Mapping the resonances of $^{12}C+^{12}C$ fusion at stellar energies using an efficient thick target method

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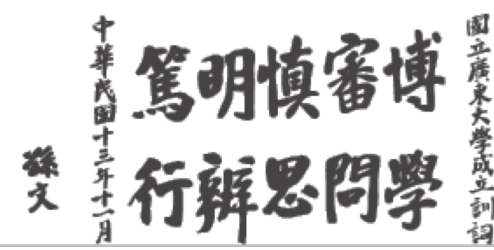

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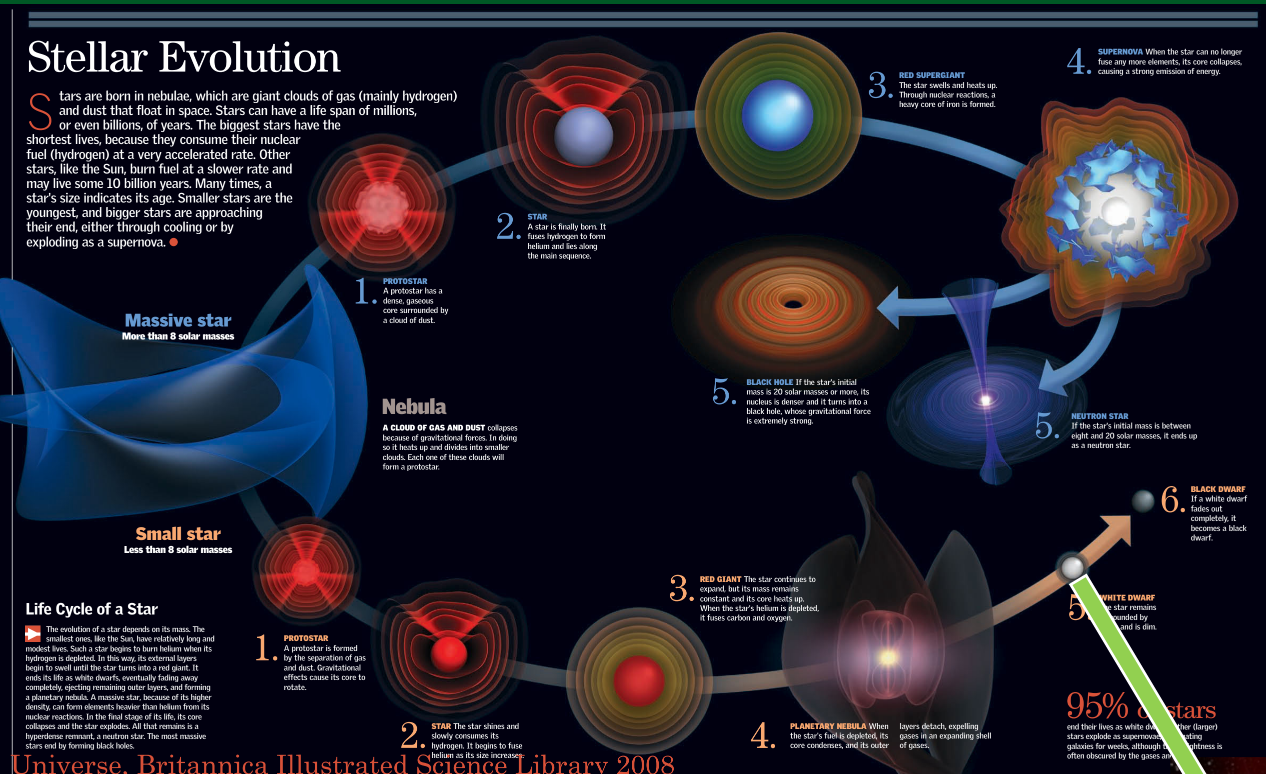
Outline

1. Role of carbon burning($^{12}C+^{12}C$) in stellar evolution
2. Introduction of $^{12}C+^{12}C$ studies
3. The principle of the efficient thick target method
4. Results and discussion
5. Summary

Role of $^{12}C+^{12}C$ in stellar evolution



Universe, Britannica Illustrated Science Library 2008

Massive star (more than 8 solar masses)

Evolutionary stages of a 25 $M_\odot$ star

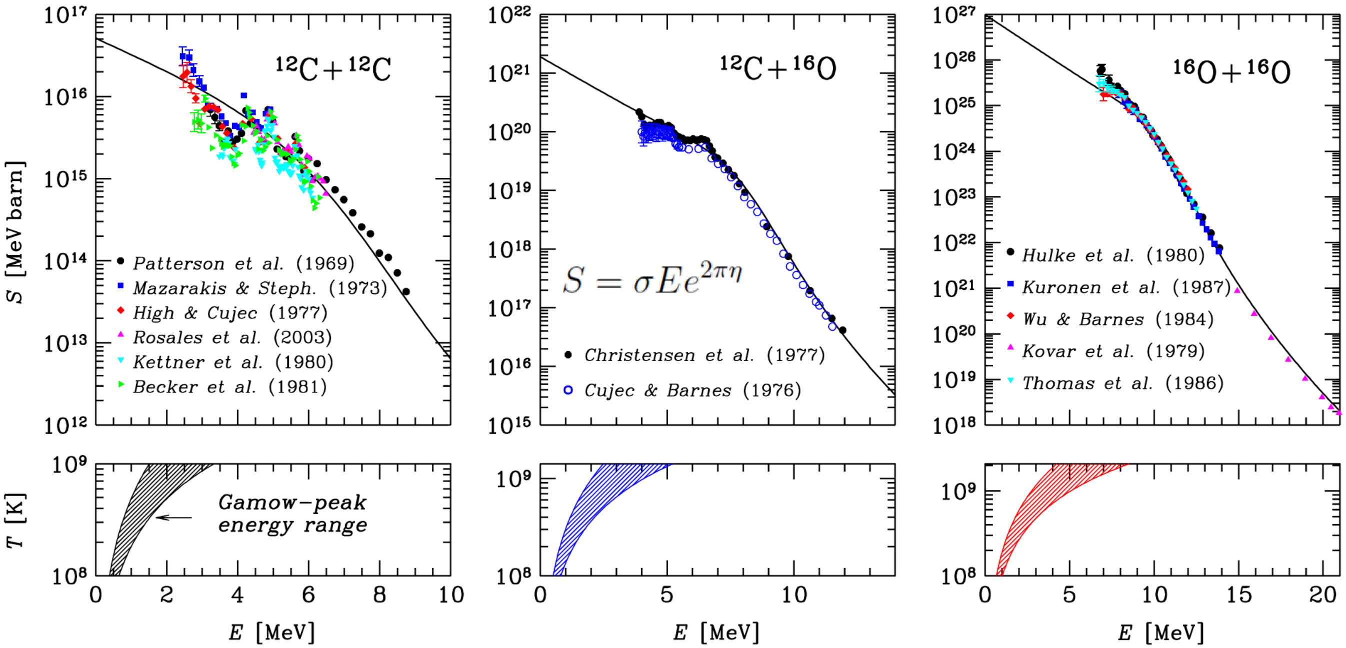
Stage	Time Scale	T9	Density (g cm^{-3})
Hydrogen burning	7×10^6 y	0.06	5
Helium burning	5×10^5 y	0.23	7×10^2
Carbon burning	600 y	0.93	2×10^5
Neon burning	1 y	1.7	4×10^6
Oxygen burning	6 months	2.3	1×10^7
Silicon burning	1 d	4.1	3×10^7
Core collapse	seconds	8.1	3×10^9
Core bounce	milliseconds	34.8	3×10^{14}
Explosive burning	0.1-10 s	1.2-7.0	Varies

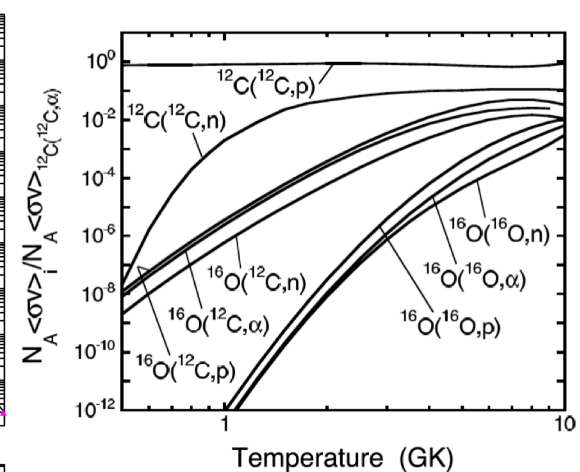
Type Ia supernova

Small star (less than 8 solar masses)

The $^{12}C+^{12}C$ fusion reaction at low energies plays important roles in the nucleosynthesis during stellar evolution of massive stars, and is considered to ignite a carbon-oxygen white dwarf into a type Ia supernova explosion.

Role of $^{12}C+^{12}C$ in stellar evolution





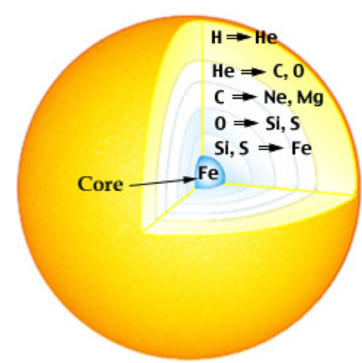
↑Astrophysical reaction rates of primary reaction channels of the $^{12}C+^{12}C$, $^{12}C+^{16}O$ and $^{16}O+^{16}O$ fusion.

↑Top: Astrophysical S factors vs. E_{cm} for the $^{12}C+^{12}C$, $^{12}C+^{16}O$, and $^{16}O+^{16}O$ reactions. Bottom: temperature T of stellar matter vs. Gamow-peak energy ranges for these reactions in the thermonuclear regime. (PRC 74, 035803,2006)

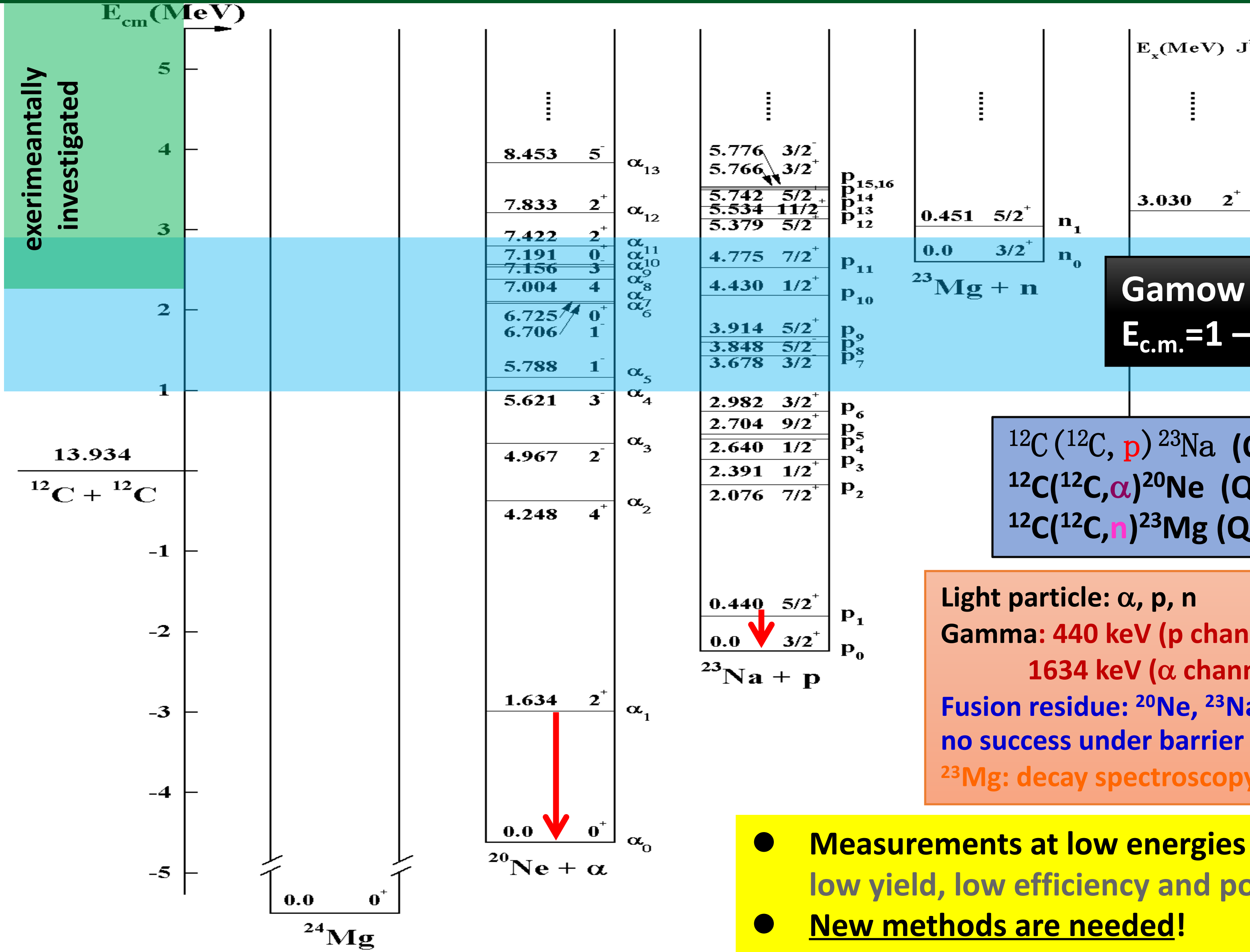
$^{12}C + ^{12}C \to p + ^{23}Na$ (Q = 2.238 MeV)
$^{12}C + ^{12}C \to \alpha + ^{20}Ne$ (Q = 4.616MeV)
$^{12}C + ^{12}C \to n + ^{23}Mg$ (Q = −2.599 MeV)

$^{12}C + ^{16}O \to p + ^{27}Al$ (Q = 5.170 MeV)
$^{12}C + ^{16}O \to \alpha + ^{24}Mg$ (Q = 6.772 MeV)
$^{12}C + ^{16}O \to n + ^{27}Si$ (Q = -0.424 MeV)

$^{16}O + ^{16}O \to ^{31}P + p$ (Q = 7.678MeV)
$^{16}O + ^{16}O \to ^{30}Si + 2p$ (Q = 0.381MeV)
$^{16}O + ^{16}O \to ^{28}Si + \alpha$ (Q = 9.594MeV)
$^{16}O + ^{16}O \to ^{24}Mg + 2\alpha$ (Q = -0.390MeV)
$^{16}O + ^{16}O \to ^{30}P + d$ (Q = -2.409MeV)
$^{16}O + ^{16}O \to ^{31}S + n$ (Q = 1.499MeV)



$^{12}C+^{12}C$ reaction channels: p, α, n



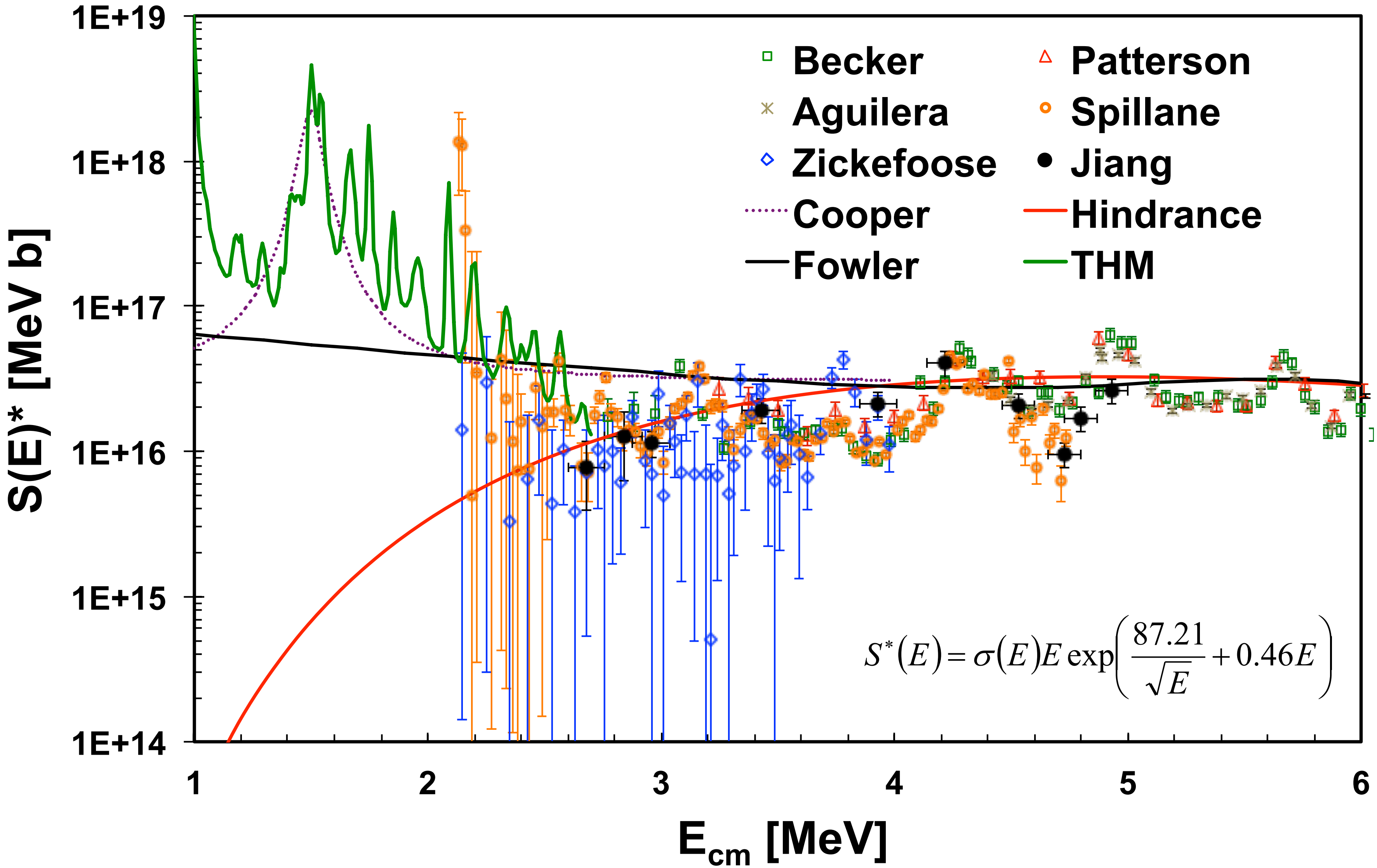
Gamow Window:
$E_{c.m.}$=1 – 3MeV

$^{12}C(^{12}C, p)^{23}Na$ (Q=2.24 MeV)
$^{12}C(^{12}C,\alpha)^{20}Ne$ (Q=4.62 MeV)
$^{12}C(^{12}C,n)^{23}Mg$ (Q=-2.62MeV)

Light particle: α, p, n
Gamma: 440 keV (p channel)
1634 keV (α channel)
Fusion residue: ^{20}Ne, ^{23}Na …
no success under barrier
^{23}Mg: decay spectroscopy

- **Measurements at low energies suffered from low yield, low efficiency and poor selectivity.**
- **<u>New methods are needed</u>!**

Review of previous work studying $^{12}C+^{12}C$



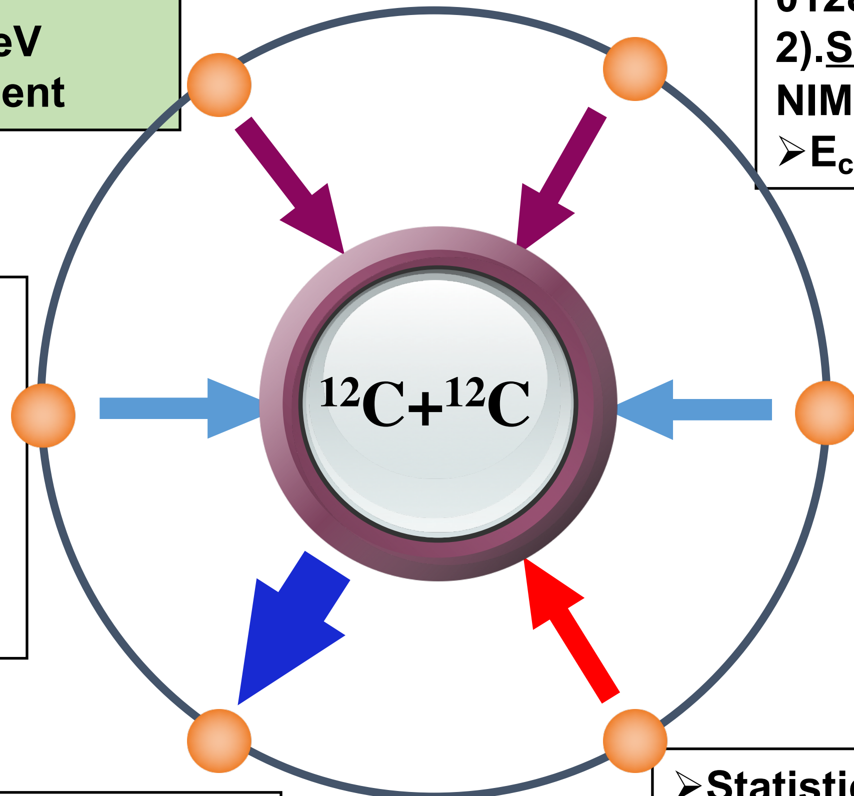
Carbon burning determination project

- Efficient thick target method
  arXiv:1905.02054
- E_{cm} = 3.0 – 5.3 MeV
- Direct Measurement

- Direct Measurement:

1). Particle-gamma coincidence
NIM A 682 (2012) 12–15, PRC 97, 012801(R) (2018)
2). Solenoid spectrometer
NIM A 871 (2017) 35–41

- E_{cm} = 1.7 – 3.0 MeV



- $^{12}C+^{13}C$, $^{13}C+^{13}C$: PRC 85, 014607 (2012)
- Set upper limit for possibly existed resonances of $^{12}C+^{12}C$

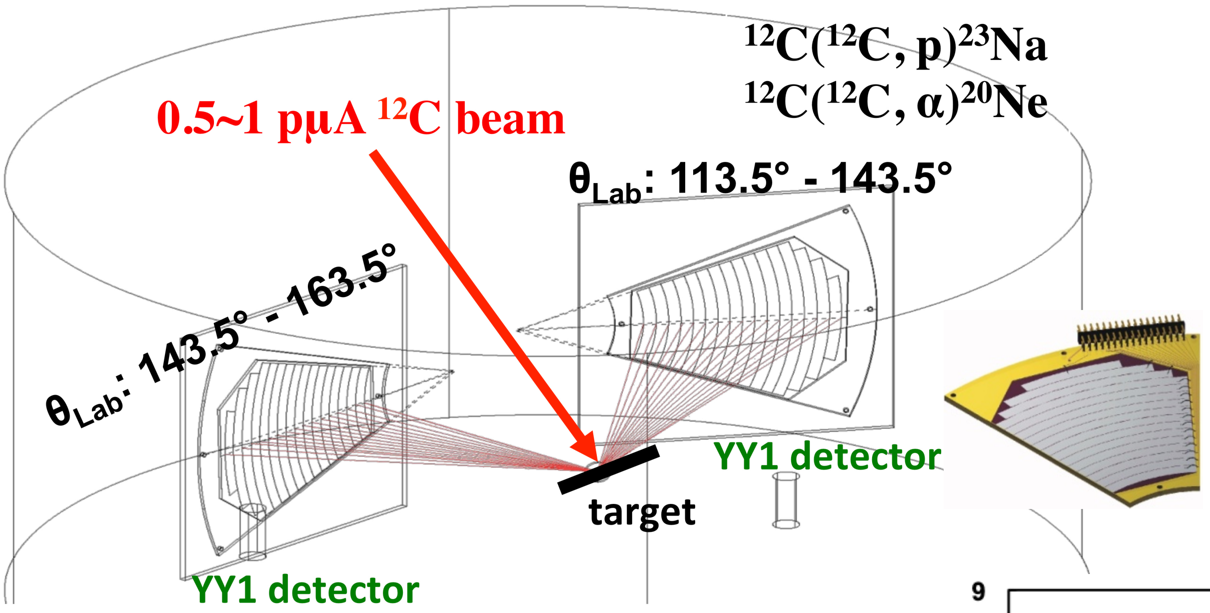
- Indirect method: $^{24}Mg(\alpha, \alpha')$ inelastic scattering
- Search the possible resonances which can't be directly measured
- E_{cm} < 1.7 MeV

- Resonances 2 – 3 MeV
- Cross section within Gamow window (1 – 3MeV): 10^{-22}b ~10^{-7}b

- Statistical model
- Calculate gamma-ray branching ratios, to give total cross section

$^{12}C(^{12}C,n)^{23}Mg$: PRL 114, 251102 (2015)

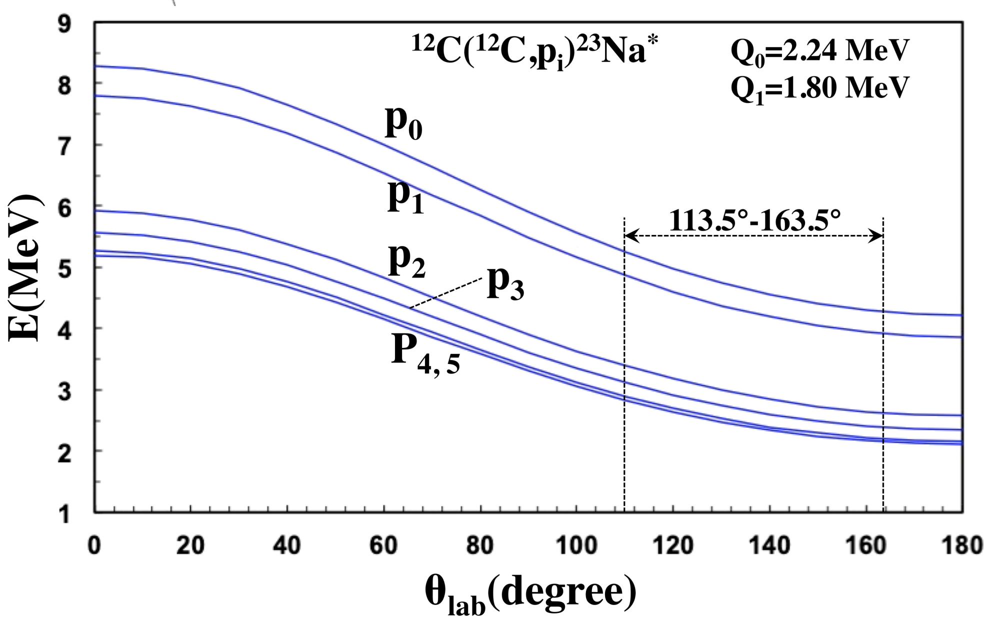
The setup of the thick target method



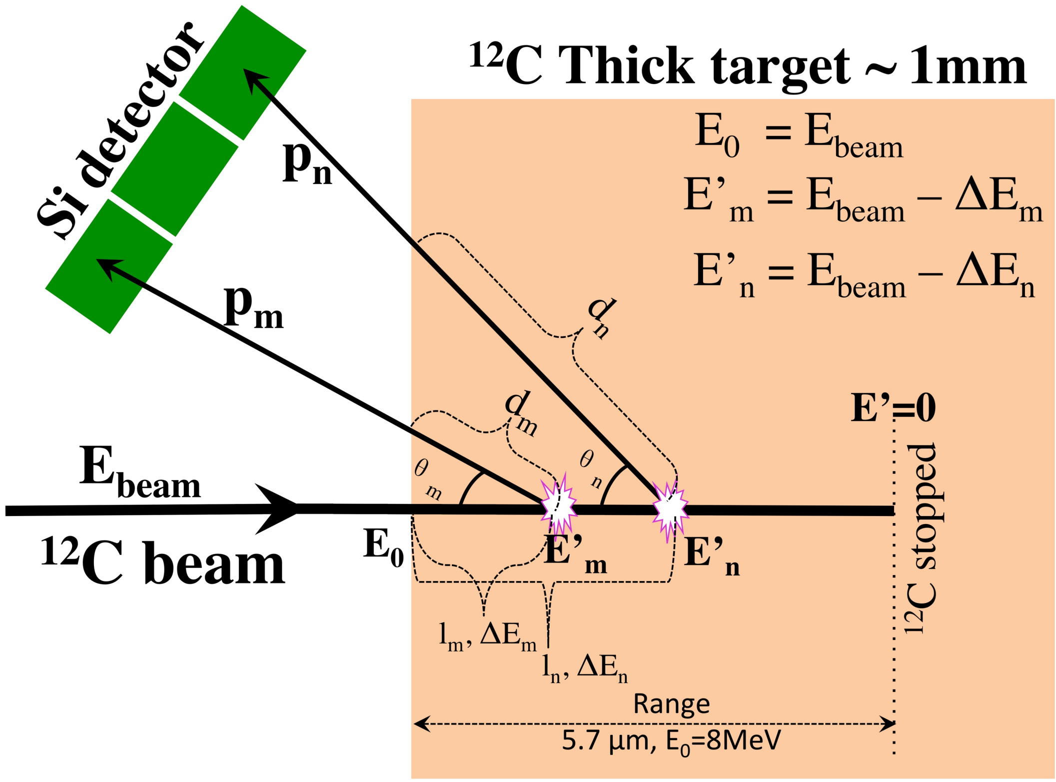
The backward angle
θ_{Lab}: 113.5° - 163.5°
θ_{cm}: 122.5° - 166.3°

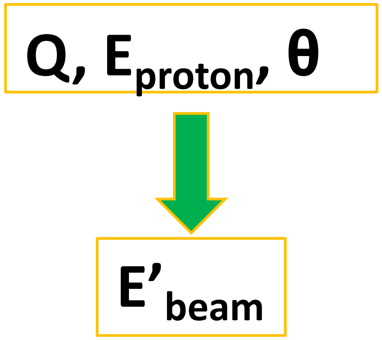
Solid angle calibrated by mixed alpha source 2.59%

- Only measure proton channel
- Two YY1 silicon detectors at backward angle, covered with Aluminum foil to stop scattered ^{12}C and produced alpha particles
- Use thick target of thickness 1mm
- Detector resolution for 5.486 MeV alpha particles is 40 keV(FWHM).



The principle of the thick target method





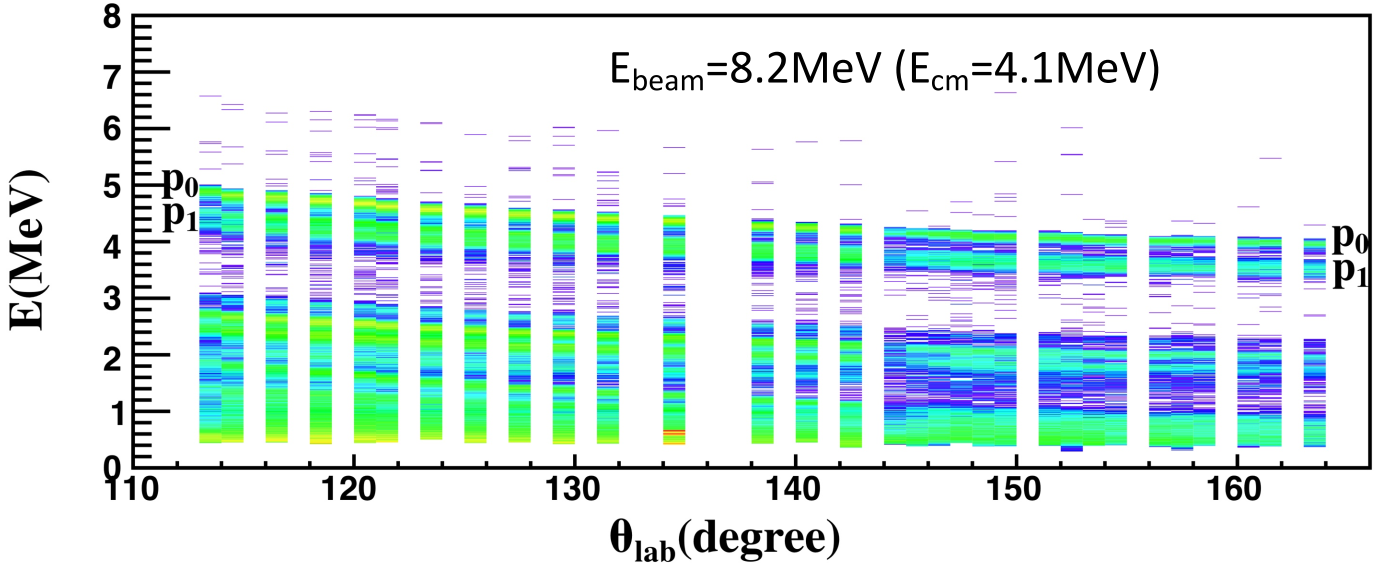
Q_0=2.238 MeV
Q_1=2.238-0.44=1.798 MeV
Q_2=2.238-2.076=0.162 MeV
......

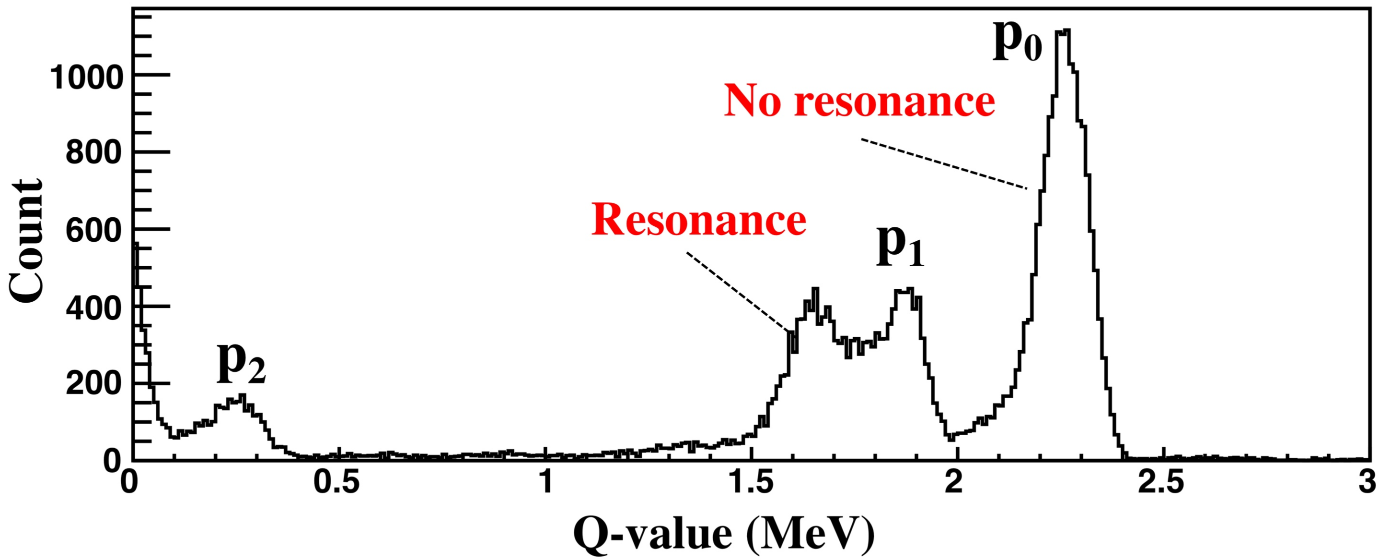
$^{12}C(^{12}C, p)^{23}Na$

$Q=Q_{n=0,1,2,3}$=2.238 MeV - $E_{excited}$ (^{23}Na)

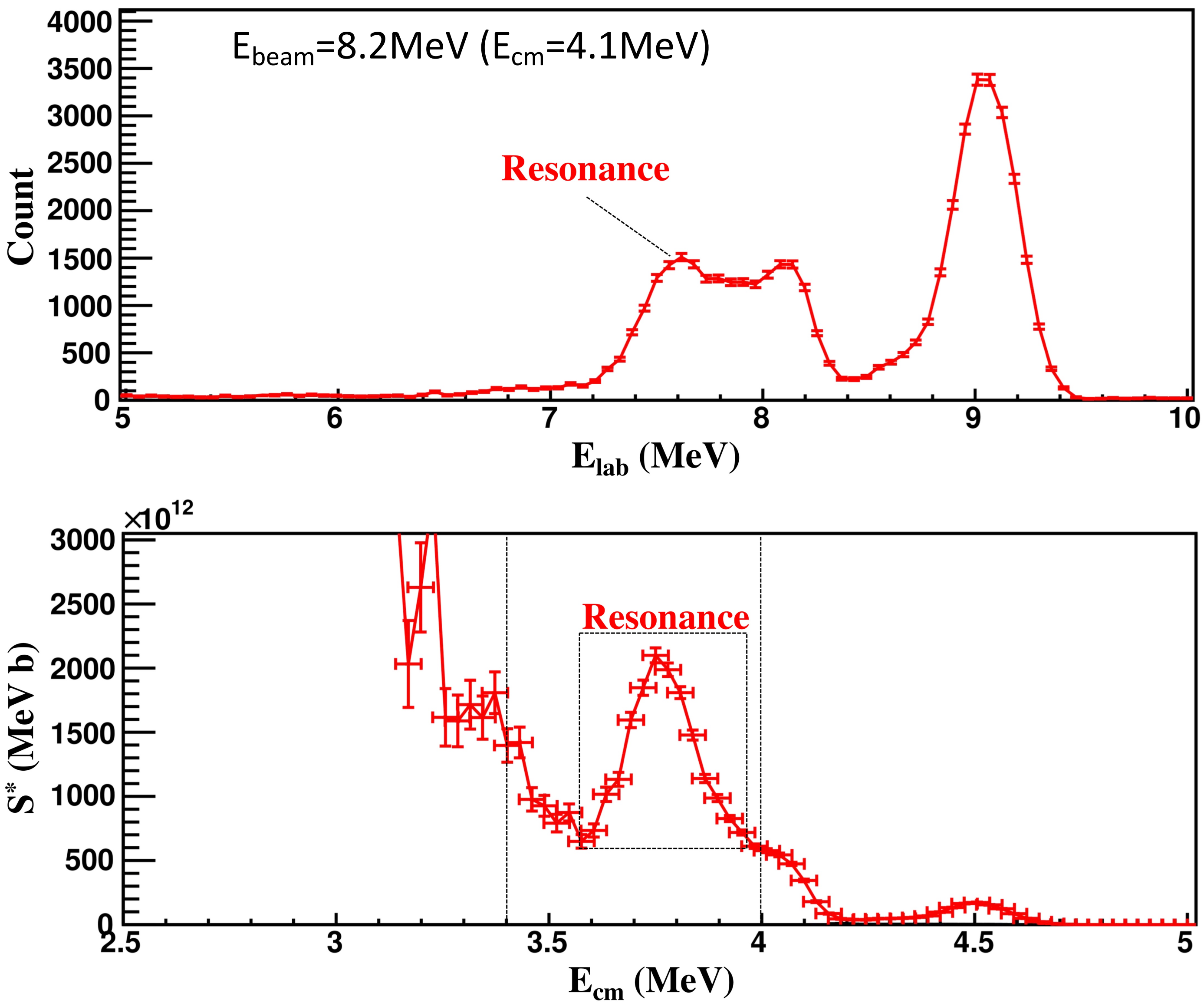
$$Q = (\frac{M_a}{M_B} - 1)E_a + (\frac{M_b}{M_B} + 1)E_b - 2\frac{\sqrt{M_a M_b E_a E_b}}{M_B} cos(\theta)$$

The principle of the thick target method

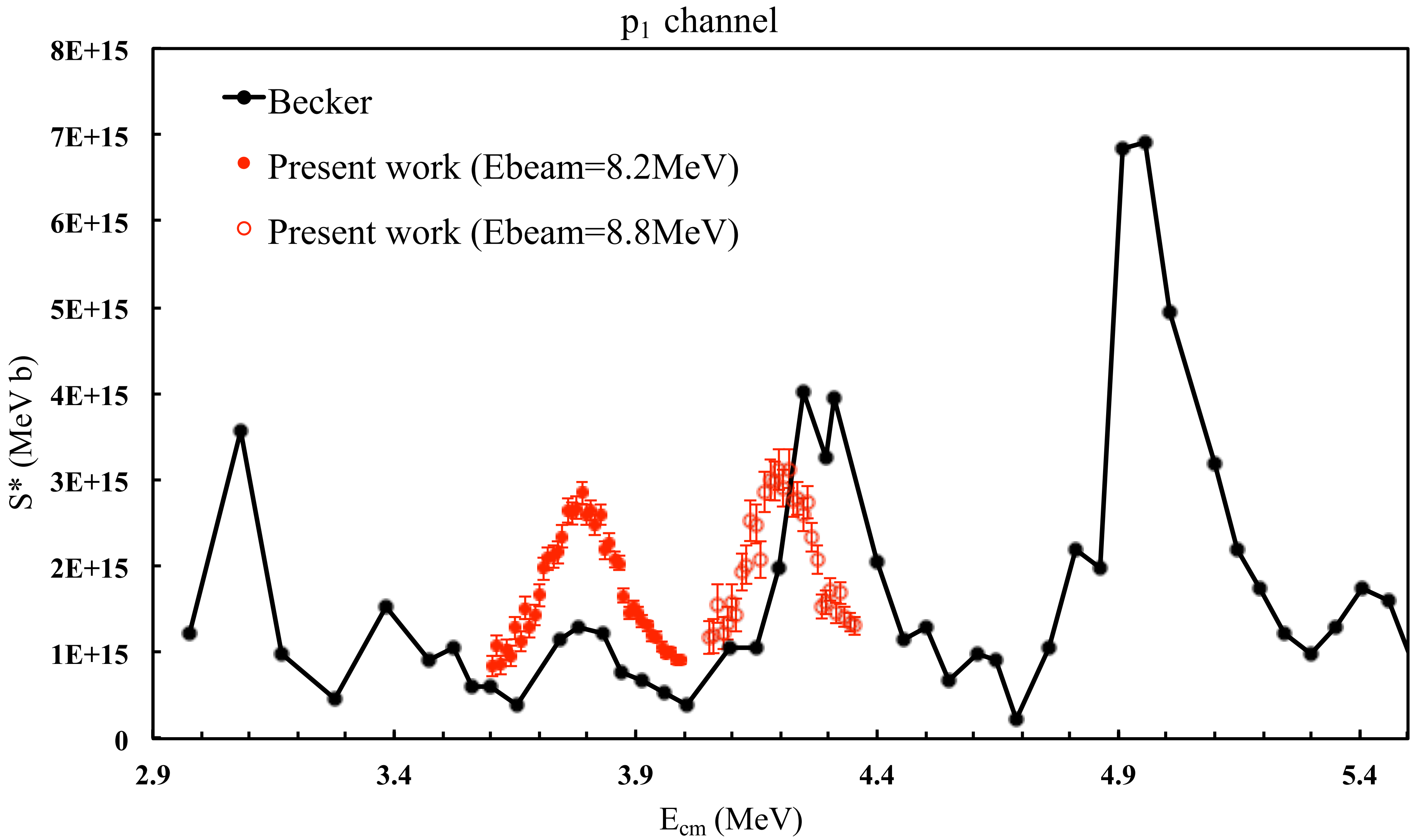




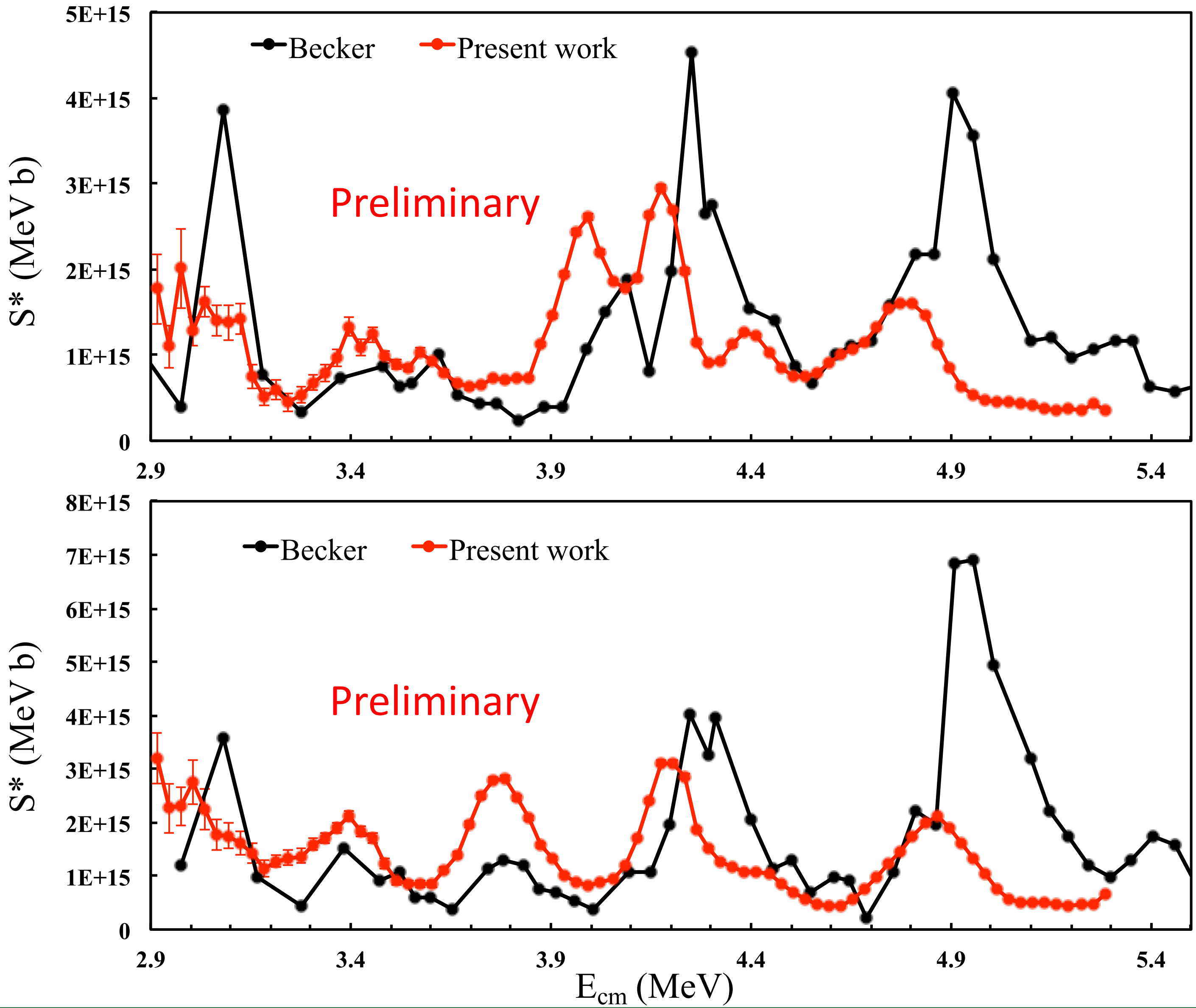
The principle of the thick target method



The S* factor of p_1 channels



The scanned S* factor of p_0 and p_1 channels

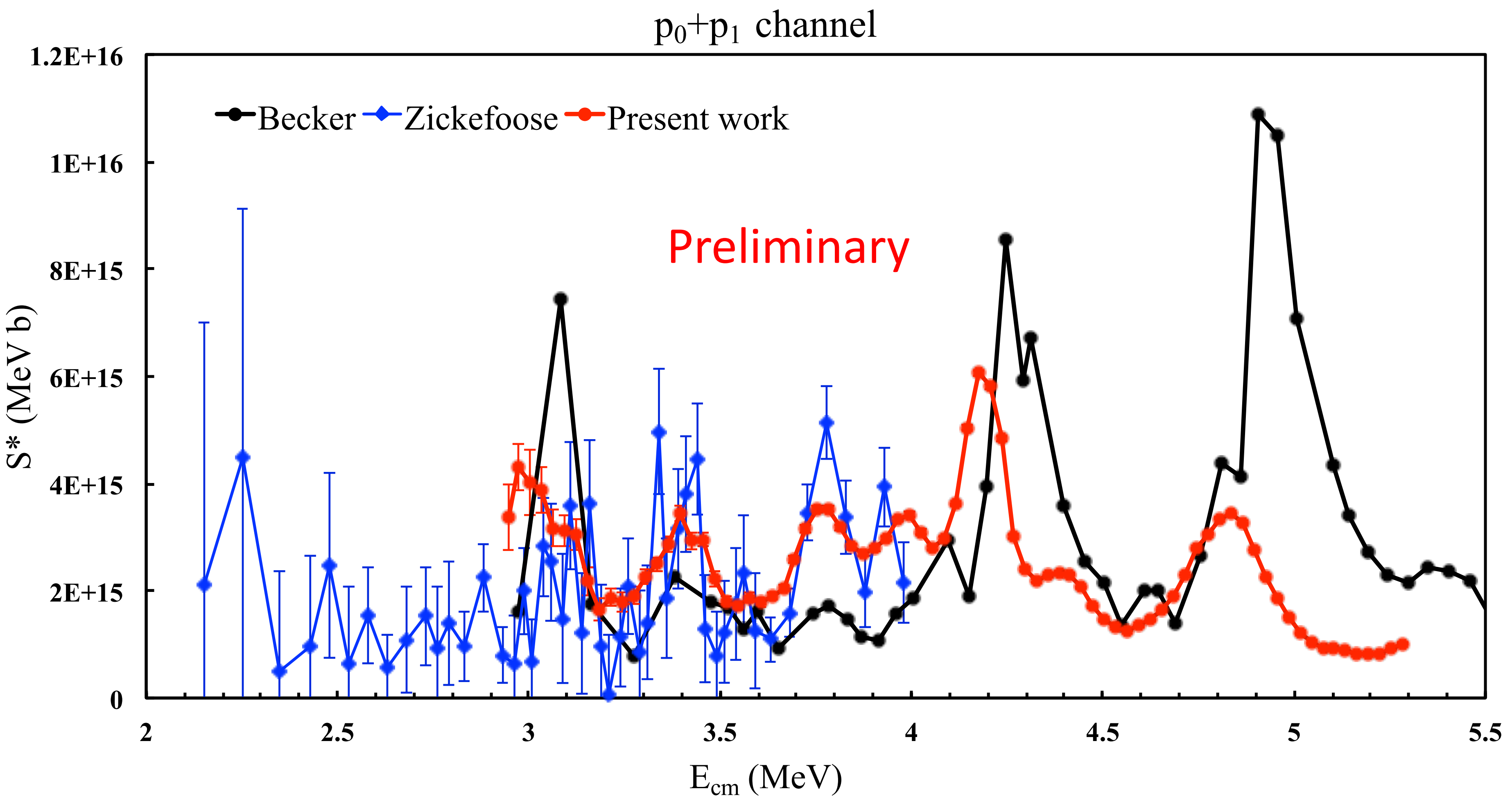


p_0 channel

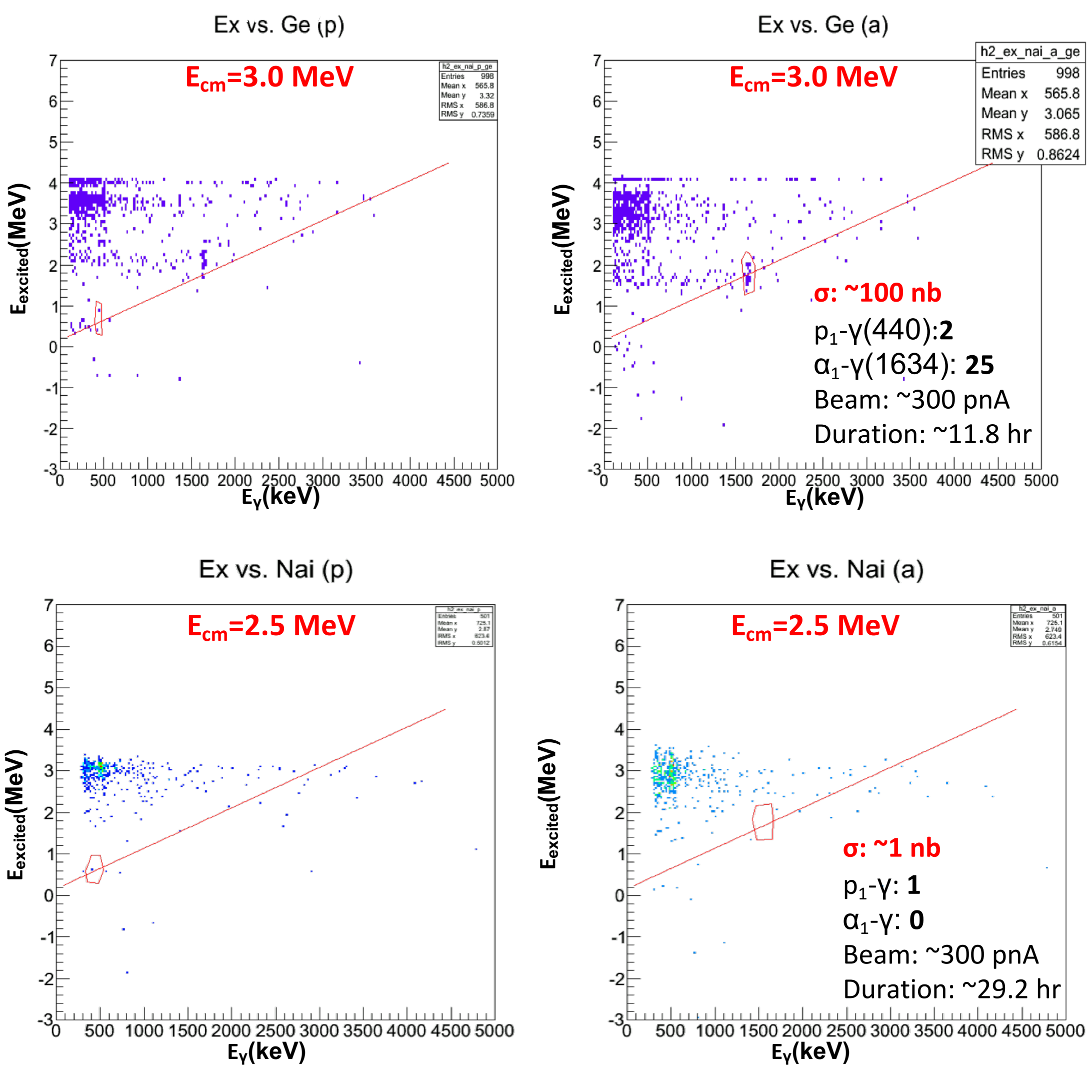
p_1 channel

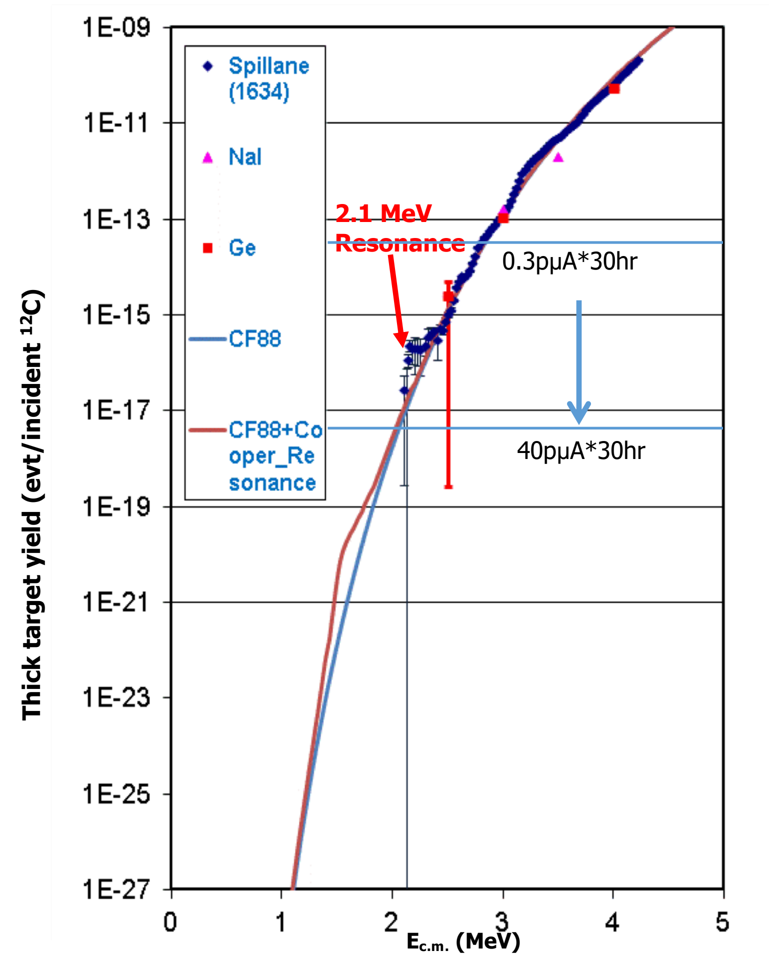
The S* factor of $p_0 + p_1$ channel

Scan the $^{12}C + ^{12}C$ using ^{12}C beam of energies E_{beam}=6.0--10.6 MeV by step 0.1 MeV.



Particle–gamma coincidence measurement





Summary

- The $^{12}C+^{12}C$ fusion reaction is famous for its complication of molecular resonances, and plays an important role in both nuclear structure and astrophysics. It is extremely difficult to measure the cross sections of $^{12}C+^{12}C$ fusions at energies of astrophysical relevance due to very low reaction yields.
- An efficient thick target method has been developed and applied for the first time to measure the complicated resonant structure existing in $^{12}C(^{12}C,p)^{23}Na$ at energies 3.0 MeV<E_{cm}<5.3 MeV.
- It can provide cross sections within a range of [E_{beam} -ΔE, E_{beam}] using a single incident energy E_{beam}.
- The efficient thick target method of the present work will be useful in searching for potentially existing resonances of $^{12}C+^{12}C$ in the energy range 1 MeV<E_{cm}<3 MeV.
- Future plan: Particle–gamma coincidence measurement for $^{12}C(^{12}C,p)^{23}Na$ and $^{12}C(^{12}C,\alpha)^{20}Ne$.

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