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Angular Distributions in Carbon Fusion Reactions with STELLA

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Abstract : Stellar nucleosynthesis is based on several burning phases, including hydrogen fusion for light stars and the fusion of heavier elements up to silicon burning for the most massive stars. Nuclear fusion of Carbon is a key stage in stellar evolution for stars larger than 9 solar masses. At stellar energies (thermal energy), this reaction is only possible thanks to the quantum tunneling effect through the Coulomb potential barrier and it is measured by STELLA (STELar LAboratory). Thus, spectra of charged particles (alpha and proton) from the decay channels of $^{24}Mg^*$ have been analysed. The charged particle distributions were identified alongside with the background noise in order to calculate the cross sections and the associated angular distributions, at a centre-of-mass energy of 4.8 MeV. Finally, the possibility of attributing the spin of the compound nucleus in a resonance is discussed, given its capacity to increase the cross-section in the core of stars.

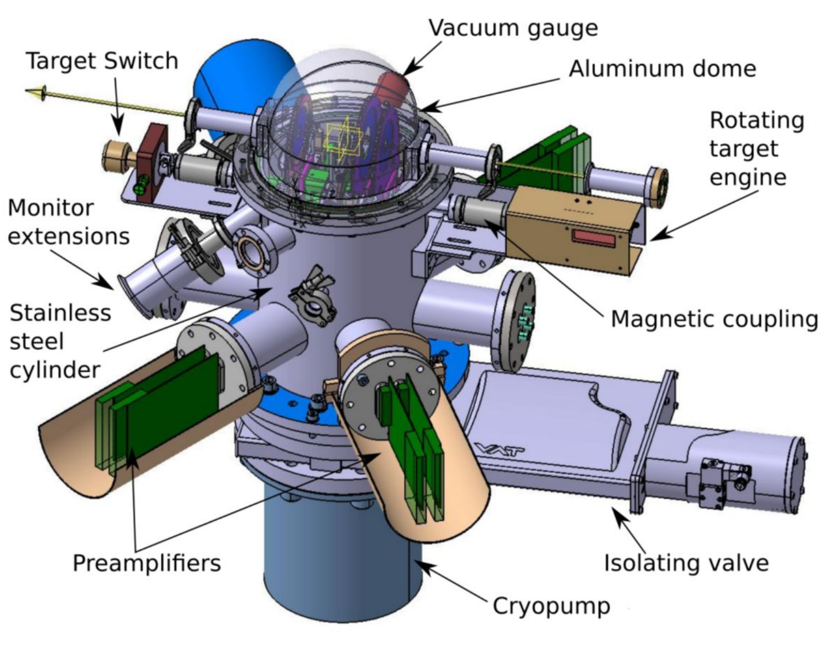

Fig. 1a : Mechanical drawing of STELLA apparatus [5]

Introduction : Thanks to stellar nucleosynthesis, elements from ^{1}H to ^{56}Fe can be created in the core of stars, depending of their masses. The thermal energy available inside is not sufficient to induce directly nuclear fusion. Despite of this lack, at low energies the quantum tunneling effect allows fusion reactions to take place through the repulsive Coulomb potential between two nuclei [1]. One of the key stage is Carbon burning which is essential for life-cycle of massive stars and impacts their death scenario. The measurement of decays channels induced by ^{12}C - ^{12}C fusion remains challenging and measured by STELLA (Fig. 1a,1b). The excitation functions of this reactions exhibit resonances at precise energies which can be linked to molecular states in the $^{24}Mg^*$ compound nucleus [2]. Thereby, the analysis of charged particles detection will be presented with 2 types of detectors at a centre-of-mass energy of 4.8 MeV from a 2022 data acquisition, in order to calculate the angular distribution of α_0 and the associated partial cross-section. A method to calculate the beam energy with uncertainties is also in development. Two fitting models with Legendre polynomials will be presented depending of the number of angular measurements [3]. This models give access to the spin of the compound nucleus in a resonance, of which information can be extracted from ground state of spinless particles in the outgoing channel $^{12}C(^{12}C, \alpha_0)^{20}Ne$ [4].

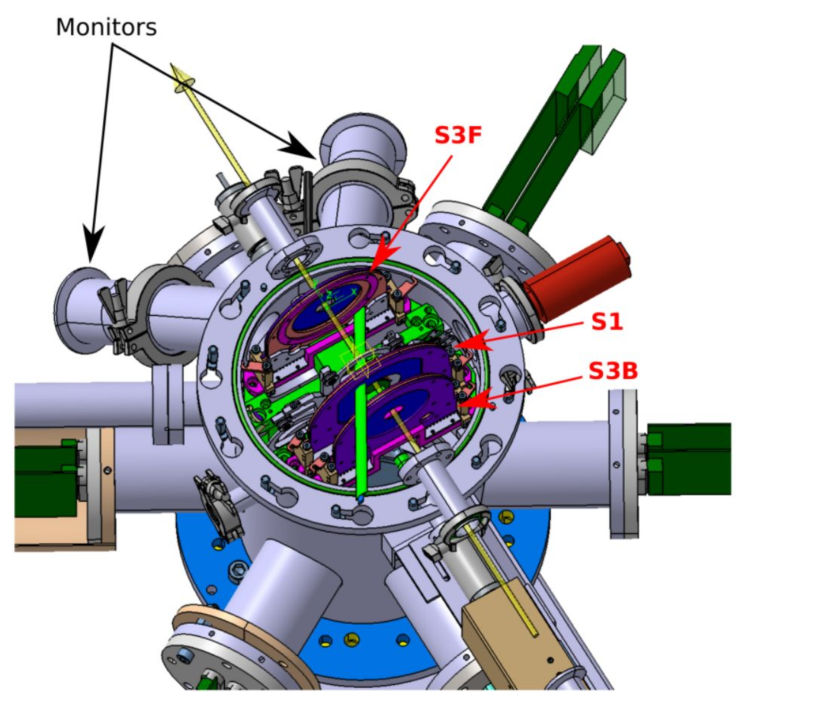

Fig. 1b : Mechanical drawing of STELLA's chamber reaction with Silicon detectors positions [5]

Experimental Setup : During this measurement, STELLA was based at Andromède Accelerator, IJCLab Orsay, where a Carbon beam energy of 9.6 MeV was used. DSSSD **S3** 500 µm thick detectors with 24 strips was placed **F**orward and **B**ackward a fixed Carbon target of 44 µg/cm², covering a solid angle of 0.7 sr and 0.9 sr respectively. Also, for the first time, a PIXEL SUPER-X3 1 mm thick detector was added, with 40.30 × 75.00 mm² of active area to improve the solid angle. All reactions take place in high vacuum chamber of 10^{-8} mbar, required to access at sub-µbarn cross-section measurements.

Framework for data Analysis : The reaction channels of Carbon fusion are given :

$$^{12}C + ^{12}C \to ^{24}Mg^* \to ^{20}Ne^* + \alpha_i \quad (\mathrm{Q} = 4.62 \text{ MeV})$$

$$^{12}C + ^{12}C \to ^{24}Mg^* \to ^{23}Na^* + p_i \quad (\mathrm{Q} = 2.24 \text{ MeV})$$

Kinematics of this channels was calculated (Fig. 2) and superimposed with data (Fig. 3) :

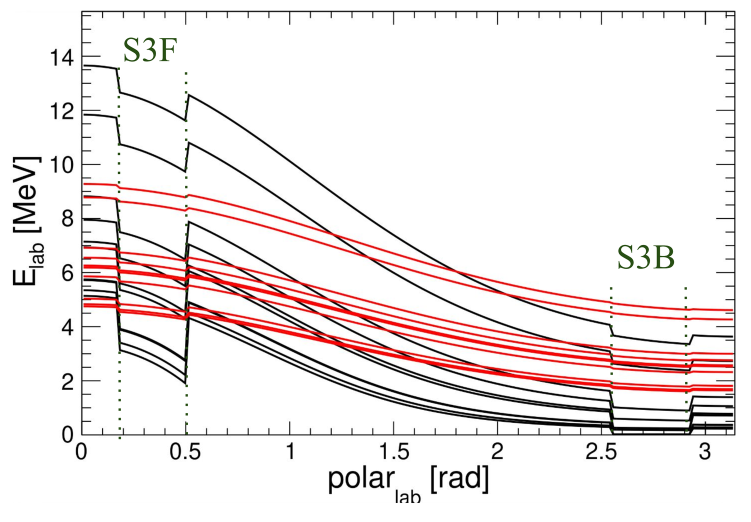

Fig. 2 : Energy kinematic calculations of evaporation residues with energy loss in Aluminium foils in front of S3

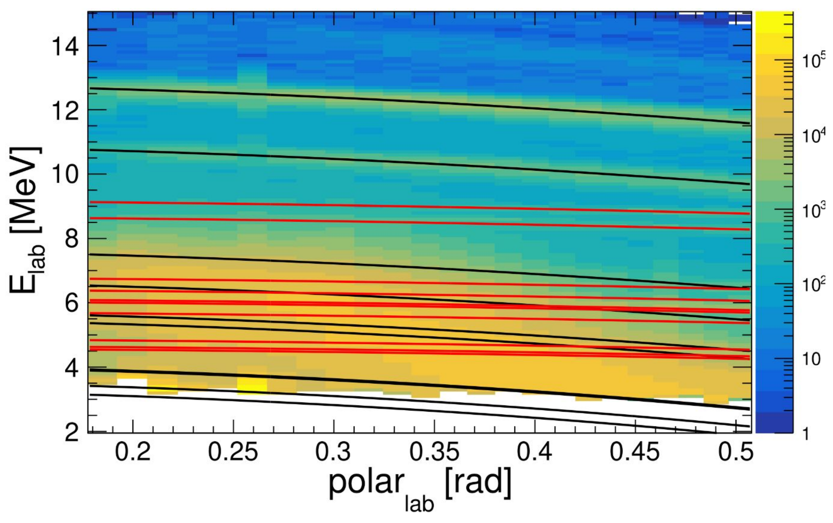

Fig. 3 : Kinematics and data superimposed in S3F strips

Particle spectra were analysed with taking into account charge sharing between multiple strips. Thanks to recalibration, charged particle distributions were identified alongside with the background noise (Fig. 4a,4b) in each strip of each detectors :

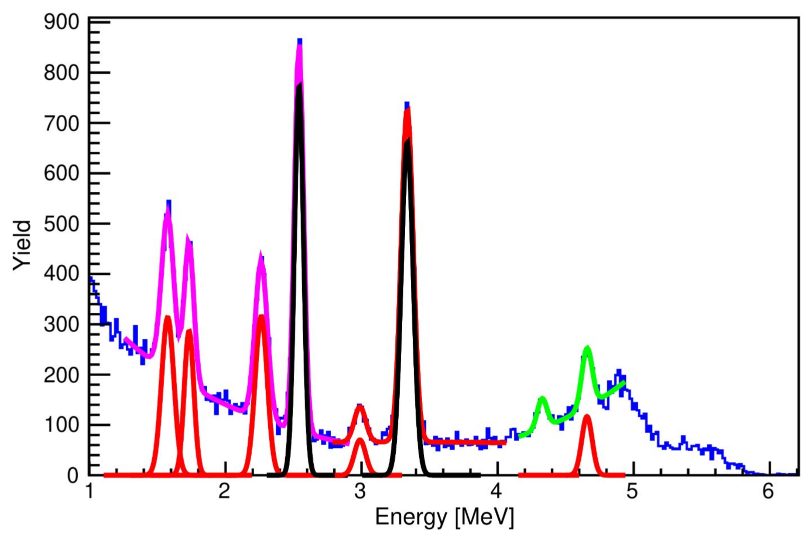

Fig. 4a : Charged particle spectra in one strip of S3B with and without background contribution

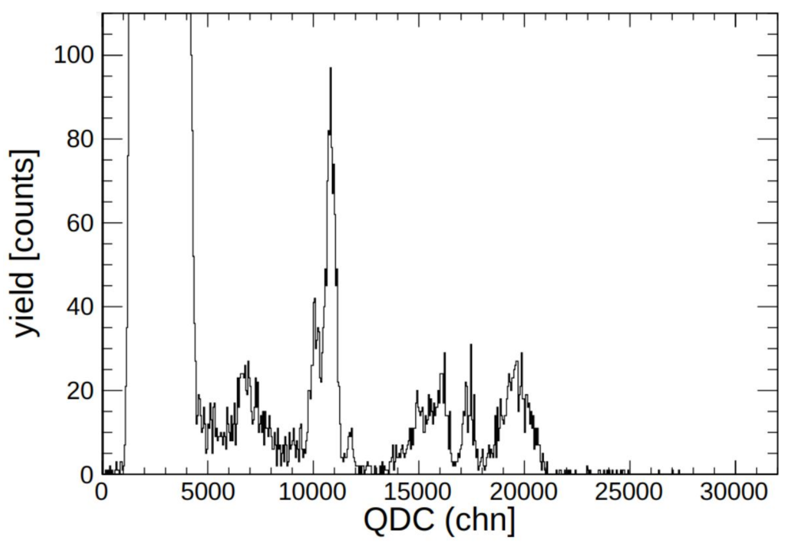

Fig. 4b : Charged particle spectra in one strip of PIXEL (preliminary)

Differential Fusion Cross-Section Calculations : The reaction probability follows from the Cross-Section determined experimentally and converted from laboratory frame to centre-of-mass frame [5,6] :

$$\left(\frac{d\sigma}{d\Omega}\right)_{lab} = \frac{S}{I \times N_t \times \Delta\Omega \times \Delta t} \longrightarrow \left(\frac{d\sigma}{d\Omega}\right)_{CM} = \left(\frac{d\sigma}{d\Omega}\right)_{lab} \frac{|1 + \gamma_3 \cos(\theta_{CM})|}{(1 + \gamma_3^2 + 2\gamma_3 \cos(\theta_{CM}))^{3/2}}$$

S is the number of count in the exit channel, *I* the integrated intensity of the beam, *Nt* the number of nuclei per surface in the target, *ΔΩ* the solid angle, *Δt* the duration of the measurement and :

$$\theta_{CM} = \arcsin\Big(\sin(\theta_{lab})(\gamma_3 \cos(\theta_{lab}) \pm (1 - \gamma_3^2 \sin^2(\theta_{lab}))^{1/2})\Big) \qquad \gamma_3 = \left(\frac{A_1 A_3}{A_2 A_4}\frac{E_{CM}}{E_{CM} + Q}\right)^{\frac{1}{2}}$$

with γ_3 function of Q value, E_{CM} and mass of incident and daughter nuclei.

Beam Energy Investigation : The value of beam energy with uncertainty can be determined by calculating the linear least square with uncertainties of all strips by inputting different energies :

$$\chi^2 = \sum_j \frac{(y_j - (ax_j + b))^2}{\sigma_j^2} \to \chi_r^2 = \frac{\chi^2}{NdF}$$

with *a* and *b* the slope and offset of the calibration, y_j the nominal energy done by kinematics, x_j the corresponding particle energy measured and σ_j the associated uncertainty

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Models for Spin Assignment : Two models with Legendre Polynomials can be used to fit angular distributions. Since identical bosons ^{12}C are in the entrance channel, ground state 0^+ of ^{20}Ne and zero-spin particles α_0 are in exit channel, only even orders of angular momentum are accessible to conserve even spin and positive parity [4,7] :

(A) $$\left(\frac{d\sigma}{d\Omega}\right)_{CM} = \sum_{L=0,even}^{L_{max}} B_L P_L(\cos(\theta))$$

→ B_L real
→ $l_{in} = l_{out} = J_{res} = (½)L_{max}$
→ $\sigma_{\alpha_0,tot} = 4\pi B_{0(L_{max})}$

(B) $$\left(\frac{d\sigma}{d\Omega}\right)_{CM} = |\sum_{l=0,even}^{l_{max}} A_l \sqrt{2l+1} P_l(\cos(\theta))|^2$$

→ $|A_l|$ complex : $|A_l| = \sqrt{Re^2 + Im^2}$
→ $l_{in} = l_{out} = J_{res} = l_{max}$
→ $\sigma_{\alpha_0,tot} = 4\pi \sum_i |A_{i(l_{max})}|^2$

Where A_l and B_L are fit parameters and the maximum order is determined by different criteria :

- until no improvement of □² (A) and (B)
- do not exceed too large statistical uncertainties (A) and (B)
- do not have statistical uncertainties > 100% (A)
- remains under investigation (B)

Results : Beam Energy (Fig. 5) and angular distribution (Fig. 6) of $^{12}C(^{12}C, \alpha_0)^{20}Ne$ at E_{CM} = 4.8 MeV

has b[...]ical and systematic uncertainties [...]lly :

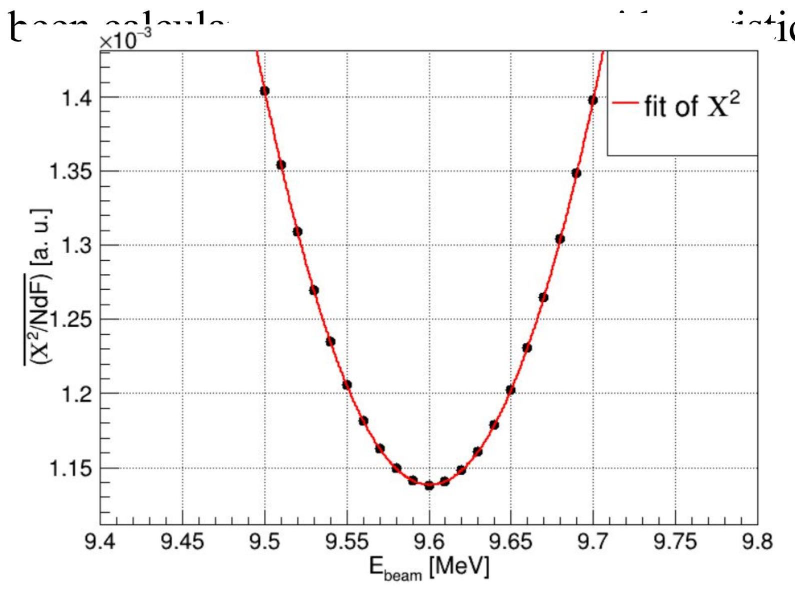

Fig. 5 : E_{beam} determination thanks to □² calculation

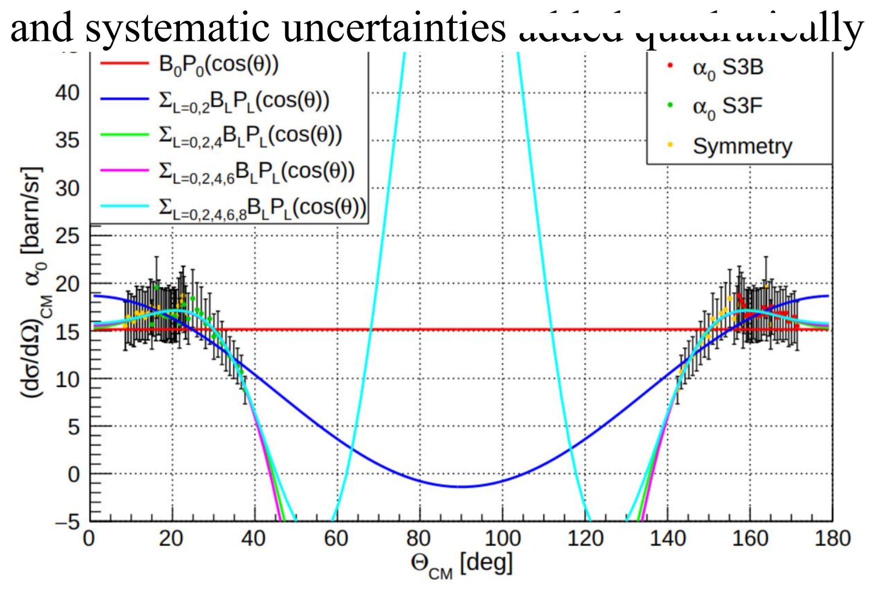

Fig. 6 : Angular distribution of α_0 fit with model A

- E_{beam} = 9.60 MeV where the uncertainties remains under investigation
- The analysis of the two different detectors S3F and S3B is consistent and well matched
- The addition of a PIXEL detector around 90° will enable the analysis to converge and provide a good description of the angular distribution, with model A and B and for cross-section calculations

Resonance Spin Assignment : At E_{CM} = 4.91 MeV (Fig. 7) and 5.00 MeV (Fig. 8), carbon fusion exhibits an increase of the cross-section. The spin is deduced by the 2 models applied for 2 experiments whose data have been digitised (Fig. 7,8) [8,9] from the reaction $^{12}C(^{12}C, \alpha_0)^{20}Ne$:

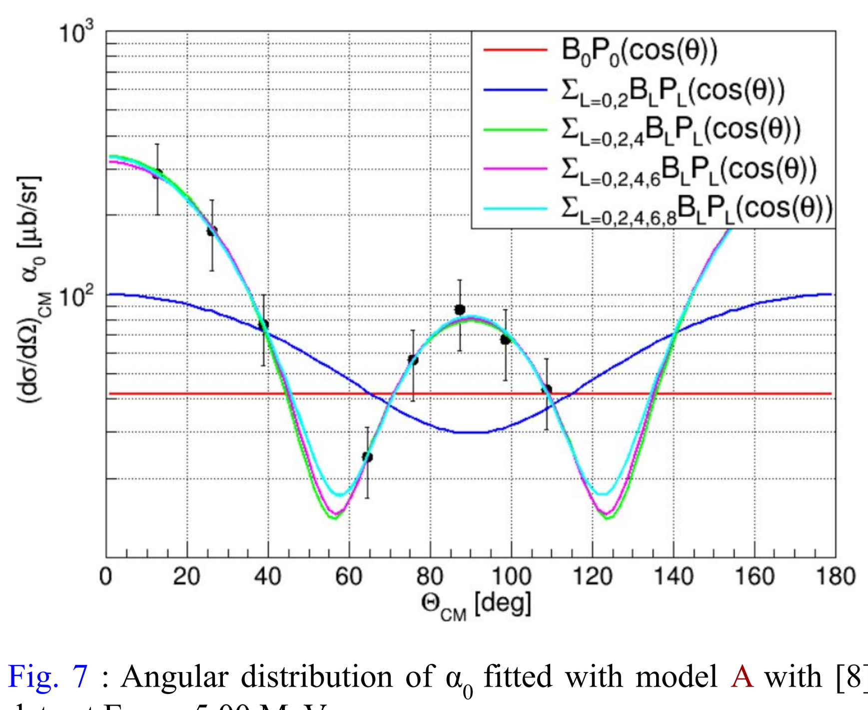

Fig. 7 : Angular distribution of α_0 fitted with model A with [8] data at E_{CM} = 5.00 MeV

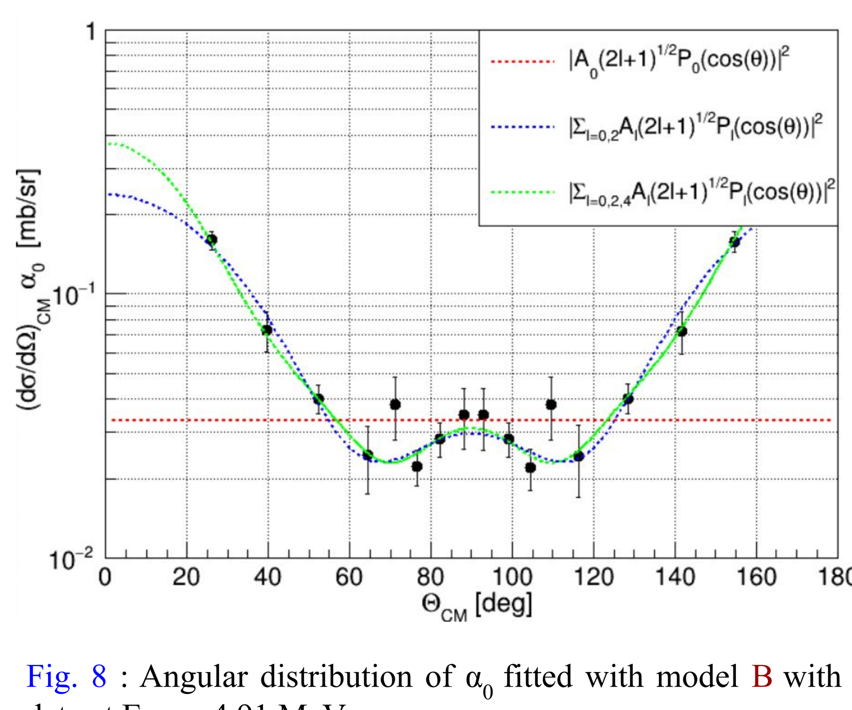

Fig. 8 : Angular distribution of α_0 fitted with model B with [9] data at E_{CM} = 4.91 MeV

The maximal order determined is L_{max} = 4 and l_{max} = 4 which corresponds to a $J^\pi = 2^+$ and $J^\pi = 4^+$ of $^{24}Mg^*$ respectively, and the associated total cross section calculated is 0.94 ± 0.13 mb (0.95 ± 0.28 mb [8]) and 0.80 ± 0.18 (0.84 mb [9]).

Conclusion : Fusion of ^{12}C + ^{12}C at E_{CM} = 4.8 MeV has been analysed. Thanks to a new PIXEL detector added to STELLA, angular distribution calculations could be improved. The resulting fitting method can be describe with 2 models depending of the number of measurements and can give access to the spin of the compound nucleus in a resonance.

Outlook : At this energy, others exit channels will be analysed such as p_0 and p_1 of $^{12}C(^{12}C, p_{0,1})^{23}Na$. In order to improve the tendency of the carbon fusion excitation function, others energy measurements will be investigated. Especially, a future experiment will be planned for very low energies to explore experimentally the Hindrance/HinRes phenomenon.