$^{12}C+^{12}C$ astrophysical factor measurement at low energies

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Abstract

$^{12}C+^{12}C$ known as carbon burning is one of the most important reactions affecting the massive stars evolution. It's astrophysical factor was never determined in the Gamow peak until now and the theoretical extrapolations of the experimental data differ by three orders of magnitude. We try to configure the best experimental setup on the ground level so that new experimental data is achieved.

1. MOTIVATION

The $^{12}C+^{12}C$ reaction was persistently measured using both gamma [1-5]and particle [6-8] detection techniques, due to its importance for the Nuclear Astrophysics: impact on the nucleosynthesis, energy production and time scale of late stellar evolution. Carbon burning is the most important phase in massive stars ($M \geq 8M_{\odot}$)following the hydrogen and helium burning and is crucial for Type Ia supernovas driven by carbon ignition in the cores of accreting massive CO white dwarfs. Two energy ranges are of interest: 1.7MeV - 3.3MeV (in the CM) for the quiescent carbon burning and 0.7MeV – 1.7MeV (in the CM) for the Type Ia Supernovae. The sum of all exit channels (^{23}Na+p and $^{20}Ne+\alpha$) have to be measured to get the reaction rate within the Gamow peaks. The measured cross section presents a structured shape (periodical resonances appear). Spillane's [9] last measurement at ground level solved the hydrogenic contamination ($^{1}H(^{12}C,\gamma)^{13}N$ (Q=1943.49keV) and $^{2}H(^{12}C,p_1\gamma)^{13}C$) which made impossible until now to run experiments as low as 2.14MeV (in the CM). The data is not yet measured in the energy range of interest (above). The astrophysical factor extrapolations to lower energies, due to different theoretical approaches differ by 3 order of magnitude (see Fig.1), bringing in large uncertainties in astrophysical models of stellar evolution and nucleosynthesis. Recent theoretical calculations [10] bring in this reaction measurement as a strong case.

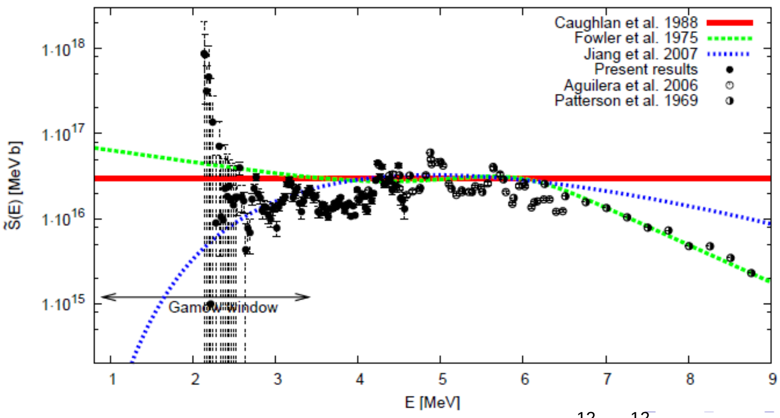

Fig.1 Astrophysical factor for $^{12}C+^{12}C$ reaction

Our goal is to get a reliable absolute cross section for the $^{12}C+^{12}C$ reaction corresponding to as low energies we'll be allowed by the detection system and by the detection shielding using the NIPNE TANDEM accelerator and the gamma and particle detection systems developed in time in the lab. We'll develop a normalization method within the γ-ray technique too. Collaboration to teams from Zagreb, Germany and USA is foreseen.

An increase in the cross section within the Gamow peak leads to lowering the mass limit for the massive stars (is it $8M_{\odot}$, $9M_{\odot}$ or $10M_{\odot}$), extend the size of the Carbon convective core and change dramatically the stellar models. Changes in the $^{12}C+^{12}C$ reaction rate would imply different ignition conditions for Carbon burning stars. A narrow resonance at E_{CM}=1.5MeV would imply that carbon ignition could start at lower temperatures than currently accepted, which means that Carbon burning may start in low-mass stars ($6\text{-}7M_{\odot}$).

The ^{12}C+^{12}C reaction is not so simple to be measured due to the surface hydrogenic contamination which is increasing the background, the exponential dropping cross section with the decrease of the energy and with the summing effects in the peaks. To solve the first issue, we plan to use the Spillane's method of first heating the target so that the ^{1}H and ^{2}H contaminants are evaporated or sputtered by the beam itself. Ultra-thin Si epitaxial detectors will be used for charged particle detection of low energy together with one or two Ge detectors. The Si detectors will be placed so that the particle discrimination is possible and to have a good resolution. We force for an increase in the beam current from the duoplasmatron or from the sputtering ion sources we have.

At these low beam energy, the expected open channels can be seen in Fig.2. In blue, the measured energies are drawn.

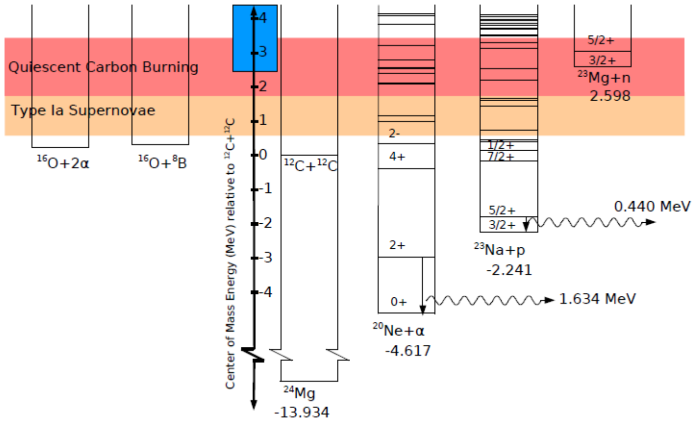

Fig. 2 Energy level

One can see that from the six possibilities, only three of them give values which can be measured (see below):

^{12}C+^{12}C =^{24}Mg + γ (Q = 13.93 MeV) negligible

^{23}Mg +n (Q = -2.62 MeV) closed at low Energy

^{20}Ne + α (Q = 4.62 MeV)

^{23}Na + p (Q = 2.24 MeV)

^{16}O + 2α (Q = -0.12 MeV) hindered by

^{16}O + ^{8}Be (Q = -0.21 MeV) Coulomb barrier

And by looking at the cross section (see Fig 3), from the three channels remain only two (the rate contribution is as follows: ^{12}C (^{12}C,α) = 0.65, ^{12}C (^{12}C,p) = 0.35 [11] and ^{12}C (^{12}C,n) ~ 0.1 % [12].

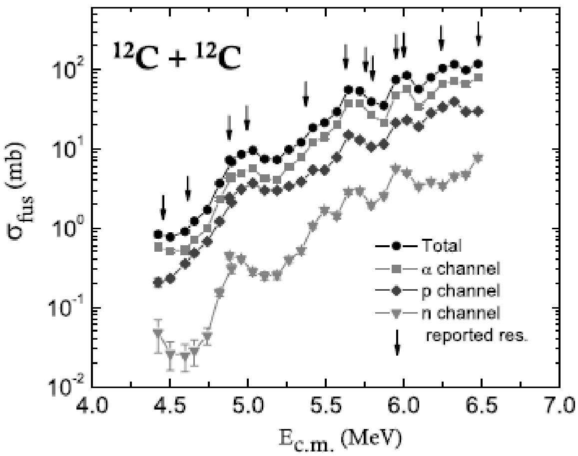

Fig. 3 Cross section variation for 3 open channels

We are going to consider the two main channels: $^{20}Ne + \alpha$ and $^{23}Na + p$. In case of a very thin C target, the cross section may be calculated as follows:

$$\sigma = \frac{Y_{prod}}{\frac{dN_{beam}}{dt}\left(\frac{atoms}{s}\right) * \Delta t(s) * \rho_T * thickness * concentration}$$

For a thick target, σ(E) is not a constant, but has a very steepy variation for low energies. All energies up to the beam energy are represented in the yield, and an integration over the energy variable is required.

$Y^{\infty}(E_0)=n\int_0^{E_0}\frac{\sigma(E)}{\varepsilon(E)}dE$, where ε(e) is the stopping power and n is a constant.

Point-to-point differentiation is one method to extract σ(E):

$Y^{\infty}(E) - Y^{\infty}(E-\Delta) \sim \frac{\Delta}{\varepsilon(E)}\sigma(E_{eff})$ [10]

If I_{12C}=4pμA, the production yield when integrating over the whole energy range is ~$2*10^5$ atoms/s starting from E=5MeV, ~$3*10^3$ atoms/s starting from E=4MeV and ~4 atoms/s starting from E=3MeV (σ = 3.4mb @ 5MeV, 0.07mb @ 4MeV and $1.7*10^{-4}$ mb @ 3MeV, and S=$1.5*10^{16}$MeVb). See Fig. 4.

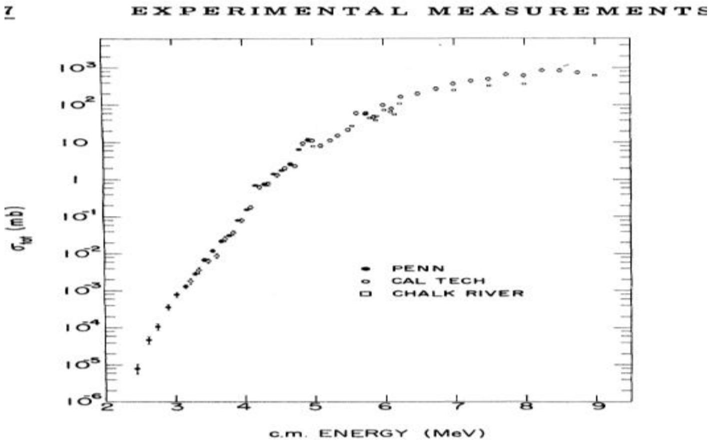

FIG. 4. Total reaction cross section in mb as a function of center-of-mass energy in MeV.

Fig. 4 Cross section variation with energy

Both protons and alphas are measured by the same Si ultra-thin detector while the irradiation.

For the reaction channel $^{12}C+^{12}C = ^{23}Na + p + \gamma$ (Q = 2.24 MeV), the protons p0,p1,p2… are measured by Si ultra-thin detectors and gamma ray 440keV together with p1,p2,… by a Ge detector. In case the absolute efficiency of the Ge detector in very close geometry (17cm far from the target) is about 2%, we get the gamma yields:

Energy(MeV CM)	Y_{prod}(for 4pμA and 1sec) 440keV	Y_{meas}(for 4pμA and 1sec) 440keV	Required time to get x counts in peak
3.0	4.0*0.35	0.028	10 hours for 10^3
4.0	$3*10^3$*0.35	21	13 hours for 10^6
5.0	$2*10^5$*0.35	1400	10min for 10^6

For the reaction channel $^{12}C+^{12}C = ^{20}Ne + \alpha + \gamma$ (Q = 4.62 MeV), the alphas α0, α1, α2… are measured by Si ultra-thin detectors and gamma ray 1634keV for α 1, α 2, … by a Ge detector. If the absolute efficiency of the Ge detector in very close geometry is 0.7%, the gamma yields are:

Energy(MeV CM)	Y_{prod}(for 4pμA and 1sec) 1634keV	Y_{meas}(for 4pμA and 1sec) 1634keV	Required time to get x counts in peak
3.0	4.0*0.65	0.018	13 hours for 10^3
4.0	$3*10^3$*0.65	14	20 hours for 10^6
5.0	$2*10^5$*0.65	910	18 min for 10^6

We have to check for the efficiency of the Ge detector in use for this experiment.
We'll try to get new values for the ratio $^{12}C(^{12}C,\alpha)/^{12}C(^{12}C,p)$, as different ratios from the one known causes variations for s-process isotopes within 50 %. The $^{12}C(^{12}C,n)$ may have an important effect on the s-process if it is ~ 1 % or stronger.

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