Determining the Direct Capture Rate of $^{11}C(p,\gamma)^{12}N$ with the $^{14}N(^{11}C,^{12}N)^{13}C$ Reaction

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The scenario of the evolution of supermassive stars with low metallicity, $M \geq 5 \times 10^5 M_\odot$, $Z \leq 0.005$ (Population III), could be changed by the updated reaction sequences

$$^{7}\mathrm{Be}(\alpha,\gamma)^{11}\mathrm{C}(\mathrm{p},\gamma)^{12}\mathrm{N}(e^+\nu_e)^{12}\mathrm{C}$$

$$^{8}\mathrm{B}(\alpha,\mathrm{p})^{11}\mathrm{C}(\mathrm{p},\gamma)^{12}\mathrm{N}(e^+\nu_e)^{12}\mathrm{C}$$

suggested by Wiescher [1] and others. $^{11}C(p,\gamma)^{12}N$ is one of the important reactions in which the direct capture into the ground state of ^{12}N, as well as the resonant capture into the first, second and third excited states of ^{12}N with $E_x = 0.96, 1.19, 1.80\,MeV$ respectively, are likely to dominate the reaction rate. The total cross section for $^{11}C(p,\gamma)^{12}N$ would be

$$\sigma(E) \propto \sum_{Lcc'} \left(\left| U^{(D,E1)}_{Lcc'} + U^{(R,E1)}_{Lcc'\lambda=2} + U^{(R,E1)}_{Lcc'\lambda=3} \right|^2 + \left| U^{(R,E2)}_{Lcc'\lambda=1} \right|^2 + \left| U^{(R,M1)}_{Lcc'\lambda=1} \right|^2 \right). \quad (1)$$

Here c and c' are the incident and outgoing channel parameters. L is the electromagnetic transition mode. λ is energy level. $U_{Lcc'}$ is the reaction amplitude. The direct capture has the same electromagnetic transition mode as the second and third resonance states, so the three amplitudes interfere.

Up to now, several indirect methods have been used to find these parameters. Based on the decay data of ^{12}B and the Weisskopf limit, Weischer's calculation show that the reaction will happen when $0.2 < T_9 < 0.4$; and the upper resonances at $E_x = 1.19, 1.80\,\mathrm{MeV}$ do not contribute greatly to the reaction rate below $T_9 = 2.0$. One experiment at GANIL [2] has studied this reaction, via ^{12}N Coulomb breakup. By fitting the relative energy spectrum of ^{11}C and p, they derived $\Gamma_\gamma = 6.0$ meV for the 2^- state and the spectroscopic factor for the direct capture (0.40 ± 0.25). With their experimental data, they claim that the main contribution in the interesting region below $T_9 = 0.3$ comes from direct capture and above this temperature from the resonance population of the first excited state.

There are at least two points about the GANIL result that need to be improved. One is the 60% uncertainty in the spectroscopic factor which is large. The other is that they neglect the interference between the direct capture and the upper resonance states which could make a 20% contribution to the total reaction rate according to their data. We are using the peripheral transfer reaction, $^{14}N\,(^{11}C,^{12}N)^{13}C$ at 10 MeV/u, to measure the ANC of $^{12}N \leftrightarrow p + {}^{11}C$ and then determine the direct capture rate. We have determined $S_{17}(0)$ with an uncertainty of 12% by this method [3]. With PTOLEMY [4], the elastic and transfer angular distributions have been calculated based on the available optical model parameters around $A \simeq 12$.

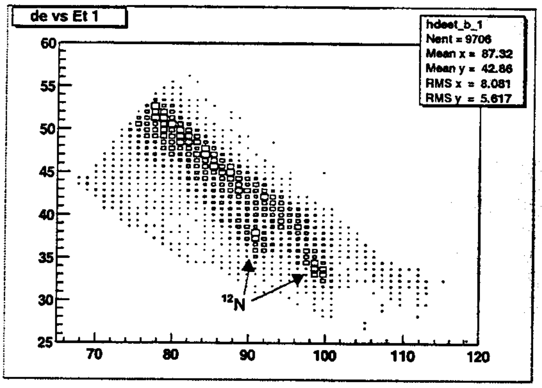

Figure 1: Particle identification using energy loss vs. total energy. There are two ^{12}N groups. The right one is from the $^{14}\mathrm{N}\left(^{11}\mathrm{C},^{12}\mathrm{N}\right)^{13}\mathrm{C}$ reaction.

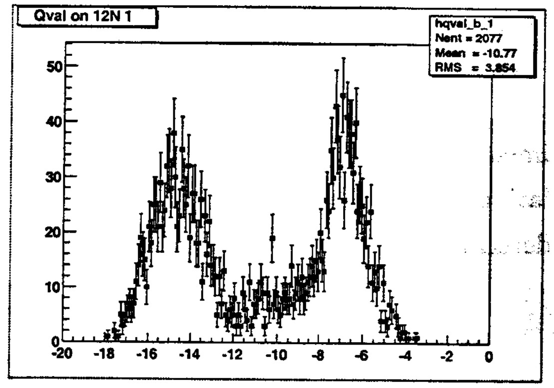

Figure 2: Q–value spectrum for transfer reactions producing ^{12}N in the data. The left peak is from the $^{14}\mathrm{N}\left(^{11}\mathrm{C},^{12}\mathrm{N}\right)^{13}\mathrm{C}$ reaction.

The experiment was performed in November of 1999. The ^{11}C beam was produced via $^{1}\mathrm{H}\left(^{11}\mathrm{B},^{11}\mathrm{C}\right)n$, using $\simeq$ 800 enA 13 MeV/u ^{11}B from the K500 superconducting cyclotron bombarding a 5.0 mg/cm^2 thick LN$_2$–cooled cryogenic H$_2$ gas cell with 0.5 mil Havar windows. The recoiling ^{11}C were separated from the primary beam with the Momentum Achromat Recoil Separator MARS [5, 6]. The resulting 10 MeV/u ^{11}C beam at the secondary target had a frequency of 0.4 MHz with an energy spread of 1.6 MeV, a beam spot size of 3×3.2 mm, and purity of more than 99%. We selected melamine ($C_3N_6H_6$) as the secondary target. The energy loss, residual energy and position of the outgoing particles were recorded in two detector telescopes, each of which consists of a position–sensitive Si detector with thickness of 60 μm backed by a 500 μm Si detector. To avoid beam hitting the detector directly and to obtain a reasonable event rate for the transfer reaction, the two telescopes were separated by 28 mm which was determined by a Monte Carlo simulation based on the experimental data for the beam and the theoretical reaction cross section obtained from PTOLEMY. Between these two telescopes, a plastic scintillator mounted on a photomultiplier tube was added to monitor the ^{11}C beam. Since the full beam intensity was too high for the scintillator, double screens, each with a transparency of 9%, were added to attenuate the beam intensity down by about 99%. During normal data acquisition, the event rate for the transfer reaction of interest was above 100 per day with about 10 Hz for elastic scattering. The particle identification using energy loss vs. total energy for the N isotope is shown in Fig. 1. The data analysis is under way. We have finished the energy calibration and partial position calibration for the two telescopes. The preliminary Q–value spectrum with cuts on the particle identification for ^{12}N is shown in Fig. 2. The peak at -6.8 MeV is from the transfer reaction $^{14}\mathrm{N}\left(^{11}\mathrm{C},^{12}\mathrm{N}\right)^{13}\mathrm{C}$ and the peak at -14.6 MeV mainly comes from $^{12}\mathrm{C}\left(^{11}\mathrm{C},^{12}\mathrm{N}\right)^{11}\mathrm{B}$. Now we are trying to refine the position calibrations to fit the experimental transfer and elastic Q–value spectra and angular distribution with a Monte Carlo simulation based on the theoretical calculations and the experimental beam parameters. Once this is done, we can compare the experimental cross section with the DWBA calculation and determine the ANC by which we determine the reaction rate of $^{11}C\,(p,\gamma)^{12}N$.

References

[1] M. Wiescher *et al.*, Ap. J. **343**, 352 (1989).

[2] A. Lefebvre *et al.*, Nucl. Phys. **A592**, 69 (1995).

[3] A. Azhari *et al.*, Phys. Rev. **C60**, 055803-1 (1999).

[4] M. Rhoades-Brown *et al.*, Phys. Rev. **C21**, 2417 (1980); **C21**, 2436 (1980).

[5] R. E. Tribble *et al.*, NIM Phys. Res. **A285**, 441 (1989).

[6] R. E. Tribble *et al.*, NIM Phys. Res. **B56/57**, 956 (1991).

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