Indirect measurements of astrophysical nuclear reactions using Q3D magnetic spectrometer

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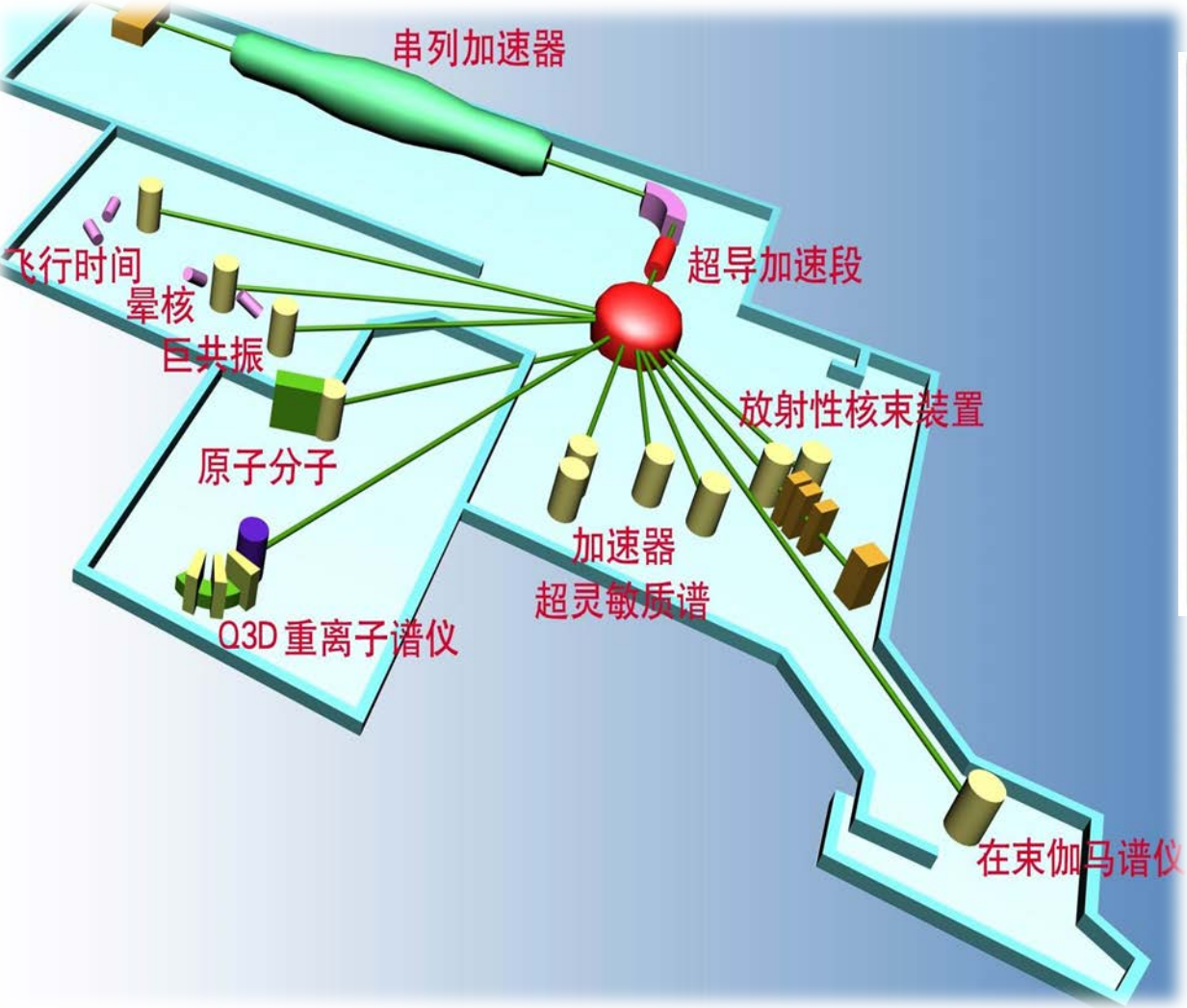
Nuclear Astrophysics at Rings and Recoil Separators GSI·Darmstadt

Outline

- The Q3D magnetic spectrometer
- Indirect measurement of the astrophysical nuclear reactions
  - One-nucleon transfer reactions
  - Elastic scattering reactions
  - Alpha-transfer reactions
- The future plan of Recoil mass separator at CIAE

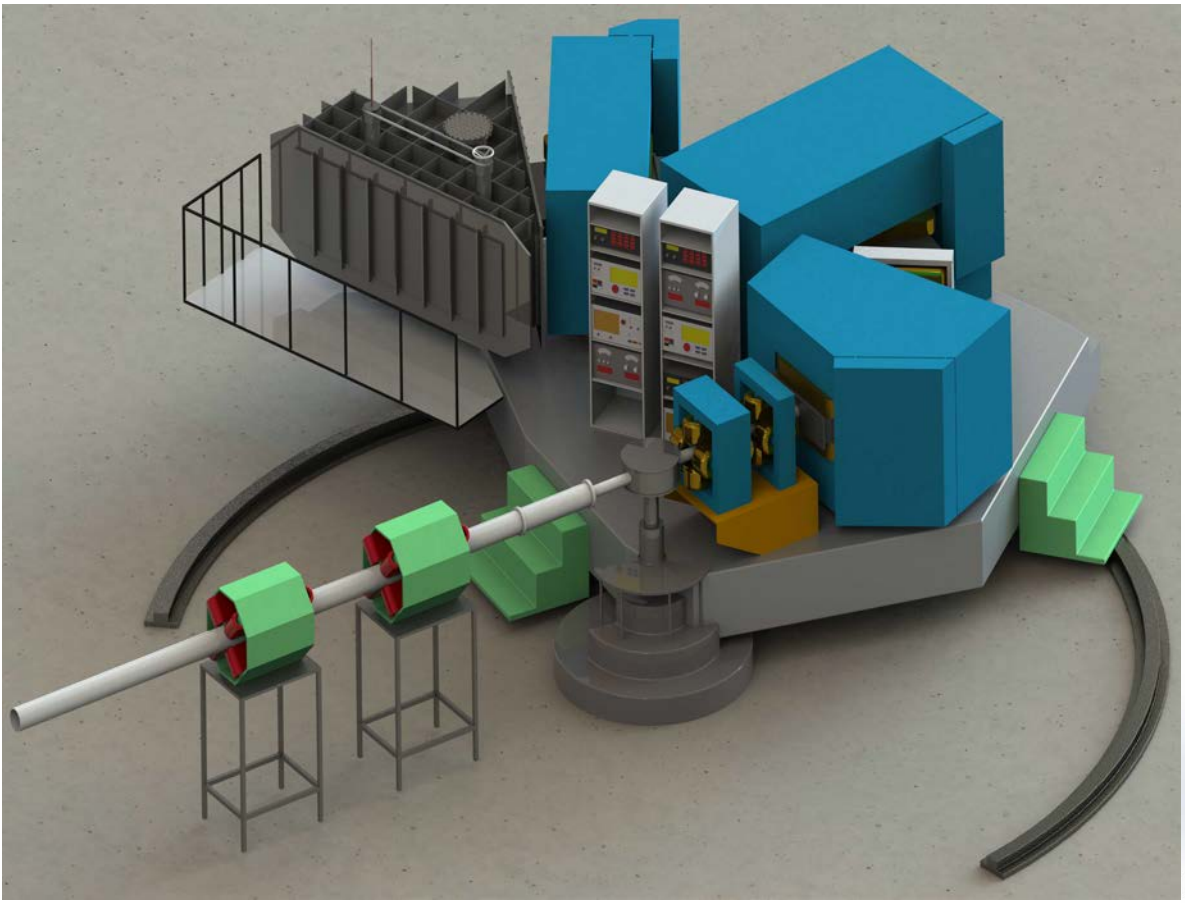
Hi-13 Tandem accelerator , Beijing

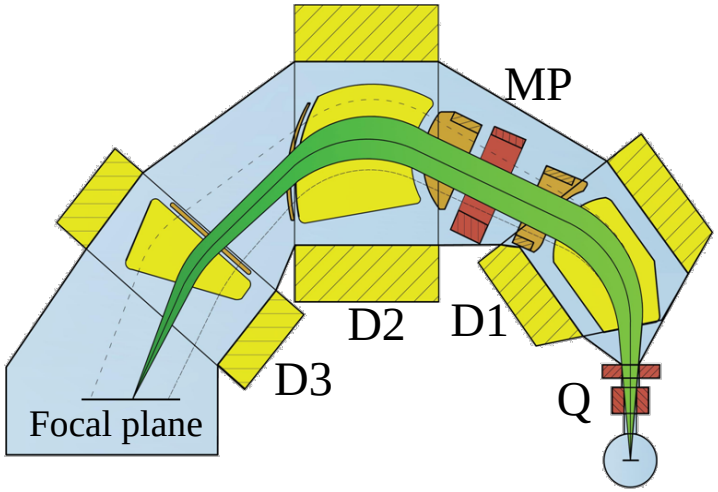


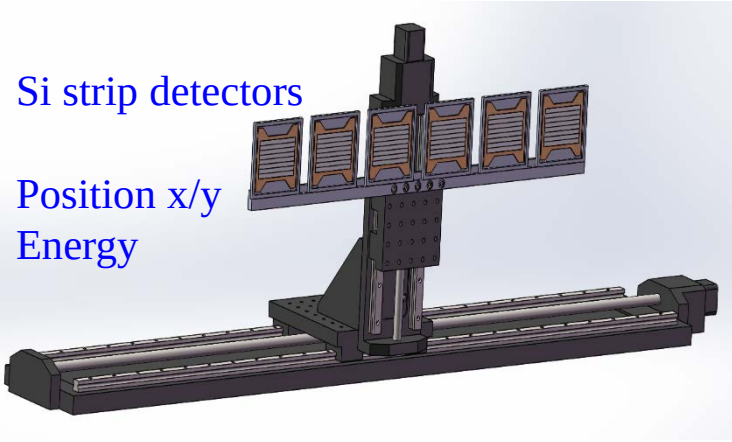
Build in 1987

Upgraded in 2017
(Proton Cyclotron Energizer unit)

The Q3D magnetic spectrometer







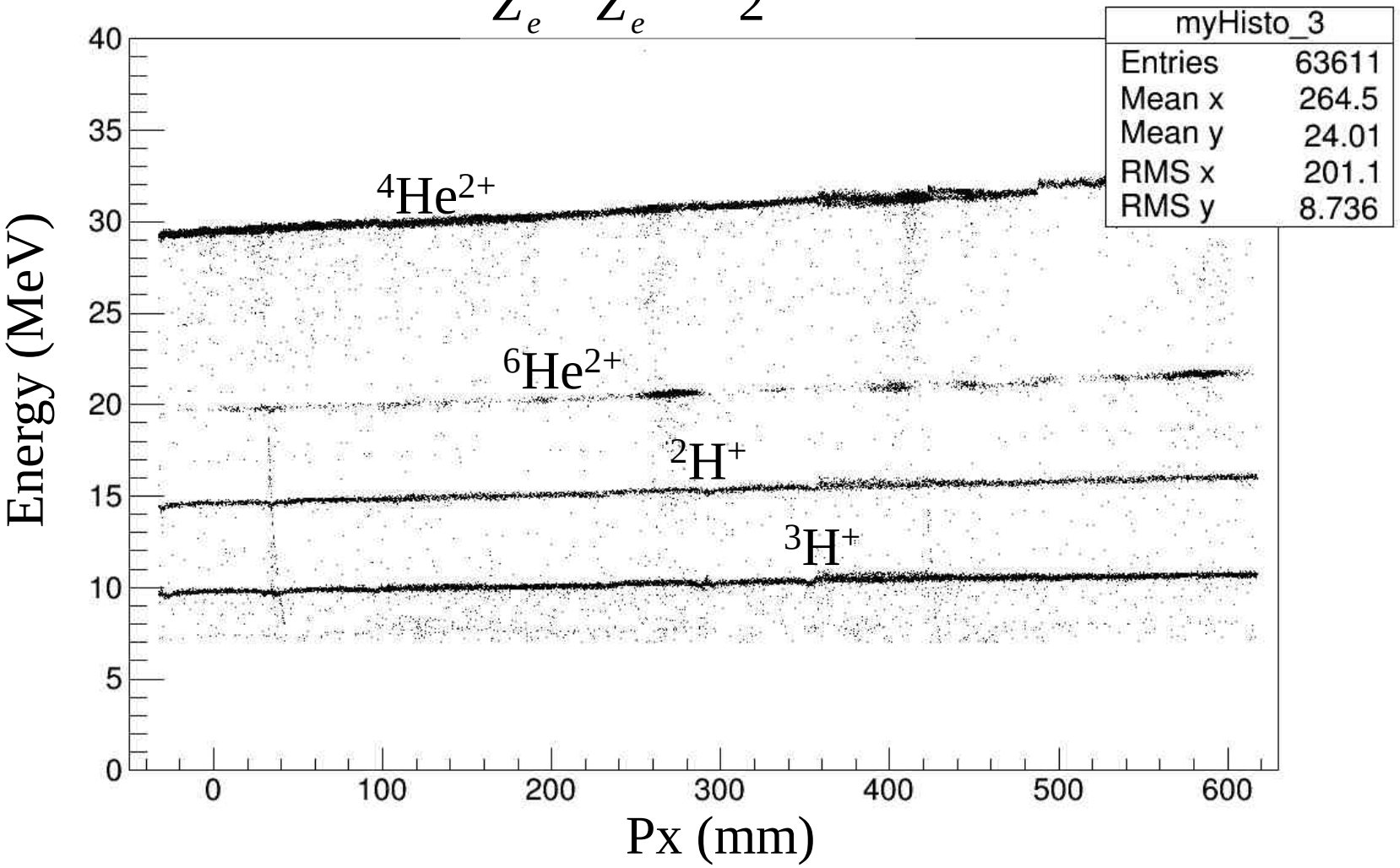
Focal plane detectors

Energy resolution： 2×10^{-4} Angle range: 0-180

Measurement the angular distribution with high resolution

Two-dimensional scatter plot of focal plane detectors

$$(\frac{M}{Z_e})(\frac{E}{Z_e}) = \frac{1}{2}(B\rho)^2$$



The indirect method

$$\sigma_{\mathrm{rc}} = \frac{16\pi}{9}\left(\frac{E_\gamma}{\hbar c}\right)^3 \frac{e_{\mathrm{eff}}^2}{k^2}\frac{1}{\hbar v}\frac{(2I_f+1)}{(2I_1+1)(2I_2+1)} S_{l_f j_f}\left|\int_0^\infty r^2 w_{l_i}(kr)u_{l_f}(r)dr\right|^2$$

Measure the transfer reaction
^{12}C(^{7}Li,^{6}He)^{13}N

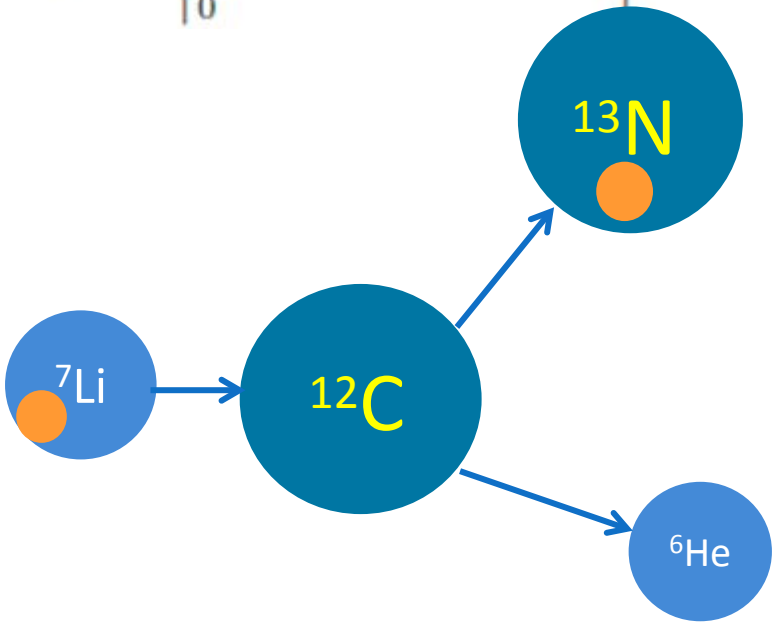
Potential parameters

$$\left(\frac{d\sigma}{d\Omega}\right)_{exp} = S_b S_B \left(\frac{d\sigma}{d\Omega}\right)_{cal}$$

Extract the spectroscopic factor
$S_{^{13}N}$

Nuclear theory — direct capture

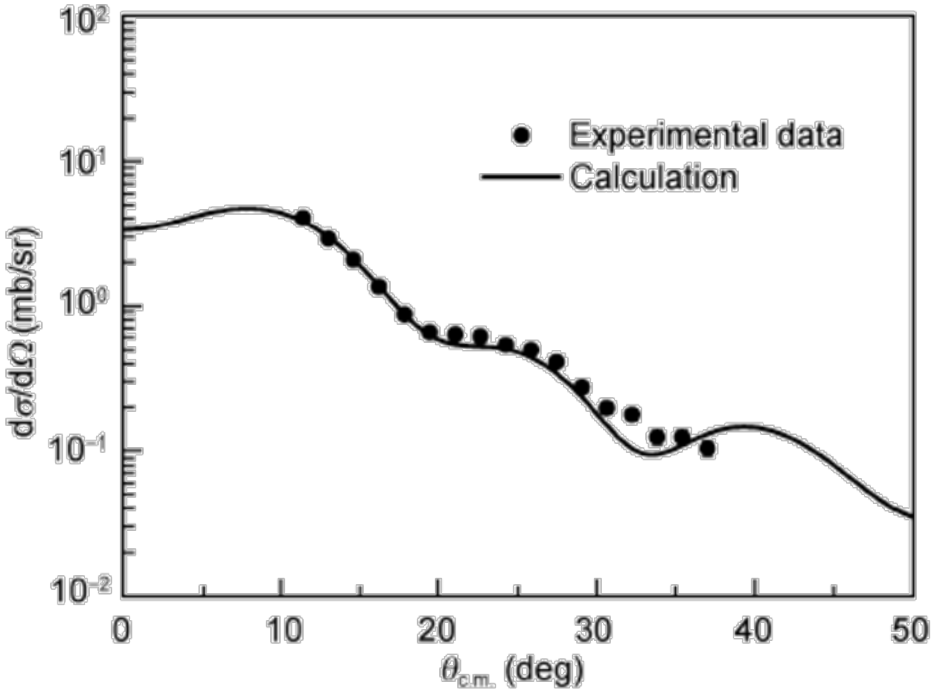
Radiative capture reactions
^{12}C(p, γ)^{13}N



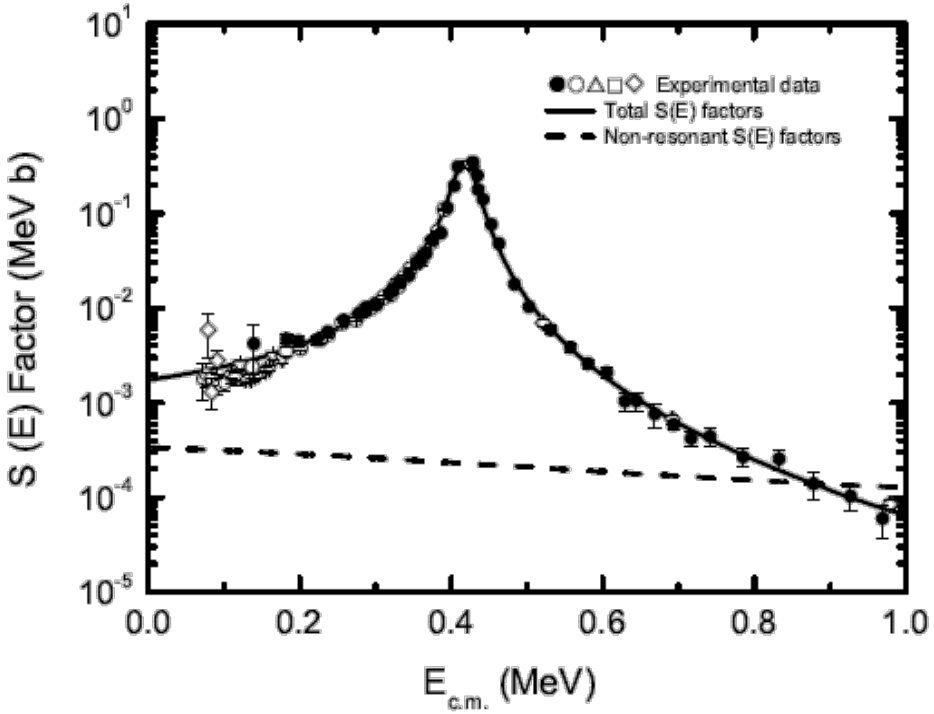
The cross section of transfer reaction is several orders of magnitude larger than that of radiative capture reaction

Resonance: $\gamma_B^2 = \frac{\hbar^2 R_c}{2\mu} S_B \phi(R_c)^2$

$^{12}C(p,\gamma)^{13}N$ astrophysical S(E) factors



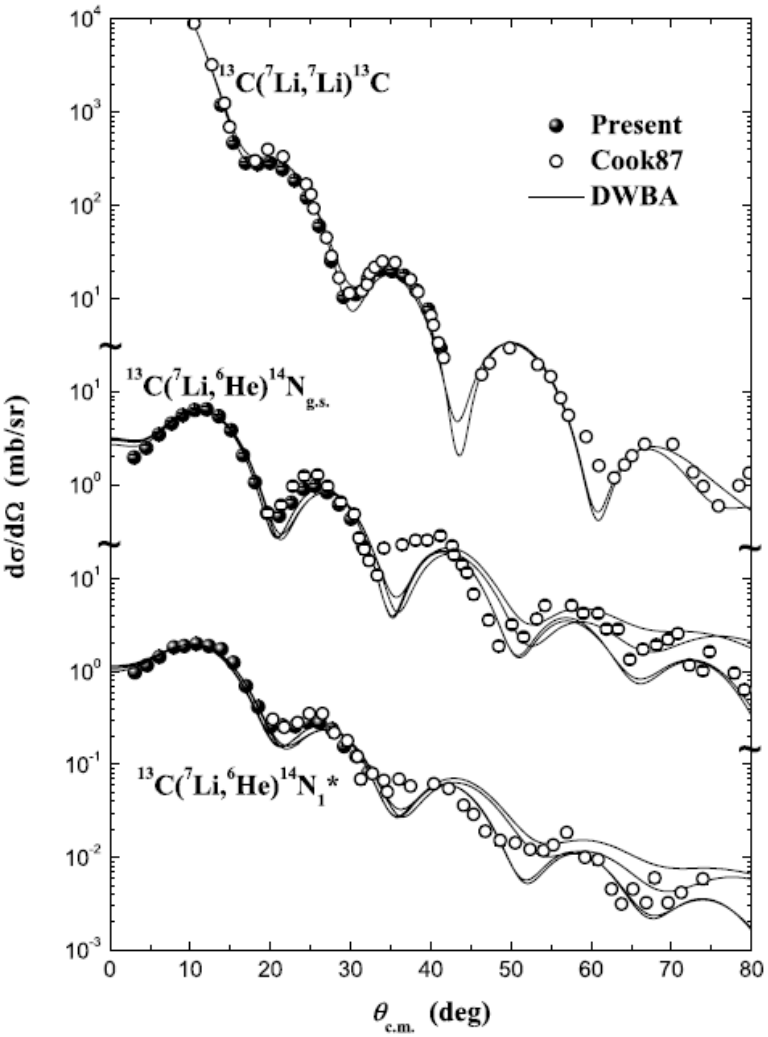
$^{12}C(^{7}Li,^{6}He)^{13}N$ angular distribution



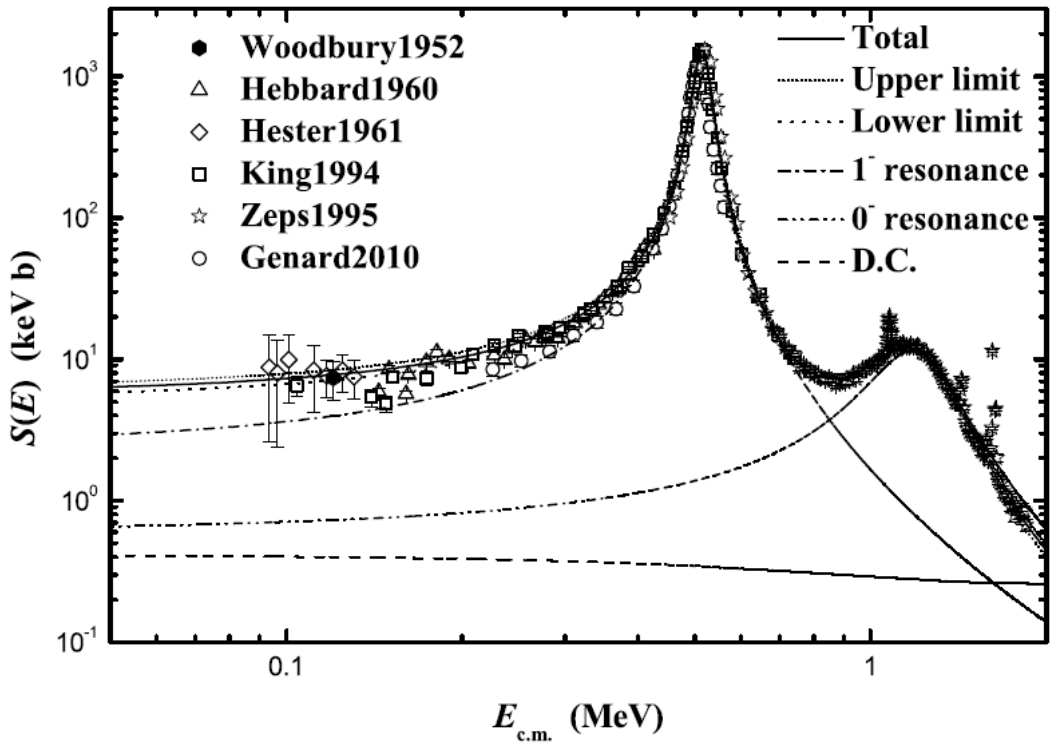
$^{12}C(p, \gamma)^{13}N$ astrophysical S(E) factors

Z.H. Li et al. Nucl. Phys. A 834 (2010) 661c–663c

$^{13}C(p, \gamma)^{14}N$ astrophysical S(E) factors



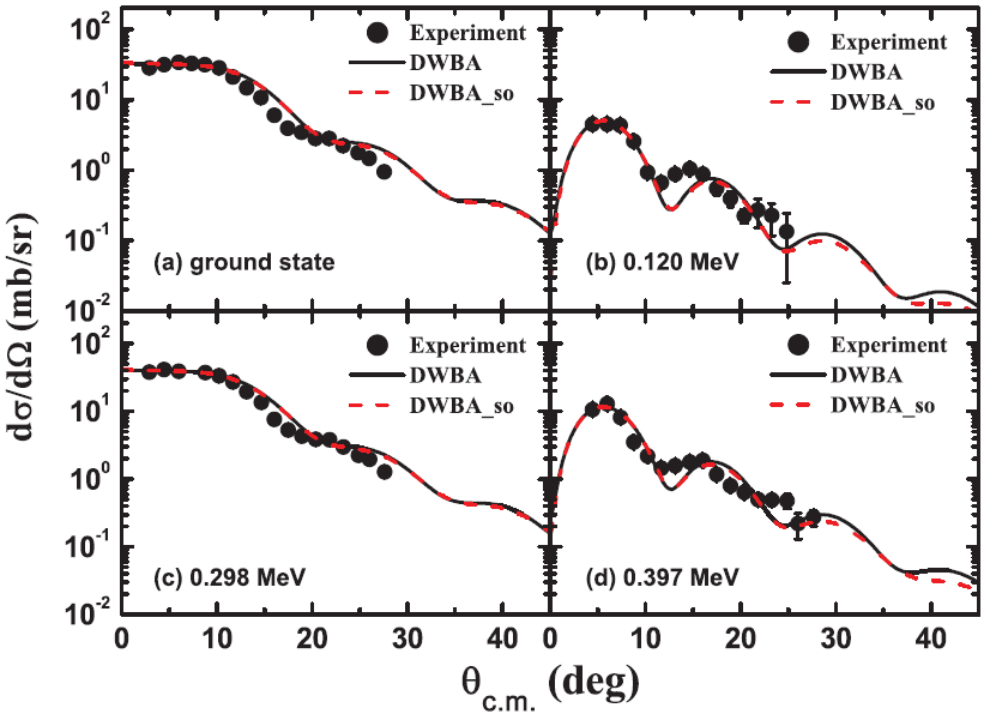
angular distributions



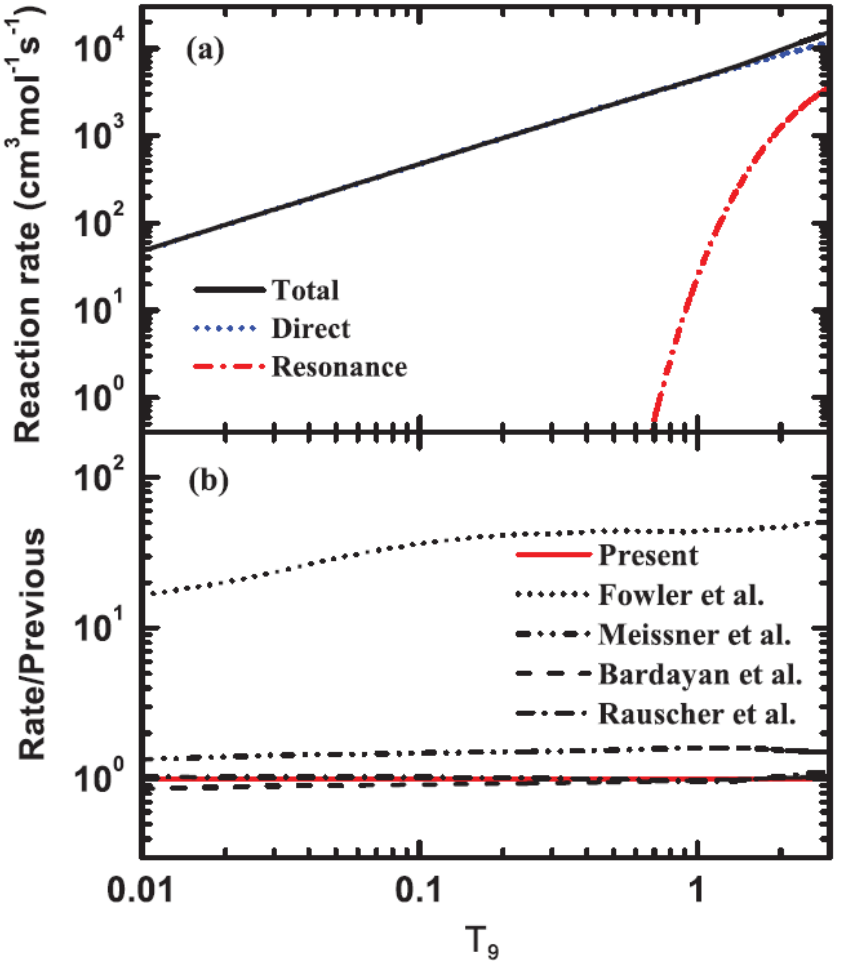
$^{13}C(p, \gamma)^{14}N$ astrophysical S(E) factors

Y.J. Li et al. Eur. Phys. J. A (2012) 48: 13

$^{15}N(n, \gamma)^{16}N$ astrophysical reaction rates



$^{15}N(^{7}Li,^{6}Li)^{16}N$ angular distributions



$^{15}N(n,\gamma)^{16}N$ reaction rate

B. Guo et al., Phys. Rev. C **89**, 012801(R) (2014)

The elastic transfer reactions

- A(B,A)B

^{7}Li(^{6}Li, ^{7}Li)^{6}Li, ^{13}C(^{12}C,^{13}C)^{12}C, ^{12}C(^{11}B,^{12}C)^{11}B

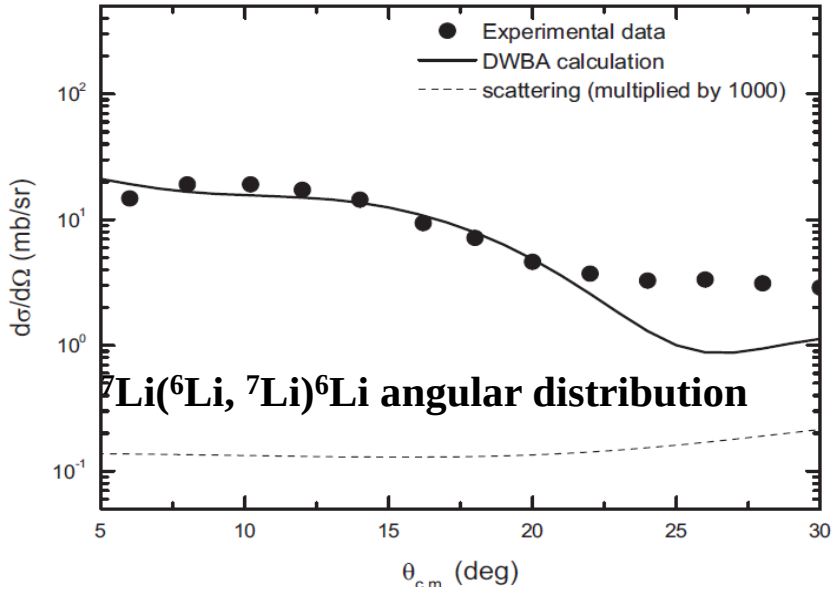
- Exist channel is same as the entrance channel
- Q-value of the reaction is zero

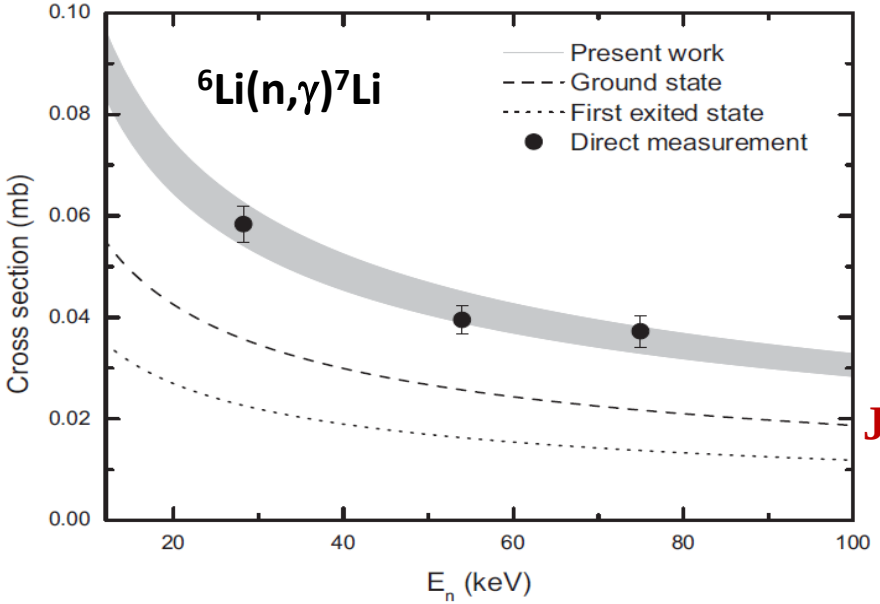
The channels are with the same potential parameters

$$\sigma_{exp} = S_B^2 . \sigma_{th}$$

The extracted spectroscopic factor has small uncertainty

$^{7}Li(^{6}Li, ^{7}Li)^{6}Li$ elastic transfer reaction



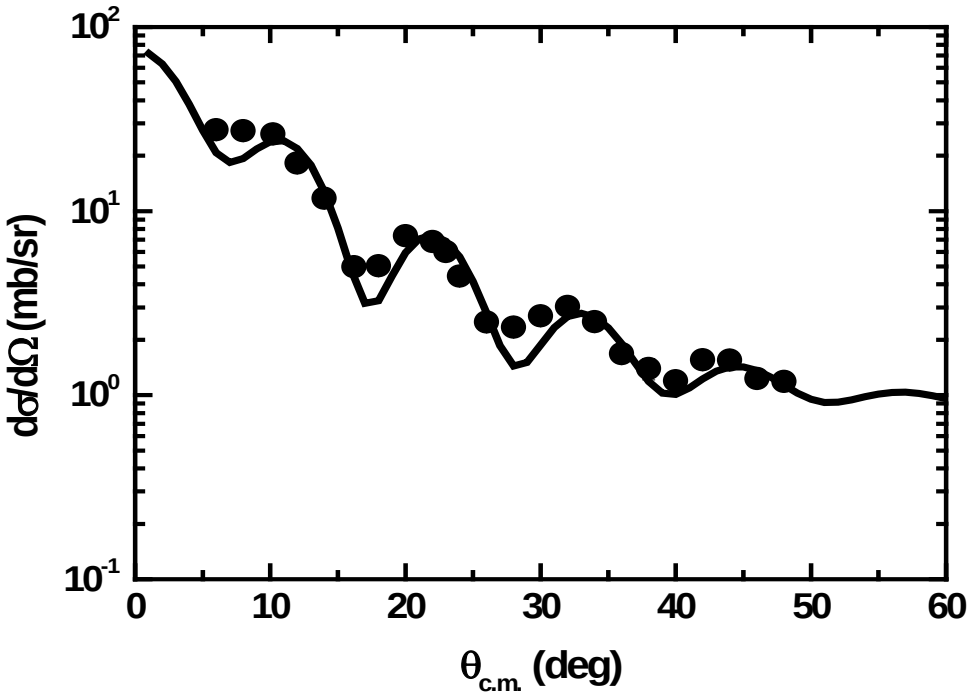


Neutron spectroscopic factor in ^{7}Li

$S_{^7Li_{g.s.}}$	$S_{^7Li_{0.48}}$	Experiments or theory	Reference
0.72	0.89	theory	[54]
0.80	0.98	theory	[56]
0.79	0.97	theory	[57]
0.77	1.07	theory	[58]
0.90	1.15	$^{6}Li(d,p)$	[38]
0.71		$^{7}Li(p,d)$	[39]
0.72 ± 0.1		$^{7}Li(p,d)$	[40]
0.87		$^{7}Li(p,d)$	[41]
1.85 ± 0.37		$^{6}Li(d,p)$	[42]
0.78 ± 0.04	1.02 ± 0.07	$^{7}Li(^{6}Li,^{7}Li)$	present work

J. Su et al. CHIN. PHYS. LETT. 27 (2010) 052101

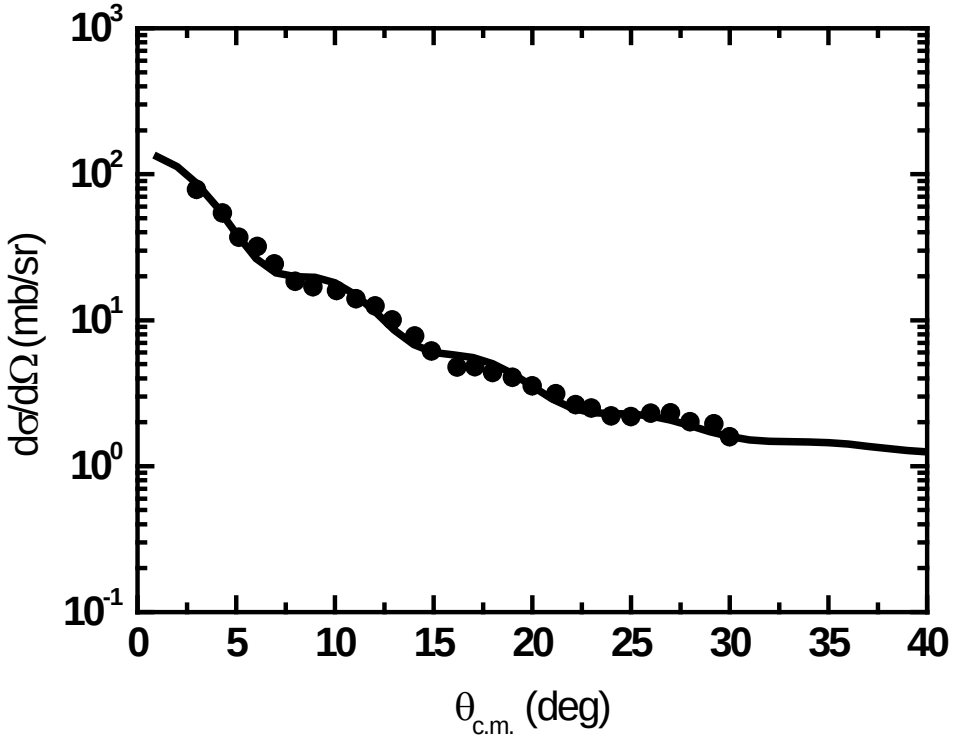
$^{12}C(^{11}B,^{12}C)^{11}B$ elastic transfer reaction



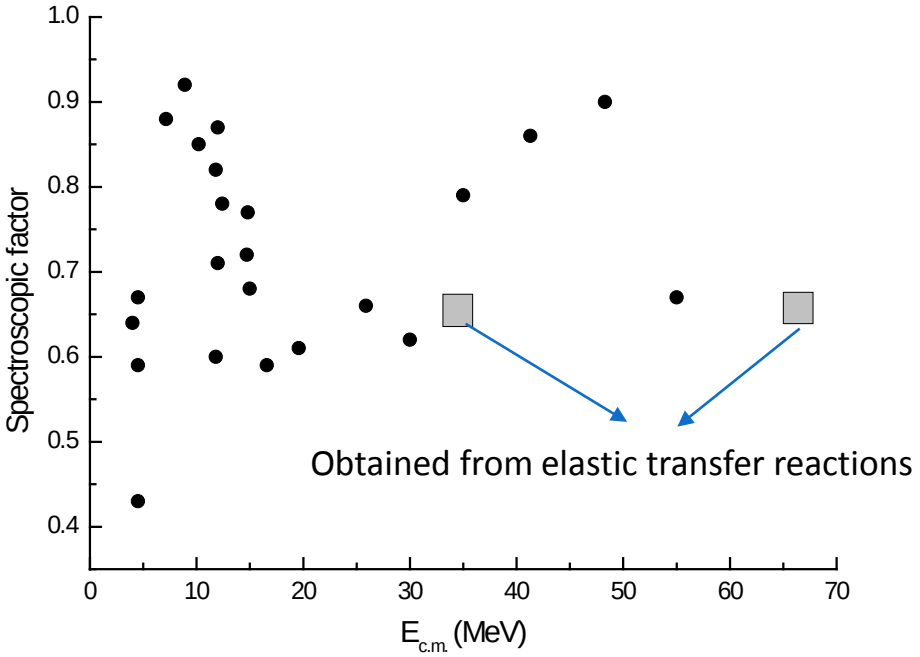
$S_{^{12}C}$	Expt. or Theor.	Ref.
2.85	Theory	[4]
1.85 ± 0.03	$^{12}C(e, e'p)^{11}B$	[5]
2.0 ± 0.2	$^{12}C(p,2p)^{11}B$	[6]
1.85 ± 0.05	$^{11}B(d,n)^{12}C$	[12]
2.125	$^{12}C(d,^3He)^{11}B$	[11]
4.10	$^{11}B(^7Li,^6He)^{12}C$	[12]
2.15 ± 0.23	$^{12}C(^{11}B, ^{12}C)^{11}B$	Present work

E. T. Li et al., PRC 90, 067601 (2014)

$^{13}C(^{12}C,^{13}C)^{12}C$ elastic transfer reaction



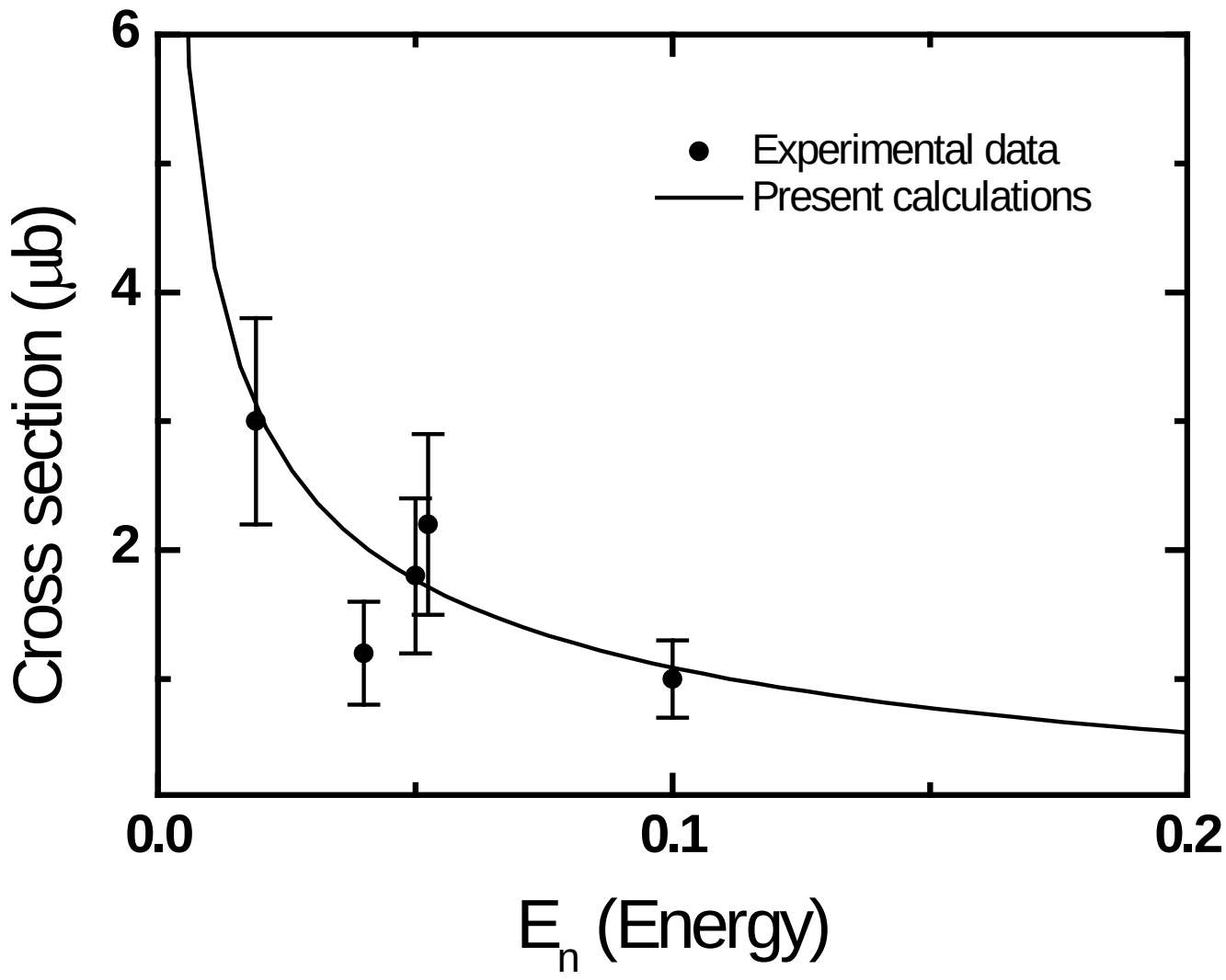
Angular distribution of transfer reaction



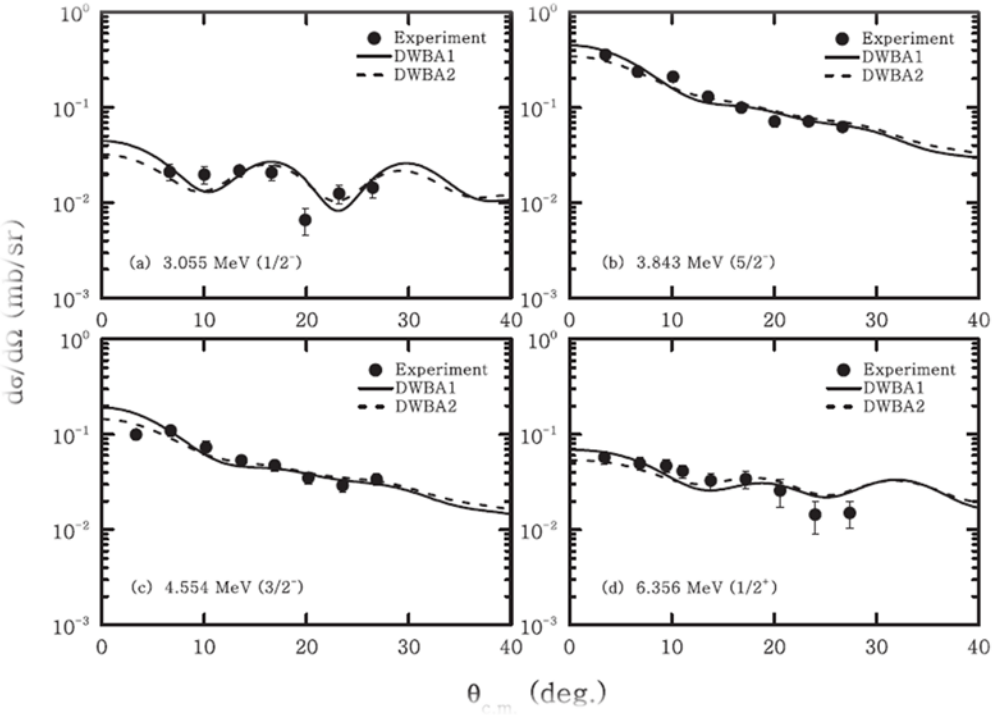
^{13}C neutron spectroscopic factors

Extracted spectroscopic factors: accuracy, stable

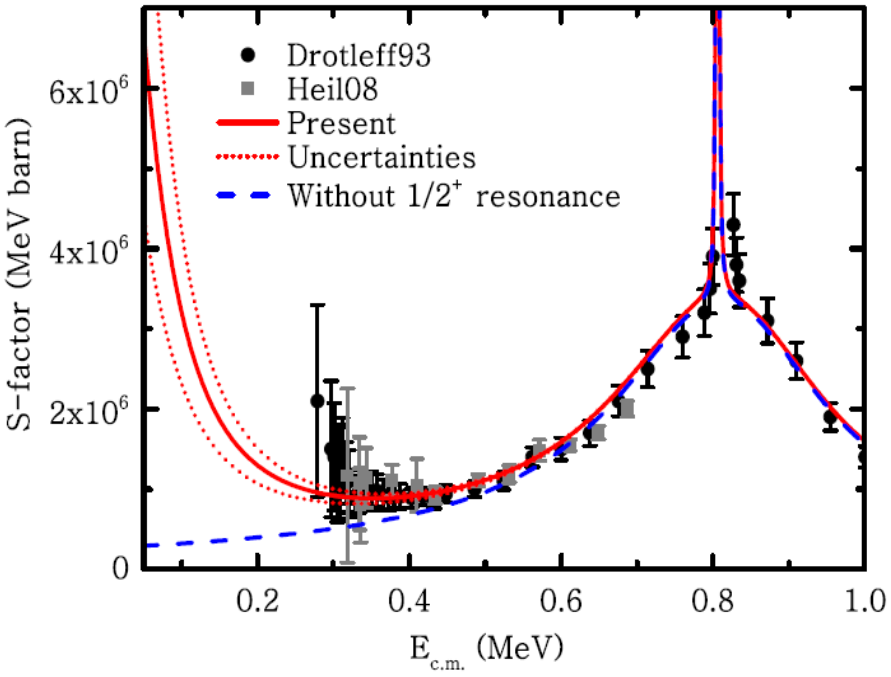
$^{12}C(n, \gamma)^{13}C$ DC cross sections



$^{13}C(\alpha, n)^{16}O$ astrophysical S(E) factors



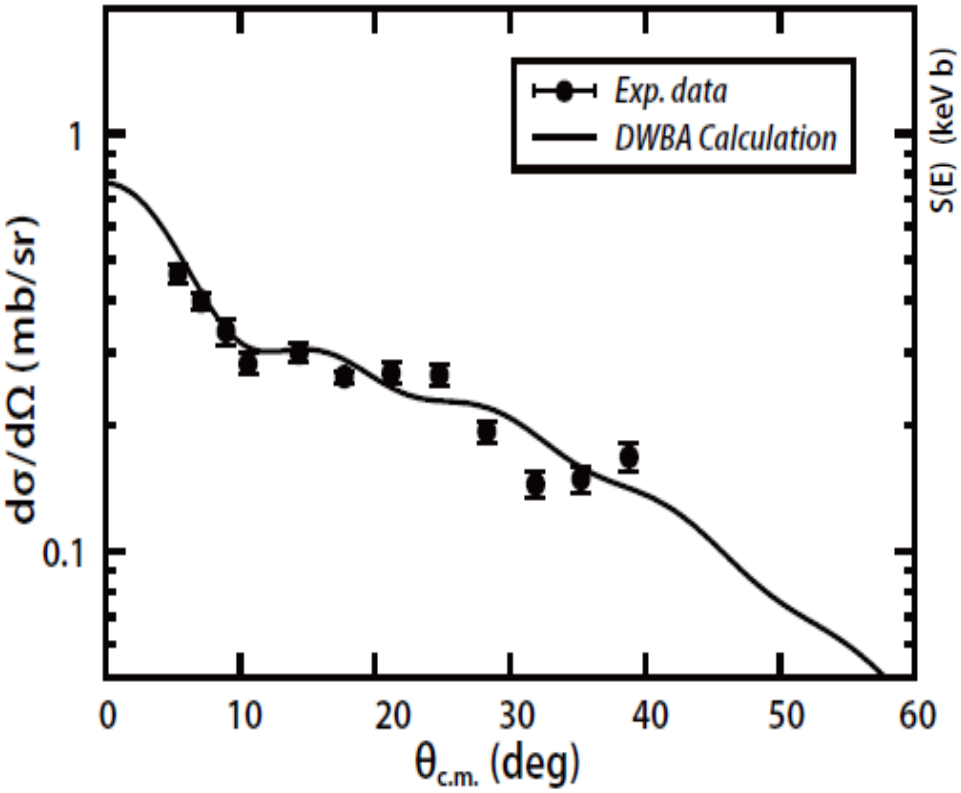
$^{13}C(^{11}B,^{7}Li)^{17}O$ angular distribution

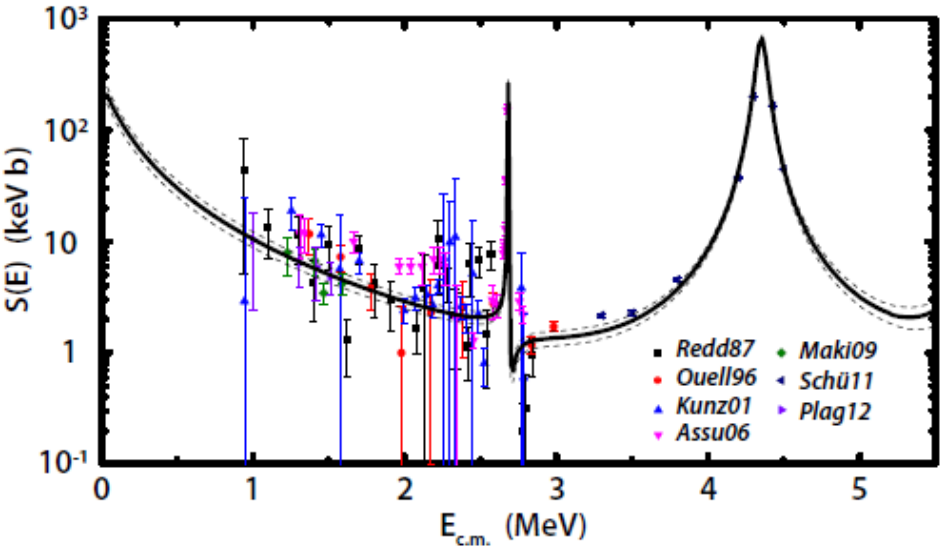


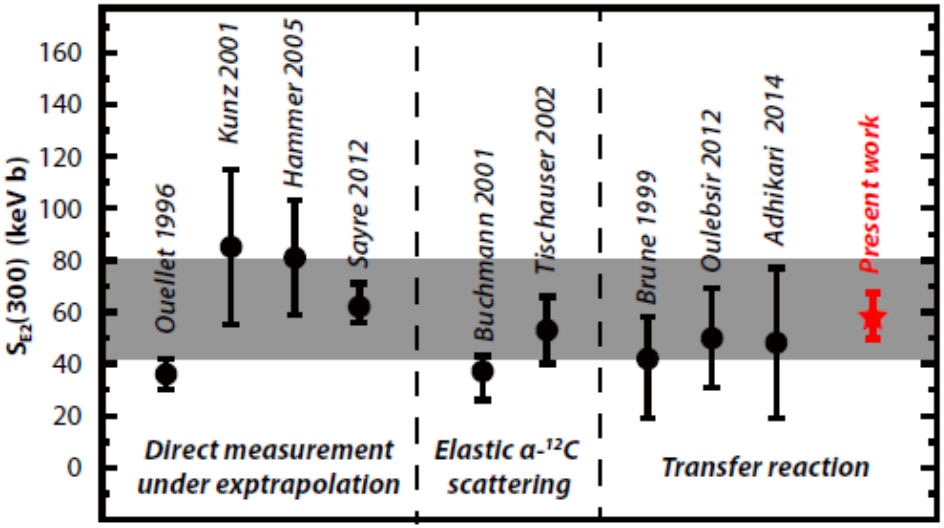
$^{13}C(\alpha,n)^{16}O$ astrophysical S(E) factors

B. Guo et al, APJ 756(2012)193

$^{12}C(\alpha, \gamma)^{16}O$ astrophysical S(E) factors







The angular distribution of $^{12}C(^{11}B, ^{7}Li)^{16}O$ reaction leading to 6.917 MeV 2^+ state of ^{16}O

$$S_\alpha = 0.21 \pm 0.03$$

The finished experiments

- Elastic scattering reactions

  $^{6,7}Li+^{6,7}Li$, ^{9}Be, $^{10,11}B$, $^{12,13}C$, $^{14,15}N$, $^{16,18}O$, $^{24,25}Mg$

  $^{9}Be+^{12,13}C$, $^{11}B+^{12,13}C$

  $^{12,13}C+^{90,91,92,94,96}Zr$, $^{116,117,118,120,124,126}Sn$

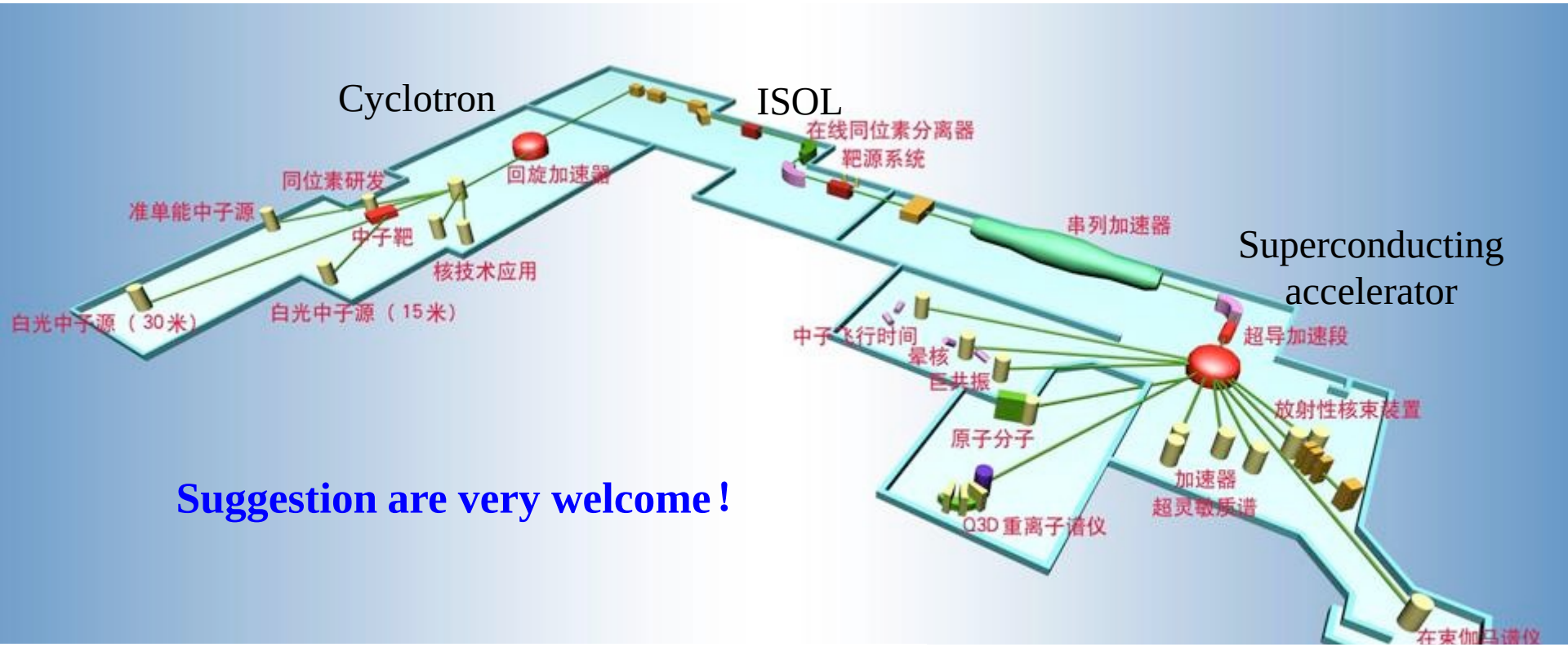
- Nucleon transfer reactions

  $^{7}Li(^{6}Li, ^{7}Li)$, $^{10,11}B$ $(^{7}Li, ^{6}Li/^{6}He)$, $^{12,13}C(^{7}Li, ^{6}Li/^{6}He)$, $^{14,15}N(^{7}Li, ^{6}Li/^{6}He)$, $^{16,18}O(^{7}Li, ^{6}Li/^{6}He)$, $^{25}Mg(^{7}Li,^{6}He)$, $^{13}C(^{9}Be, ^{8}Li/^{10}Be)$, $^{12}C(^{11}B,^{12}C)$, $^{13}C(^{12}C,^{13}C)$, $^{90,91,92,94}Zr(^{12,13}C,^{13,12}C)$

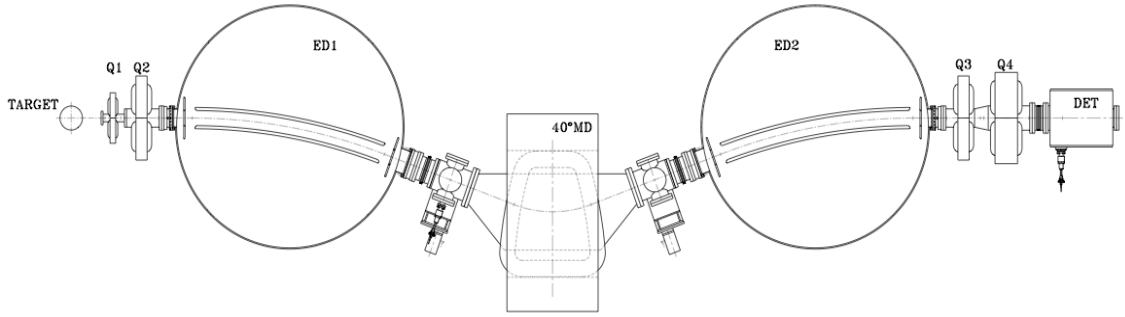
- Alpha transfer reactions

  $^{12,13}C(^{11}B,^{7}Li)^{16,17}O$, $^{18}O(^{6}Li,d)^{22}Ne$, $^{7}Li(^{6}Li,d)^{11}B$

The Beijing Radioactive ion-beam Facility (BRIF)



Suggestion are very welcome !



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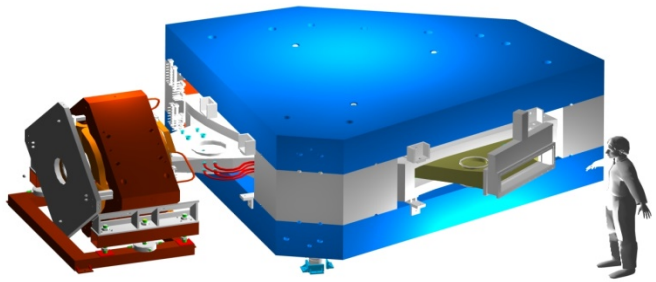

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