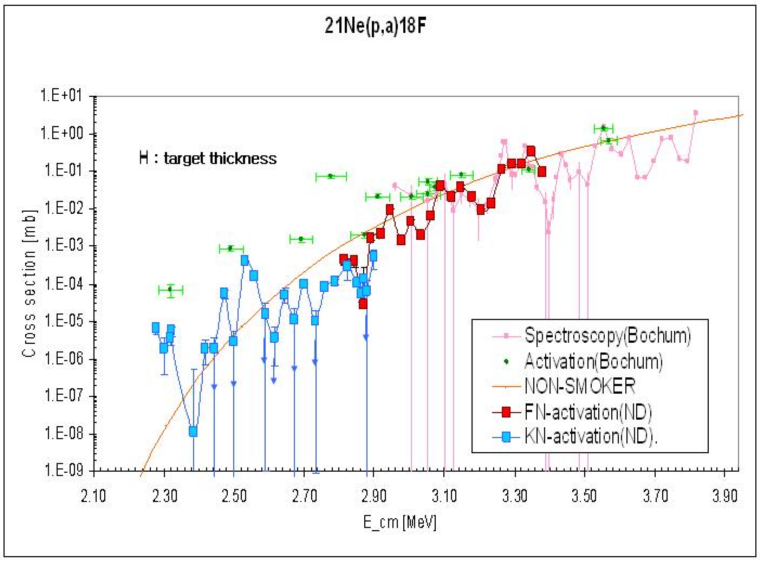

Figure 3. The total cross section (preliminary) of ^{21}Ne(p,α)^{18}F after ^{18}O(p,n)^{18}F yield subtraction. Bochum refers to the previous measurement [9] and ND refers to the activation measurement done at the University of Notre Dame.

The lowest peak at the energy of about 2.30 MeV in the c.m. system shows the existence of a narrow resonance. From the observed reaction yield [11], the resonance strength of 6.1×10^{-5} eV was determined. Owing to the lack of nuclear information, such as precise resonance energies and spin-parity assignments in the compound nucleus ^{22}Na [12, 13, 14], no unique R-matrix analysis of the experimental data is possible [15, 16].

4. Astrophysical implications

To compare the measurements with theoretical calculations, we employ the yield, which is the cross section integrated over target thickness and is a good expression in the case of a thick target measurement. Fig. 4 shows the overlaid plots (the upper) and the direct ratio (the lower) between the yield of the measurement and that of the calculated total cross section (Hauser-Feshbach). The lower plot shows that above proton energy of 3MeV in lab. system, there is an averaged normalization factor of 0.4. Below this energy the ratio varies according to the energy of proton. After applying this normalization factor to the calculated reaction rate, the full network code calculation [17] was performed to look for any evidence of ^{21}Ne production. Fig.

5 shows the sudden increase of the ^{21}Ne abundance (a purple solid line) at around 1.8 seconds. The complete network code analysis is currently in progress.

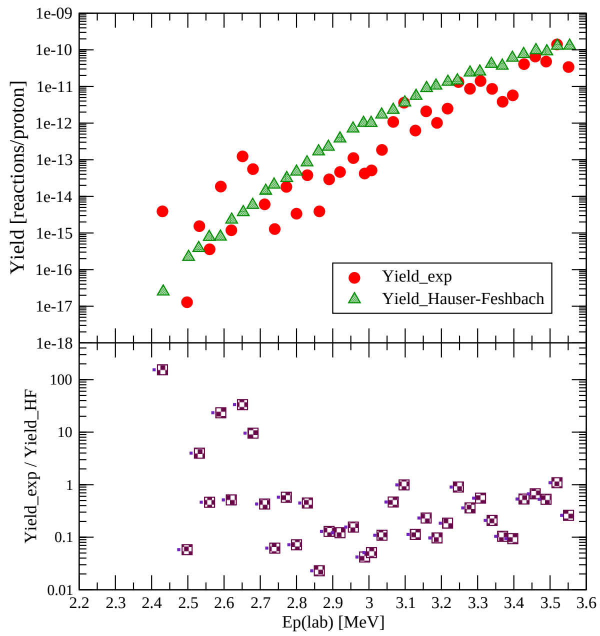

Figure 4. The yield comparision between measurements and calculations.

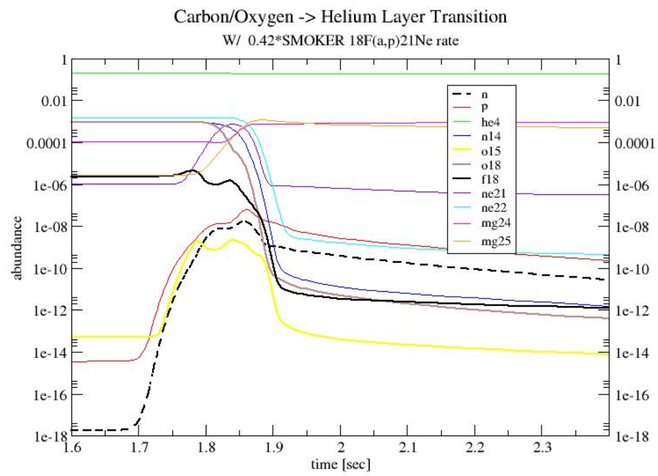

Figure 5. Elemental abundances at the helium layer after the shock front wave passes through in pre-supernova.

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References

[1] C. Seden, *Nature* **409**, 673 (2001).

[2] J.W. Truran, J.J.Cowan, in the proceedings of *the 10th workshop on 'Nuclear Astrophysics' Ringberg Castle*, eds. W.Hillebrandt, E.Müller, MPA/P**12**, P.64 (2000).

[3] J.W. Truran, J.J.Cowan, A.G.W.Cameron, *Astrophys. J.* **222**, L63 (1978).

[4] J. Görres, et al., *Phys. Rev*. C**62**, 055801 (2000).

[5] M. Cogneau, et al., *Nucl. Instr. and Meth.* A**420**, 489 (1999).

[6] W. Bradfield-Smith, et al., *Nucl. Instr. and Meth.* A**425**, 1 (1999).

[7]W.H. Schulte, et al., *Nucl. Instr. and Meth.* B**64**, 383 (1992).

[8] S. Dababneh, et al., *Nucl. Instr. and Meth.* A**517**, 230 (2004).

[9] U. Giesen, *Diploma Thesis*, Universitat Münster (1987).

[10] J.K. Bair, *Phys. Rev*. C**8**, 120 (1973).

[11] W.A. Fowler, *Rev. Mod. Phys*. **20**, 236 (1948).

[12] J.D. Garrett, et al., Nuc. Phys. A**164**, 449 (1971).

[13] J.N. Hallock, et al., Nuc. Phys. A**306**, 229 (1978).

[14] W.J. Vermeer, et al., Phys. Lett. B**217**, 28 (1989).

[15] R. Azuma, Multichannel R-matrix code, AZURE, to be published.

[16] H.Y. Lee, PhD Thesis, University of Notre Dame (2006).

[17] T. Elliot and H. Schatz, MSU network code, unpublished.