Sub-Coulomb fusion excitation function for $^{12}$C + $^{12}$C

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Fusion excitation functions are measured for the α, p and n evaporation channels in the fusion of the $^{12}$C + $^{12}$C system at center of mass energies between 4.5 and 6.5 MeV, with energy steps of 75 keV. The γ-ray technique is used with a new absolute normalization method which is independent of charge collection and allows at the same time to monitor the Carbon buildup on the target. Good agreement is obtained with absolute cross section values previously measured using particle detection techniques, but smaller energy steps are used in the present experiment. As in previous works much structure is seen in the excitation function which is consistent with the positions of resonances reported in the literature for this system.

Keywords: Sub-barrier fusion; γ-ray technique; nuclear molecules.

Se miden funciones de excitación para los canales de evaporación α, p y n en la fusión del sistema $^{12}$C + $^{12}$C a energías del centro de masas entre 4.5 y 6.5 MeV, con pasos de energía de 75 keV. Se usa la técnica de rayos γ con un nuevo método de normalización absoluta que no depende de la sección de carga, permitiendo al mismo tiempo determinar el apilamiento de carbón en el blanco. Se obtiene buen acuerdo con valores de la sección eficaz absoluta medidos previamente con técnicas de detección de partículas, pero el presente experimento usa pasos de energía más pequeños. Al igual que en trabajos anteriores, se observó mucha estructura en la función de excitación, la cual es consistente con las posiciones de resonancias reportadas en la literatura para este sistema.

Descriptors: Fusión sub-barrera; técnica de rayos γ; moléculas nucleares.

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1. Introduction

Through the many studies that have been made on $^{12}$C + $^{12}$C, both experimental and theoretical, this system stands out as one of the most interesting ones. Much evidence has been found for quasimolecular structure in it, coming mainly from excitation function measurements for many of the possible reaction channels [1–13]. The fusion-evaporation channel, in particular, has been measured at sub-Coulomb energies as low as around $E_{c.m.} = 2.5$ MeV [9, 14, 15], or $E_{c.m.} = 3$ MeV [11, 16]. This is near but still at the top of the region of astrophysical interest (1-3 MeV) that characterizes the carbon-burning nucleosynthesis that presumably occurs for massive stars in the late stages of stellar evolution [17–19]. The extrapolation from current data to these lower energies is difficult for at least two reasons. One is related to the resonant structures observed even in the low energy part of the excitation function, which makes unreliable any extrapolation using the statistical model, and the other important reason is that the various data sets show considerable discrepancies, as illustrated with a few examples in Fig. 1 for the energy range between 4.5 and 7 MeV. Considerable structure is evident in any of these data sets, but there are clear discrepancies between them, which in some cases fall far away from the reported uncertainties. It is important to specify that three of these works used the gamma-ray technique and only in Ref. 16 the results were obtained by detecting the evaporated particles. For these kind of measurements, where considerable structure is expected, it is important to take data with small energy steps, which implies using thin targets. This fact, combined with the low cross section values at sub-Coulomb energies, necessarily produces low yields of reaction products. The gamma-ray technique has the advantage that large solid angles may be covered, thus reducing the counting time for a given statistics and given beam current.

![Figure 1](https://via.placeholder.com/150)

**Figure 1.** Comparison of some experimental fusion excitation functions for $^{12}$C + $^{12}$C in the region between 4.4 and 7 MeV.
The disadvantage is that the absolute normalization of the cross sections heavily relies on collecting the beam charge, a task that the undesirable secondary electrons render very hard to accomplish with good precision. The data are thus usually renormalized to some independently measured value, which is possibly the main reason for the observed discrepancies in the gamma-ray measurements of Fig. 1. The main goal of this work was to use an improved normalization method within the gamma-ray technique in order to get good absolute cross section values for the fusion of $^{12}\text{C} + ^{12}\text{C}$ in the energy region displayed in Fig. 1, with the purpose of helping solve some of the existing discrepancies.

2. Experimental procedure

The experiment was performed with 9-13 MeV $^{12}\text{C}$ ions from the ININ EN-Tandem accelerator, with energy steps of 150 keV. A schematic diagram of the experimental setup is presented in Fig. 2. The target was a 15 $\mu$g/cm$^2$ C foil deposited onto a thick Ta backing. Two Ge detectors were used to measure the $\gamma$-rays at 125° and 55°. Measurements at these angles effectively reduce the effects of possible anisotropies in the $\gamma$-radiation [20] and the comparison of spectra at the two angles permits easy identification of any Doppler shift effect.

A lead shield 5 cm thick was placed around the first detector in order to reduce the room background. Because of geometry limitations, the shield for the second detector was only 8 mm thick. An SSB detector was placed at 160° in order to measure the $^{12}\text{C}$ ions elastically scattered from the Ta backing. This produces a thick-target spectrum that can be used to determine the absolute normalization factor [21]. A sample spectrum is shown in Fig. 3, obtained at a bombarding energy of 13 MeV, together with a Rutherford backscattering simulation (solid curve). The height of the plateau is directly related to the number of projectiles while the position of the rapid drop off depends, through kinematic and energy loss calculations, on the thickness of the carbon foil, thus allowing us to monitor the carbon buildup in the target and make the appropriate correction in the normalization factor. Further details of the calculations as well as some separate tests showing that, within a good approximation, this buildup varies linearly with the accumulated number of projectiles, will be given in Ref. 22. Buildup rates of 0.019 $\mu$g/cm$^2$ per particle-$\mu$C were observed in this experiment. Several C-foils were used in order to prevent too much target thickening. The effective beam energies in the target included corrections for both energy loss and average variation of the fusion cross section and were determined in the way described in Ref. 23.

3. Results and discussion

A typical $\gamma$-ray spectrum is presented in Fig. 4. The lines of interest, corresponding to g.s. transitions, are indicated in the figure. As shown, the $\alpha$, p and n evaporation channels could be identified. The lines corresponding to the p and n channels, although separated by only 11 keV, could be resolved despite the Doppler shift, present in both of them. This is illustrated in the inset of Fig. 4. The $^{20}\text{Ne}$ line did also show a considerable Doppler shift which was properly taken into account during peak integrations.

![Figure 2. Experimental setup.](image)

![Figure 3. Typical thick-target spectrum, obtained at $E_{\text{c.m.}} = 6.5$ MeV, at laboratory $^{12}\text{C}$ energy of 13 MeV. The energy calibration is 6.7 keV/channel.](image)

![Figure 4. Typical $\gamma$-ray spectrum, obtained with the 125° detector at $E_{\text{c.m.}} = 6.5$ MeV. The inset shows an enlargement of the region containing the lines of interest for the p and n channels.](image)
The obtained excitation functions are shown in Fig. 5. The error bars, in most cases smaller than the symbol size, represent the statistical errors. An additional 5% systematic error is related to the uncertainties in the number of projectiles and the target thickness determination. The arrows indicate the positions of previously reported resonances in this system [24]. Some correlation is observed between these positions and the bumps in our total cross section data. This correlation remains when the individual evaporation channels are observed, consistent with true resonances.

In Fig. 6 we compare our total fusion cross section data with the data of Patterson et al. [16], obtained with particle detection techniques. Good general consistency is observed between the two data sets, although some discrepancies still remain, specially in the high energy region, where our data are quite consistent with the behaviour shown by the data of Satkowiak et al. [12], as can be seen in Fig. 1. This discrepancy could thus be possibly ascribed to the main limitation of the γ-ray technique, which can not account for evaporation residues produced directly in their ground states. However, it is not clear that such differences should occur only in limited portions of the excitation function. Indeed, that limitation does not seem to affect the region below 6.1 MeV in Fig. 6, where both the γ-ray technique and the particle detection technique give consistent results. The structure seen in the excitation function has been interpreted as due to the formation of quasimolecular states which serve as doorway states for fusion (Ref. 25 and references therein). In a latter publication [26], a comparison will be made of our data with model calculations along these lines as well as with the results of other models that describe the average behaviour of the data and have thus some potential use in extrapolations to the region of astrophysical interest. In addition, a more exhaustive comparison with other data sets will also be done.

4. Summary and conclusions

Excitation functions were measured for all fusion-evaporation channels of the $^{12}C + ^{12}C$ reaction in the region between 4.5 and 6.5 MeV in the center of mass system. The γ-ray technique was used with a new normalization method that allows a simultaneous determination of both, the number of incident projectiles and the target thickness produced by carbon buildup. Good overall agreement is observed with previous data obtained by using particle detection techniques but our data have lower error bars and smaller energy steps.

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