20th Russbach School on Nuclear Astrophysics

Study of Resonances in Gamow windows for $^{12}C+^{12}C$ fusion reaction via thick-target inverse kinematics method

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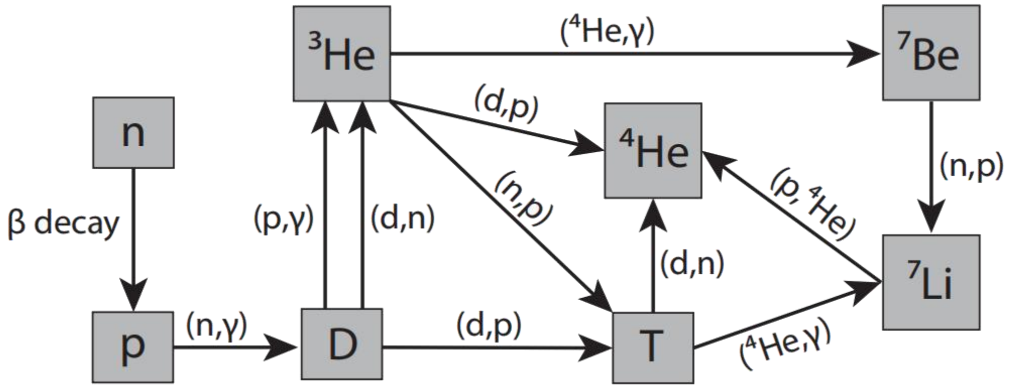
Nuclear Astrophysics

nuclear astrophysics:

Nuclear astrophysics is an interdisciplinary field combining nuclear physics and astrophysics, focused on understanding element formation in the universe and stellar evolution.

Several nuclear reactions, such as $^{12}C(\alpha, \gamma)$, $^{12}C+^{12}C$, $^{59}Fe(n, \gamma)$, have not yet been accurately measured, making them hot topics in the field.

Big Bang nucleosynthesis: formation of nuclei with mass number A < 8.



Fusion of charged particles or particle capture reactions in stars: Producing various elements from carbon to iron.

Hydrogen burning: pp chain, CNO cycle.

Helium burning: 3α process, $^{12}C(\alpha, \gamma)^{16}O$

Carbon burning: $^{12}C(^{12}C, p)^{23}Na$、$^{12}C(^{12}C, \alpha)^{20}Ne$

……

Nucleosynthesis of elements heavier than iron.

s-process (He-shell interlayer of AGB stars).

r-process (core-collapse supernovae, neutron star mergers).

p-process: Photodisintegration and proton capture reactions occurring on heavy nuclei (e.g., in supernovae).

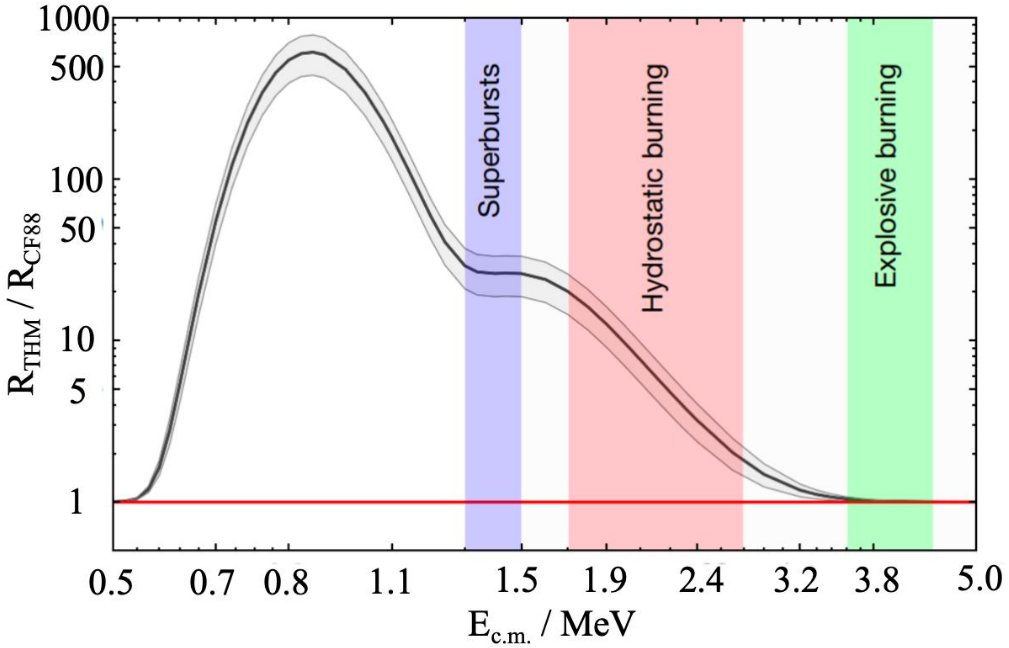
rp-process (accreting neutron stars)

$^{12}C+^{12}C$ fusion reactions

Evolutionary stages related to carbon-carbon fusion reactions:

1. Late stages of massive stars.

Relevant energy range: 1.7 - 4.5 MeV.



2. Ignition reactions of Type Ia supernovae.

An increase in the fusion reaction rate of $^{12}C+^{12}C$ would lead to a decrease in the ignition temperature, affecting the final products of a white dwarf supernova explosion (either a neutron star or a Type Ia supernova).

3. The $^{12}C+^{12}C$ fusion reaction is the ignition reaction for superbursts.

E_G: 1.2-1.8 MeV

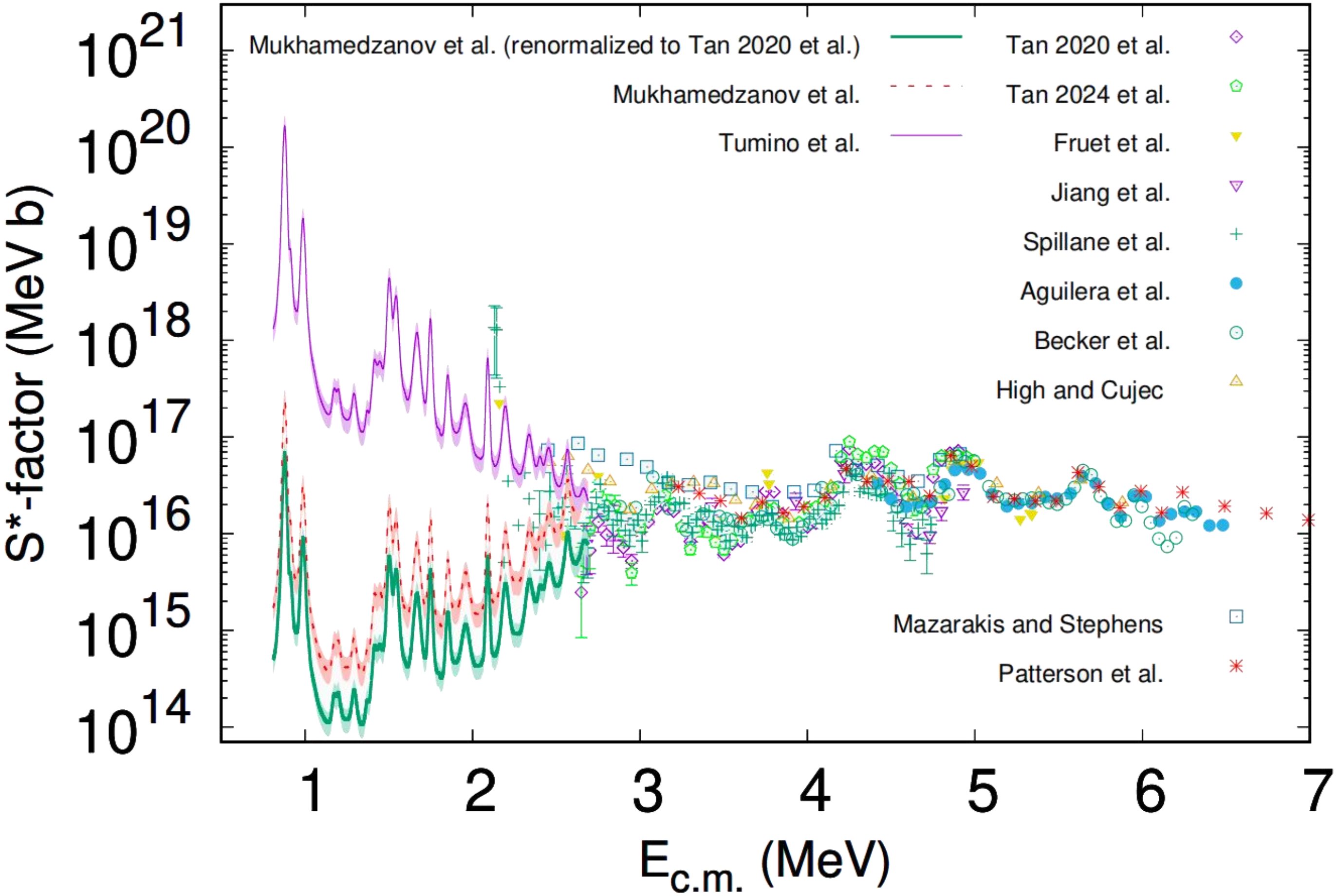
What is superbursts:

On the surface of a neutron star, X-ray bursts lasting from a few hours to a day are known as "superbursts."

Tumino A. et al. Nature(2018)557, 687-690

An agreement on the ^{12}C ignition temperature and depth with model predictions relies heavily on the existence of a strong resonancce at $E_{c.m.} \approx 1.5$ MeV.

Astrophysical S^* factor of $^{12}C+^{12}C$ fusion reaction



Wiecher M. et al., Rev. Mod. Phys., 2025.

1、Diret experiments are unlikely to reach low energies due to rapidly decreasing cross-sections.

2、The hindrance effect in $^{12}C+^{12}C$ system has not yet been confirmed experimentally or theoretically.

3、The Trojan Horse Method (THM) has been successfully applied to study the low-energy contribution to the $^{12}C+^{12}C$ fusion process.

4、The antisymmetrized molecular dynamics (AMD) approach combined with the R-matrix has been successful in yielding some fusion resonances at stellar energies.

5、Using indirect methods to study the resonances of ^{24}Mg would be a good approach.

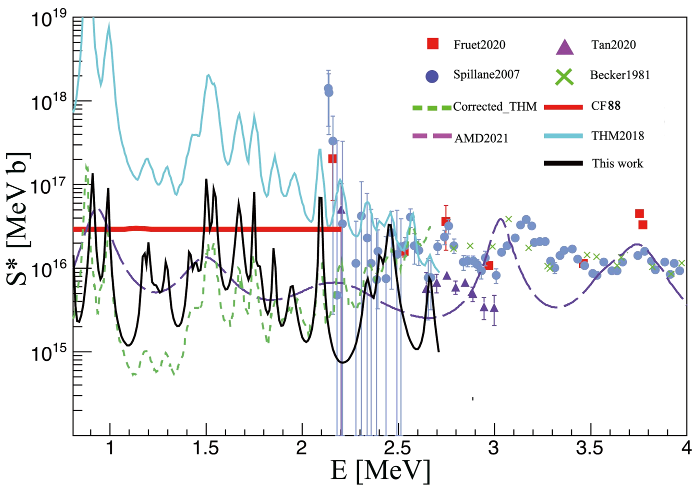
^{23}Na+p thick-target scattering experiment

The entrance width of ^{12}C+^{12}C

populate to the ^{24}Mg* excited state, extract the exit channel information from excitation functions

The astrophysical S*-factor for ^{12}C+^{12}C fusion reaction

$\theta_c^2 = 0.031 \pm 0.027$



single resonance Breit-Wigner fomula

$$\sigma(E) = \frac{\pi \hbar^2 (2J+1)}{\mu E} \frac{\Gamma_{in}\Gamma_{out}}{(E-E_R)^2 + \frac{\Gamma^2}{4}}$$

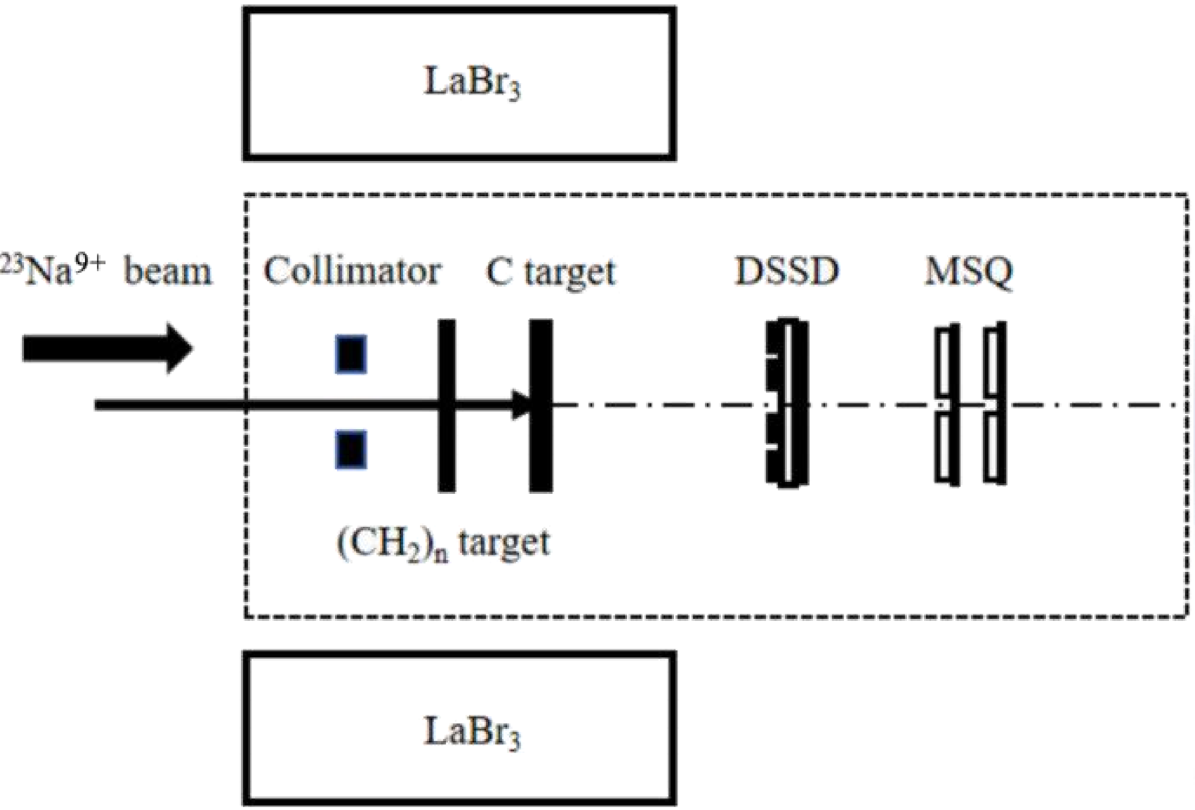
$$S^*(E) = E\sigma(E) exp(2\pi\eta + 0.46MeV^{-1}E)$$

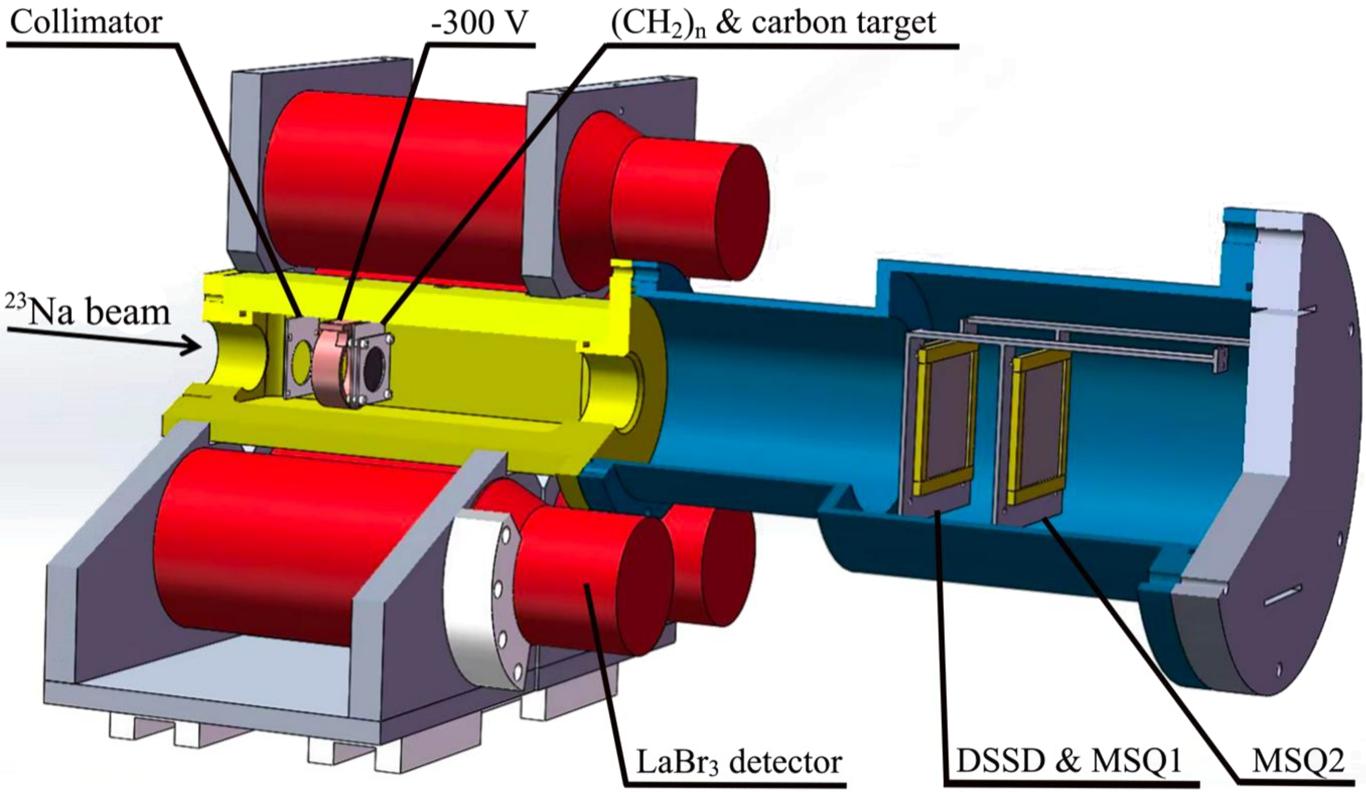
^{12}C+^{12}C entrance channel width

$$\Gamma_c = 2P_l \times \gamma_c^2$$

$$\gamma_c^2 = \theta_c^2 \gamma_\lambda^2, \quad \gamma_\lambda^2 = \frac{3}{2}\frac{\hbar^2}{Ma^2}$$

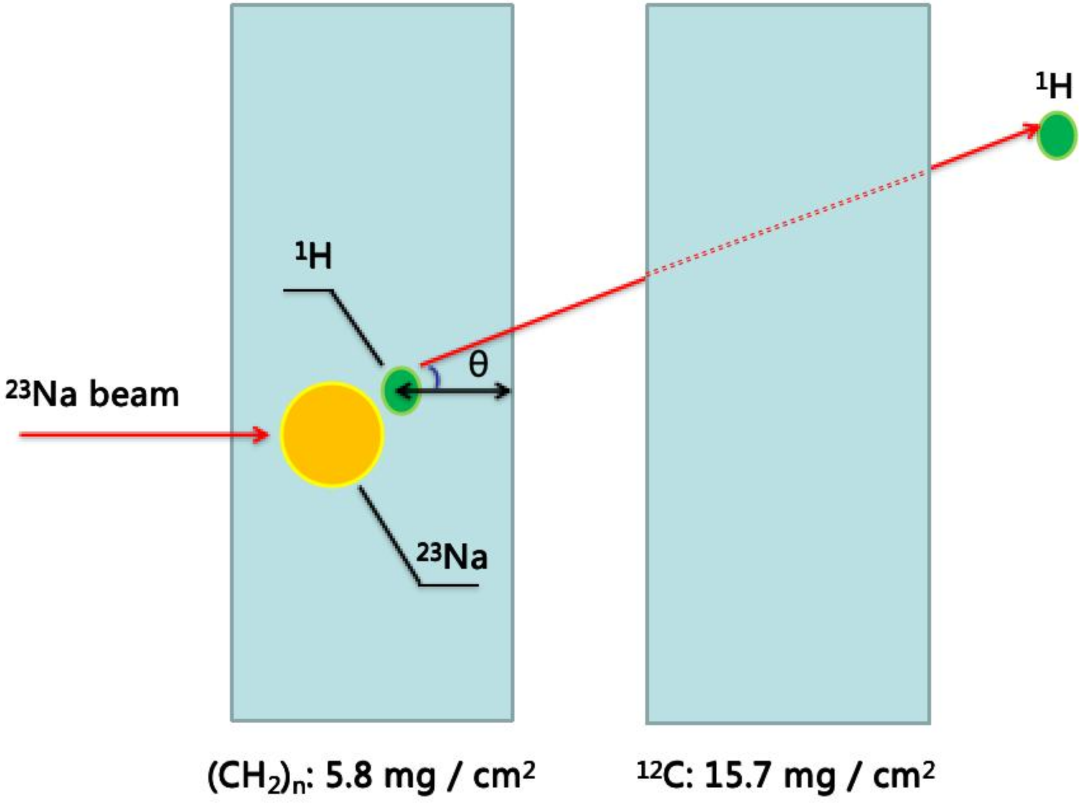
Experimental Setup



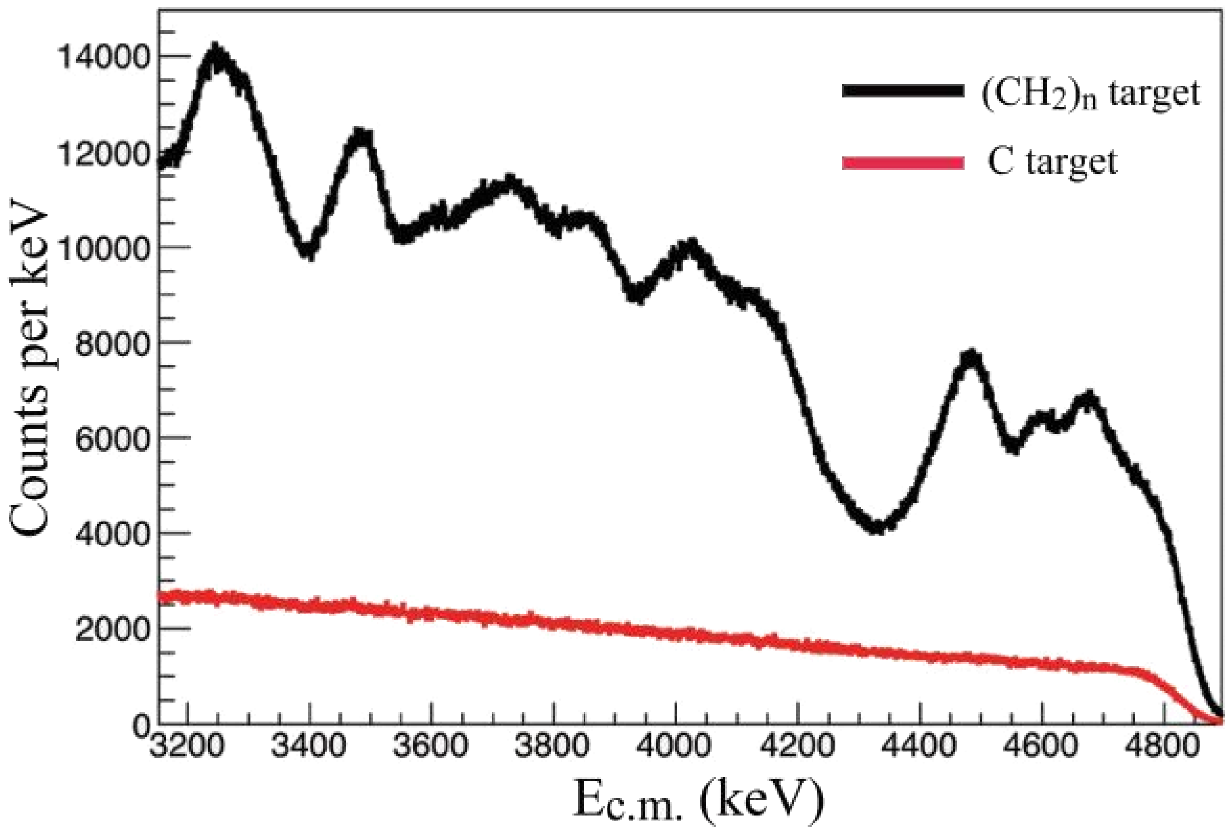


$^{23}Na+p$ thick-target scattering experiment

$^{23}Na + p$ reaction



p_0 energy spectrum of carbon and $(CH_2)_n$ target



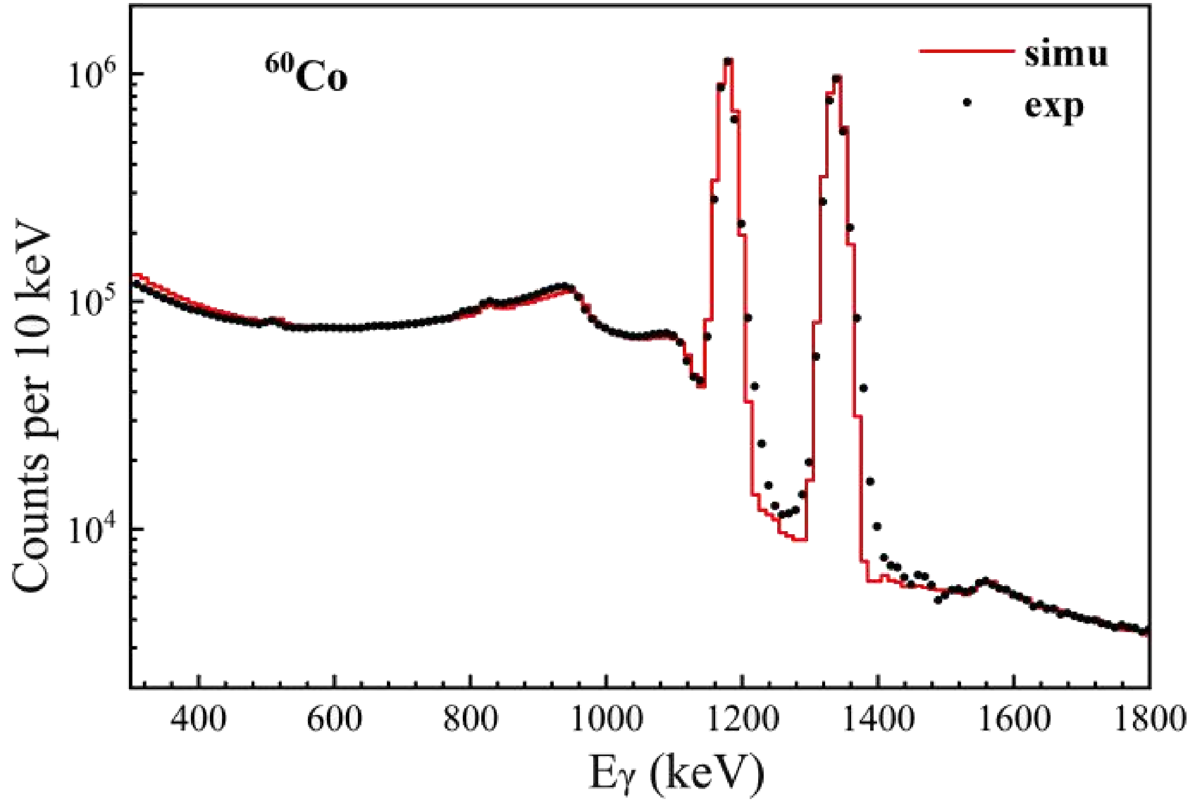
^{23}Na+p thick-target scattering experiment: γ effieciency

γ efficiency:

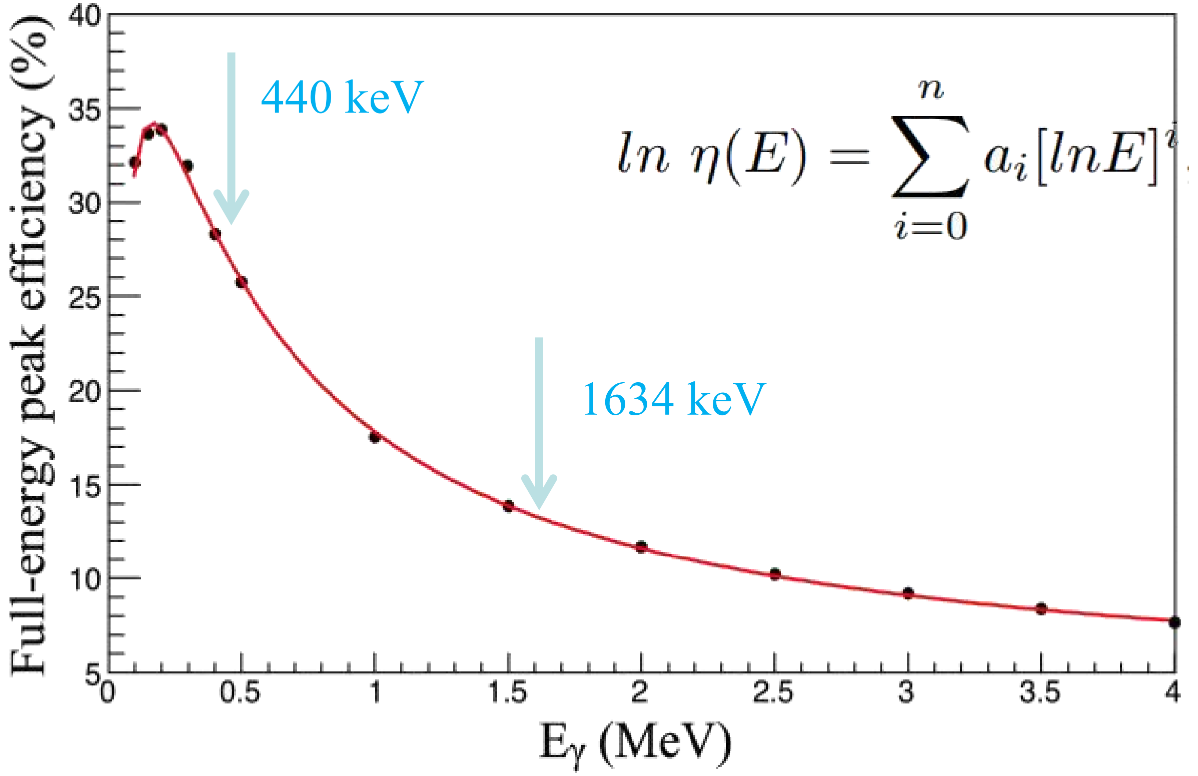
440 keV: 28.2 %; 1634 keV: 12.6 %

W. K. Nan, et al., 35, 208 (2024)

^{60}Co γ source and Geant4 simulation

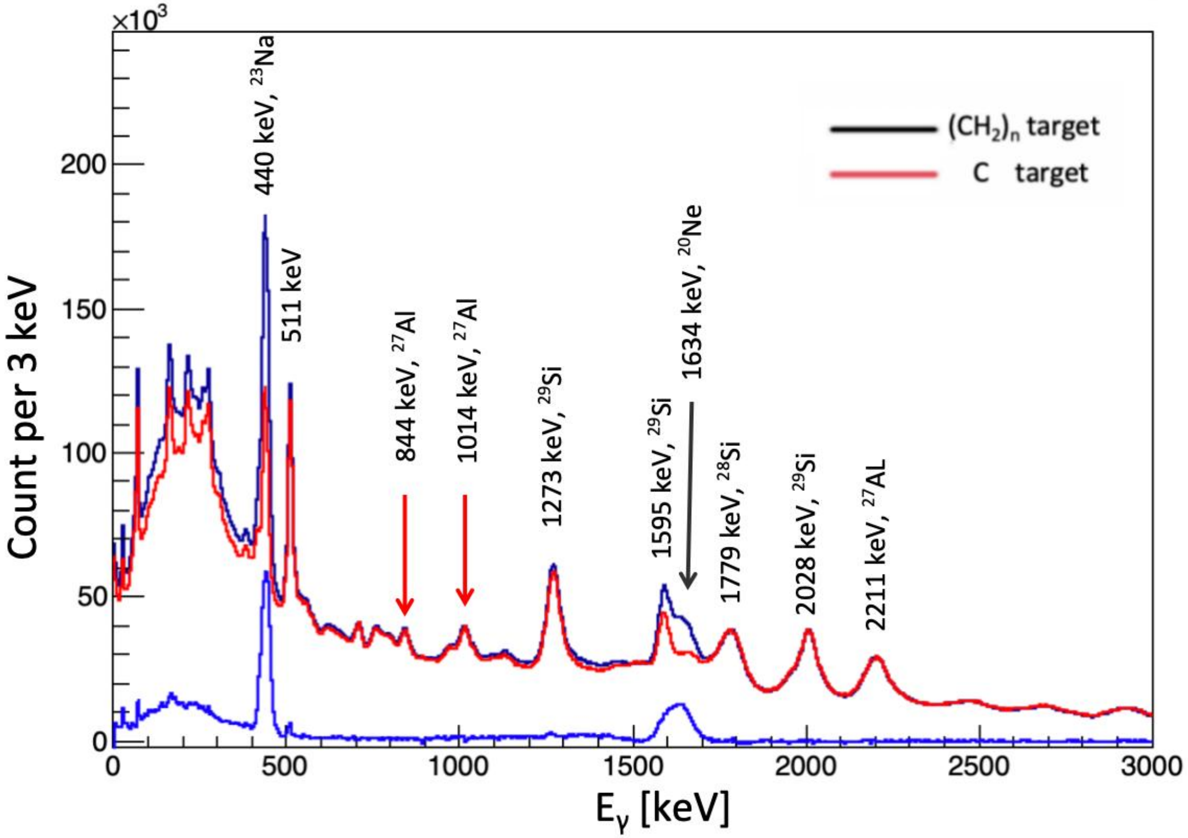


LaBr$_3$ array efficiency curve

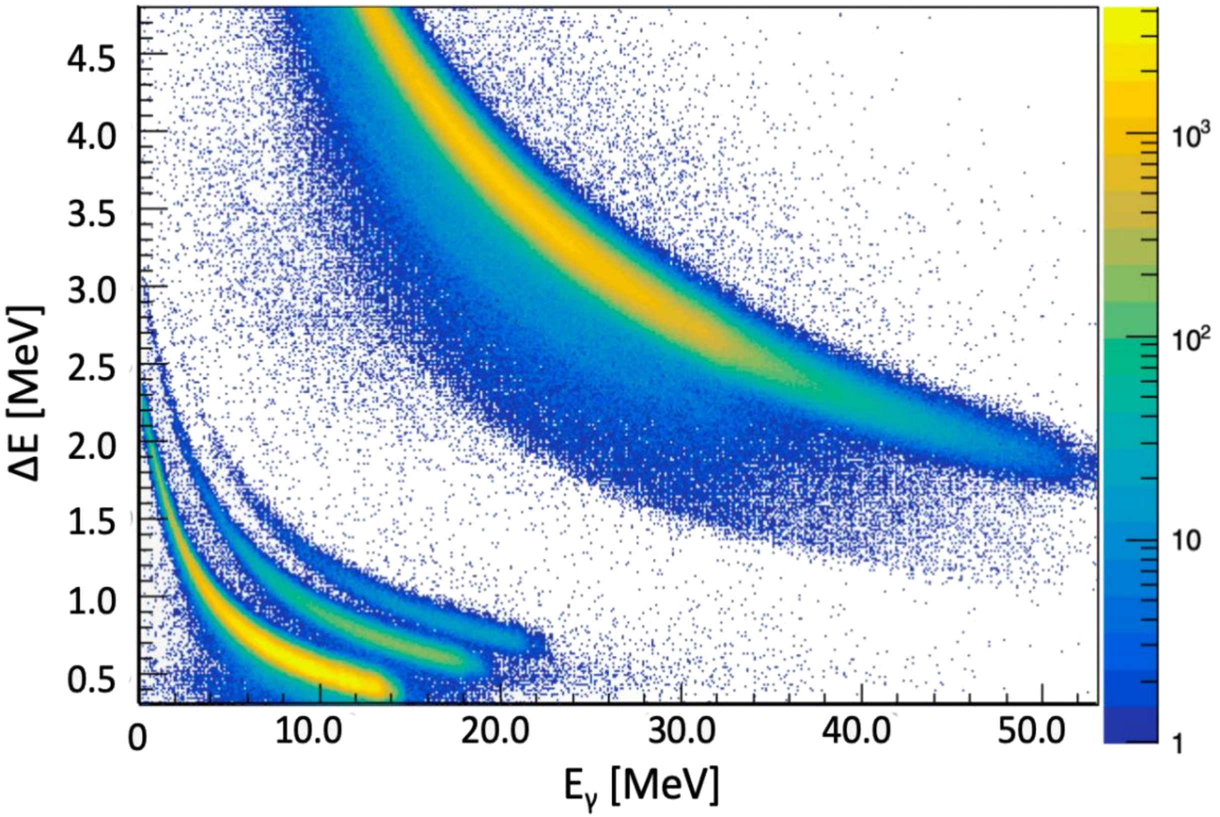


^{23}Na+p thick-target scattering experiment

γ spectium



ΔE-E two-dimension particle identification spectium



main exit channels: p_0, p_1, α_0, α_1

Excitation fuctions and R - matrix fitting

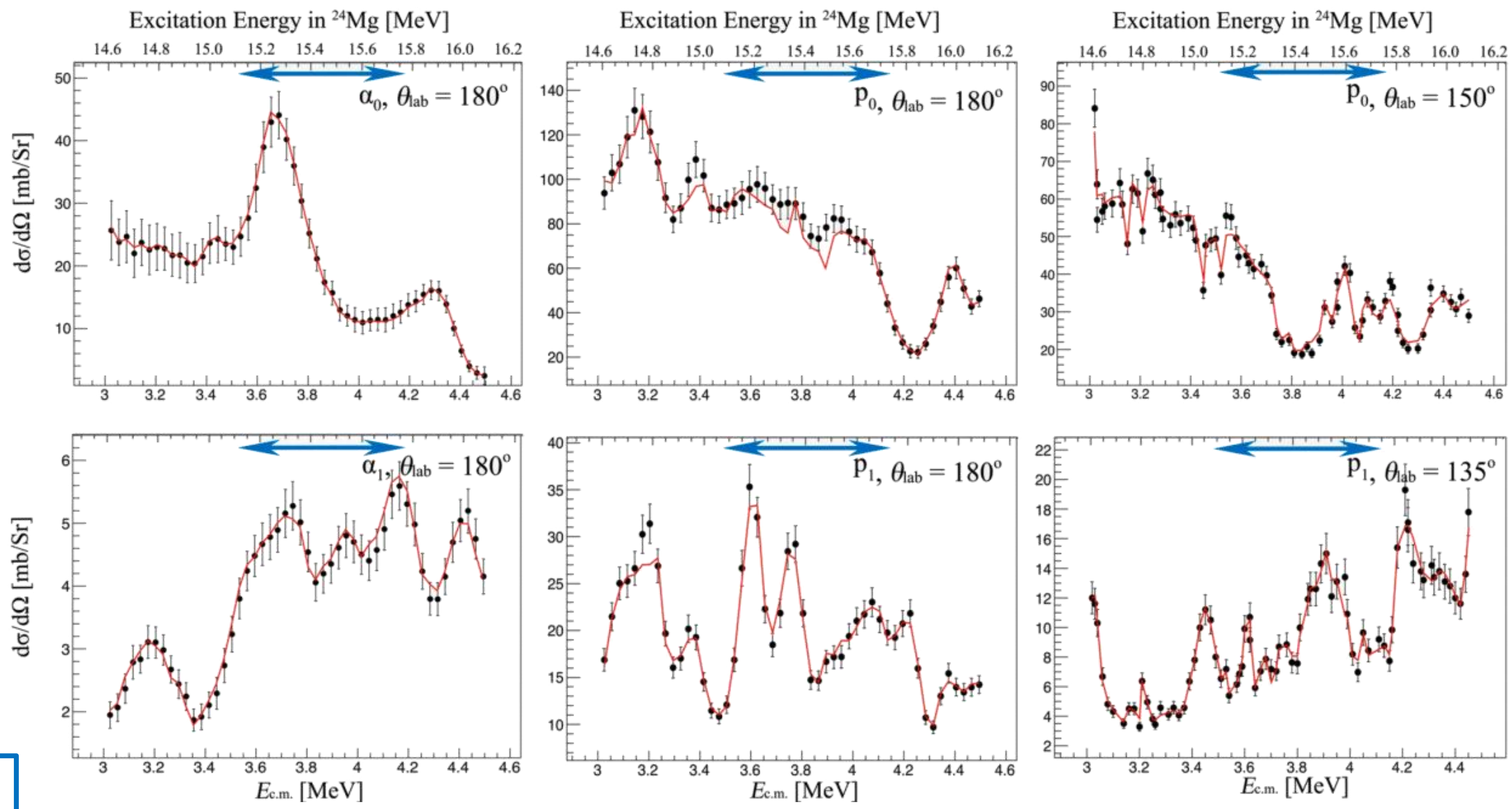
The excitation functions were carefully analyzed by performing a simultaneous multi-channel R-matrix.

The deduced ^{24}Mg resonance parameters from the best R-matrix fit are list in (W. K. Nan, 2025).

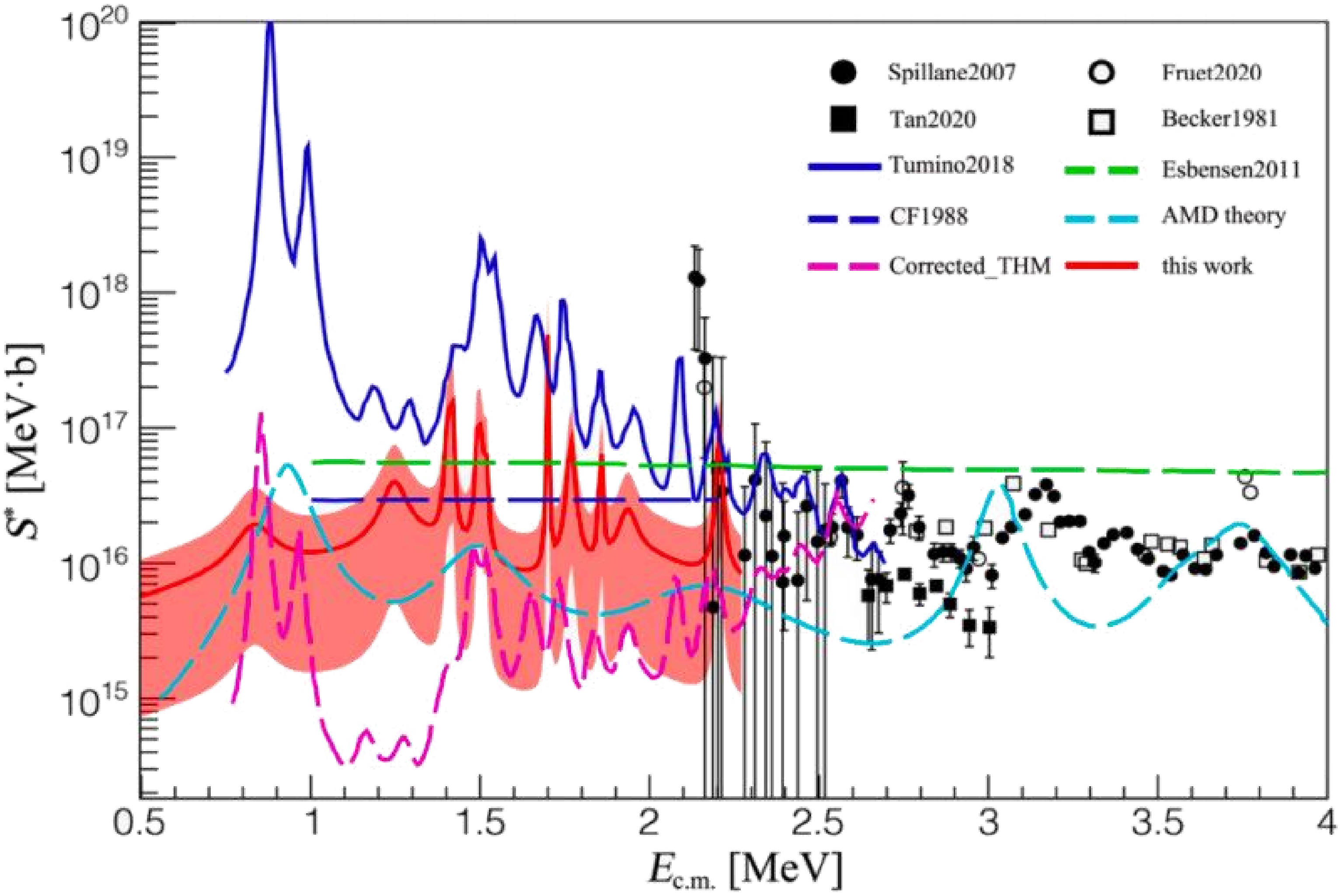
Only 0^+, 2^+, 4^+ etc., resonant states in ^{24}Mg are accessible through the identical $^{12}C+^{12}C$ two-boson system and the astrophysical S facvtor is dominated by the 0^+ and 2^+ states.

W. K. Nan, et al., 862, 139341 (2025)

excitation function of p_1, p_0,α_1,α_0 decay channels from the $^{23}Na+p$ entrance system



Astrophysical S^* factor of $^{12}C+^{12}C$ fusion reaction



AMD predicts a 2^+ state with a θ_c^2 (dimensionless reduced width) = 0.029 at $E_{c.m.}$ = 1.5 MeV.

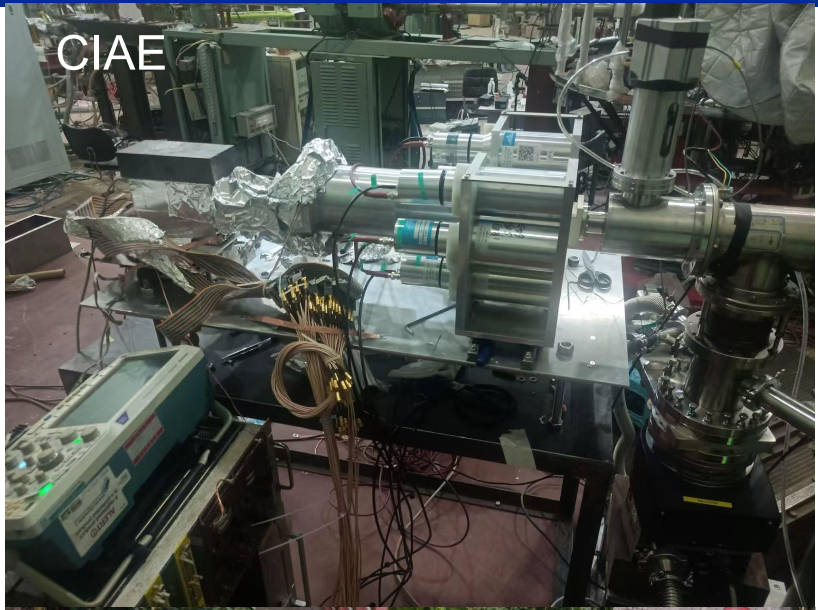
The uncertainty mainly comes from directly measured data points provided by Spillane at al. near 2.45 MeV.

The THM measurement is successful in exploring the resonances, however the number of resonance is seemingly more than expectation the identical $^{12}C+^{12}C$ two-boson system. The $^{23}Na+p$ channel used in this work has a similar problem.

Conclusion

1、The ^{23}Na + p thick-target kinematics method is used to explore the key resonances in ^{24}Mg related to carbon-carbon burning process. By applying γ-charged particle coincidence method, the excitation functions for the pronton α emission channels are obtained.

2、The resonance parameters are deduced through simultaneous multi-channel R-matrix analysis. The 0^+ and 2^+ states exposed in the most relevant excitation energy of ^{24}Mg are particular interesting, which arrowed for the evaluation of the partial cross sections to the different ^{12}C+^{12}C exit channels.

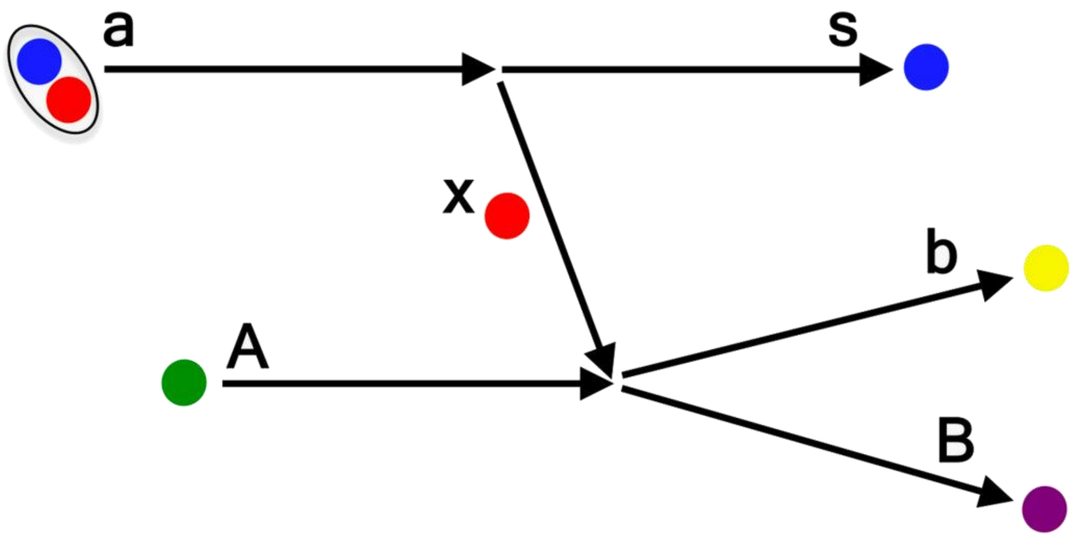


back up

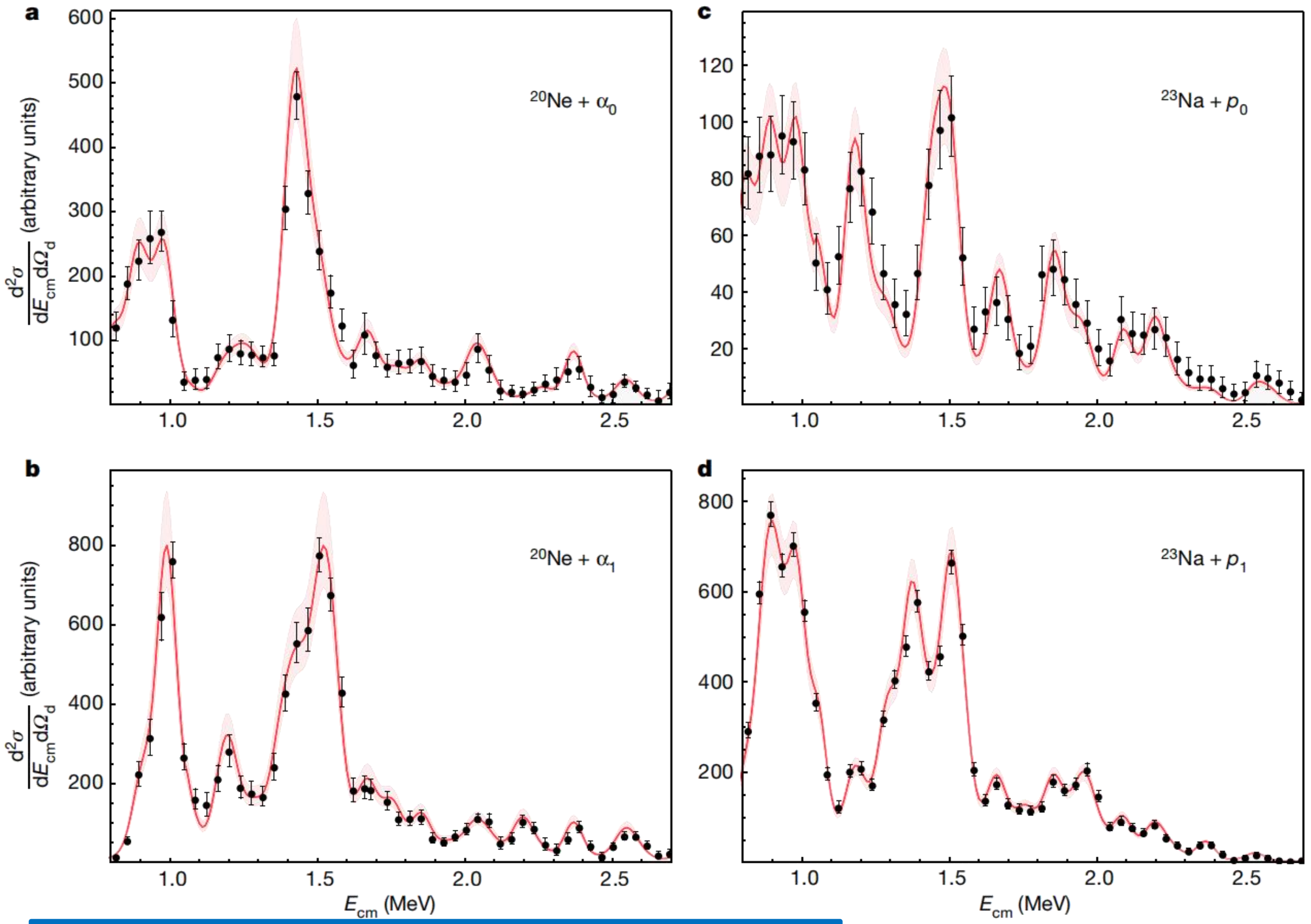
Tumino2018:

$^{12}C(^{14}N, \alpha^{20}Ne)^{2}H$ and $^{12}C(^{14}N, p^{23}Na)^{2}H$
from 0.8 to 2.7 MeV
four channels: p_0, p_1, α_0, α_1

A(a, bB)s反应中的准自由机制示意图

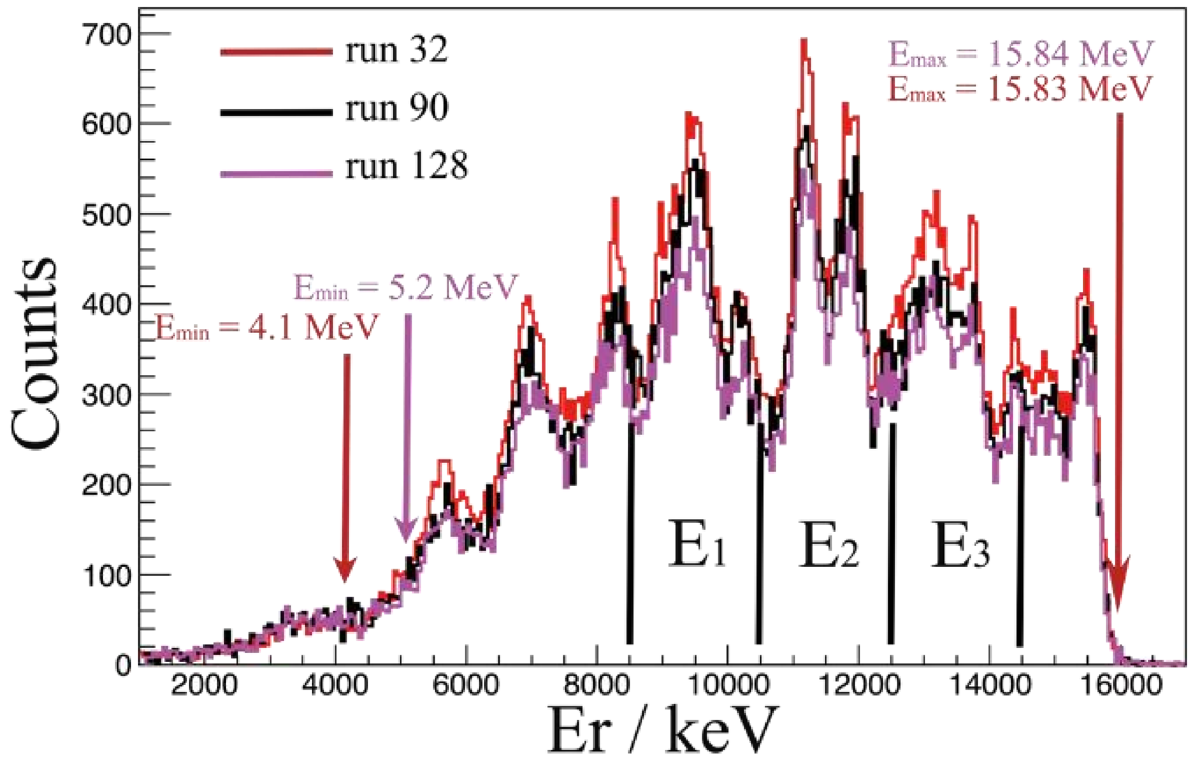


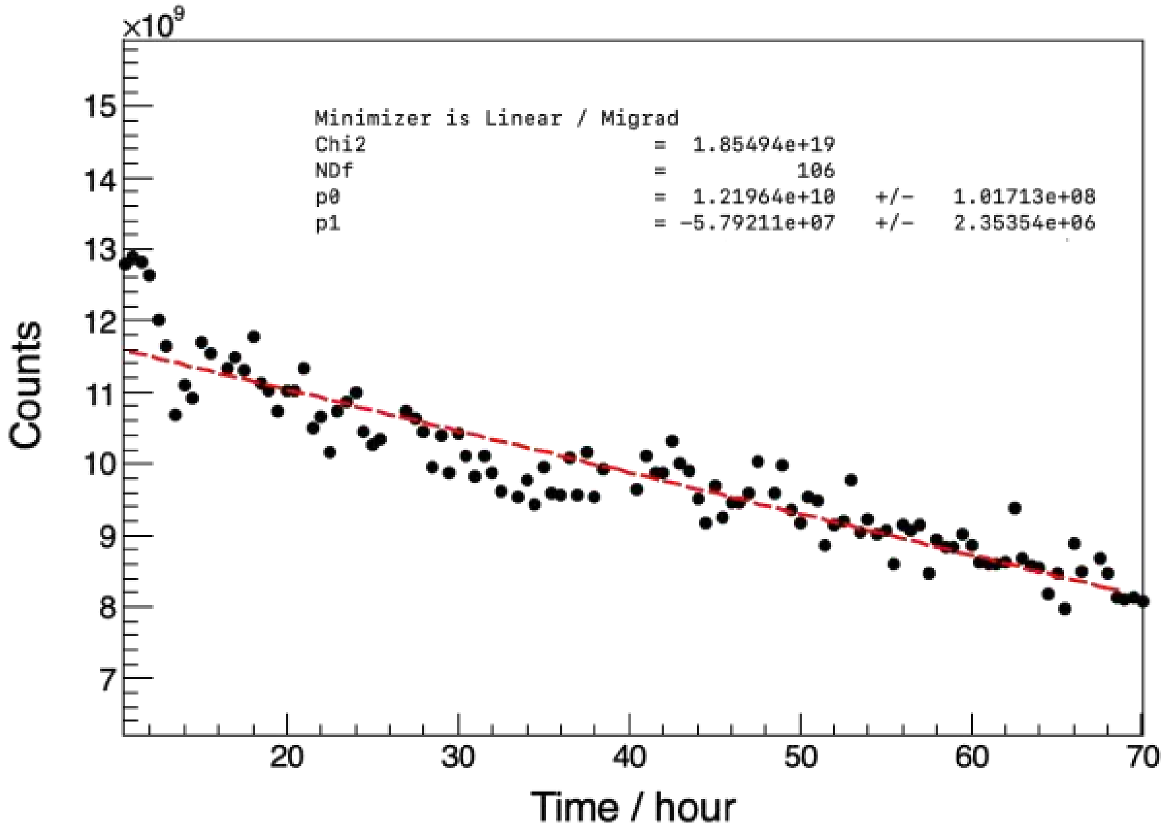
excitation function



Tumino A. et al. Nature(2018)557, 687-690

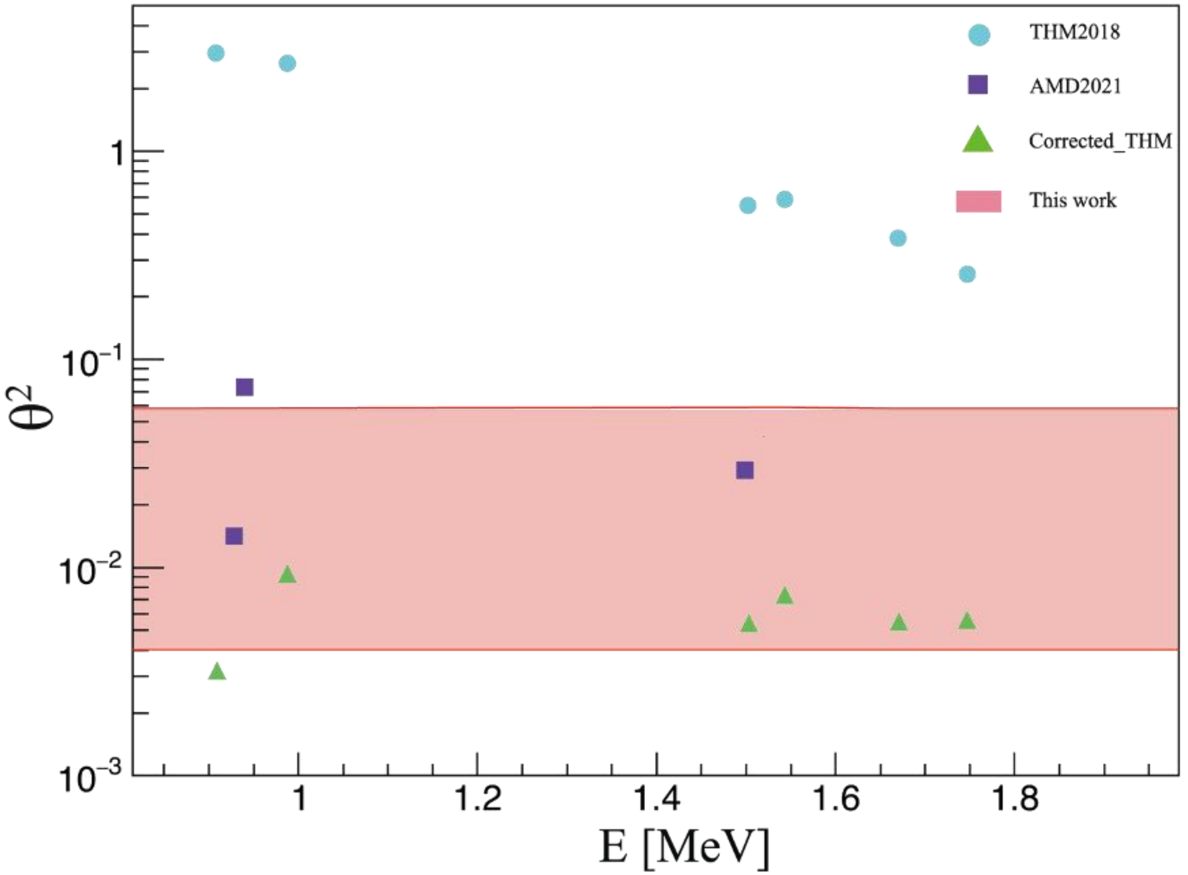
back up: 靶材料损失修正





$^{12}C+^{12}C$熔合反应天体物理S*因子研究现状

$^{12}C+^{12}C$熔合反应入射道无量纲约化宽度



入射道无量纲约化宽度计算结果

在2.45 MeV处归一得到的入射道无量纲约化宽度，与反对称分子动力学模型(AMD)给出的理论计算结果十分接近。

Y. Taniguchi, M. Kimura. ^{12}C + ^{12}C fusion S-factor from a full-microscopic nuclear model. Phys. Lett. B, 2021, 823, 136790.

W. K. Nan, et al., Nucl. Phys. Rev., accepted, 2024.

$^{12}C+^{12}C$ 熔合反应天体物理 S* 因子的研究现状

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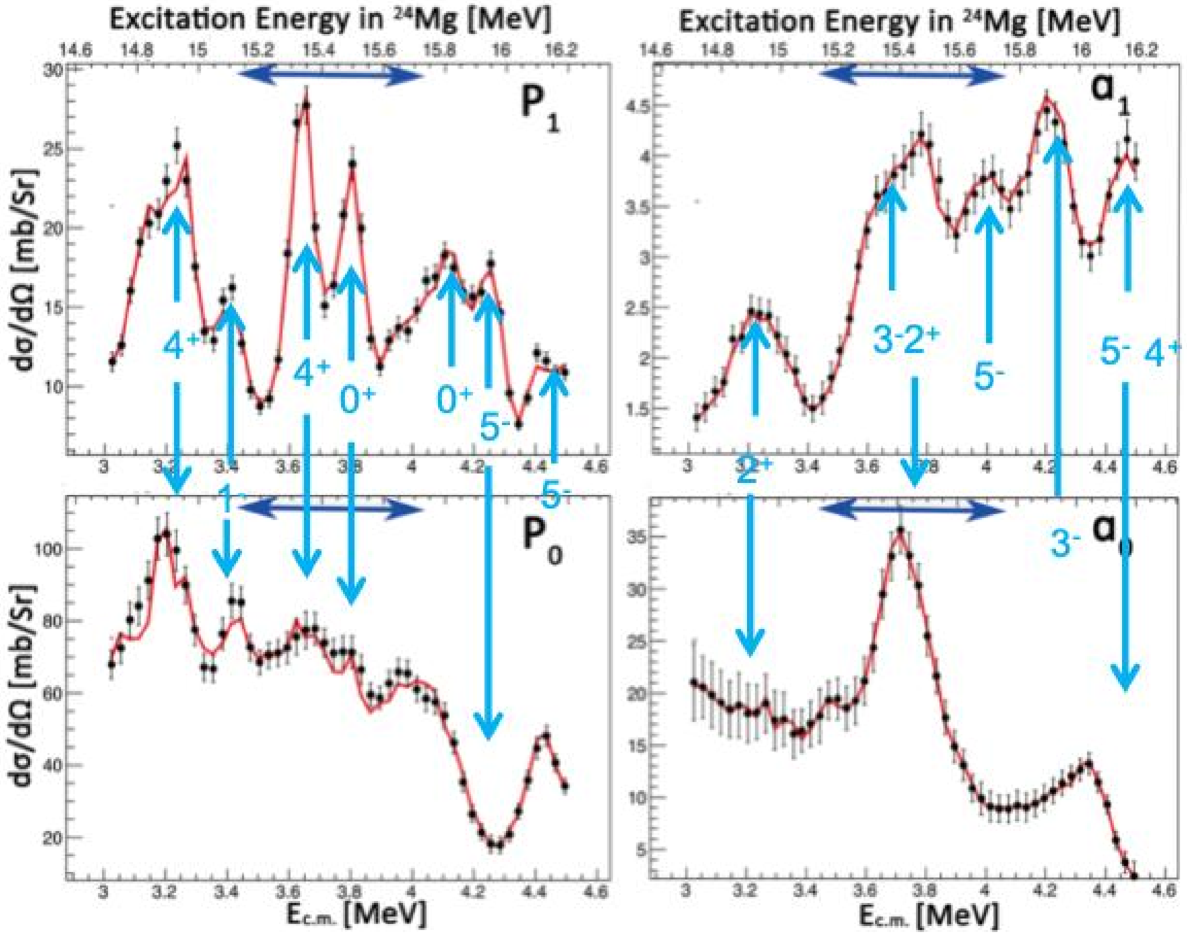
基于^{23}Na+p出射道激发函数的R矩阵分析

^{23}Na+p厚靶实验出射道R矩阵拟合



激发函数各峰值主要共振结合R-矩阵拟合结果在左图标出

^{23}Na+p作为入射道会引入共振的^{24}Mg共振态，需要提取其中的0^+，2^+共振态