Radiative neutron capture rate of $^{11}B(n,\gamma)^{12}B$ reaction from the Coulomb dissociation of ^{12}B

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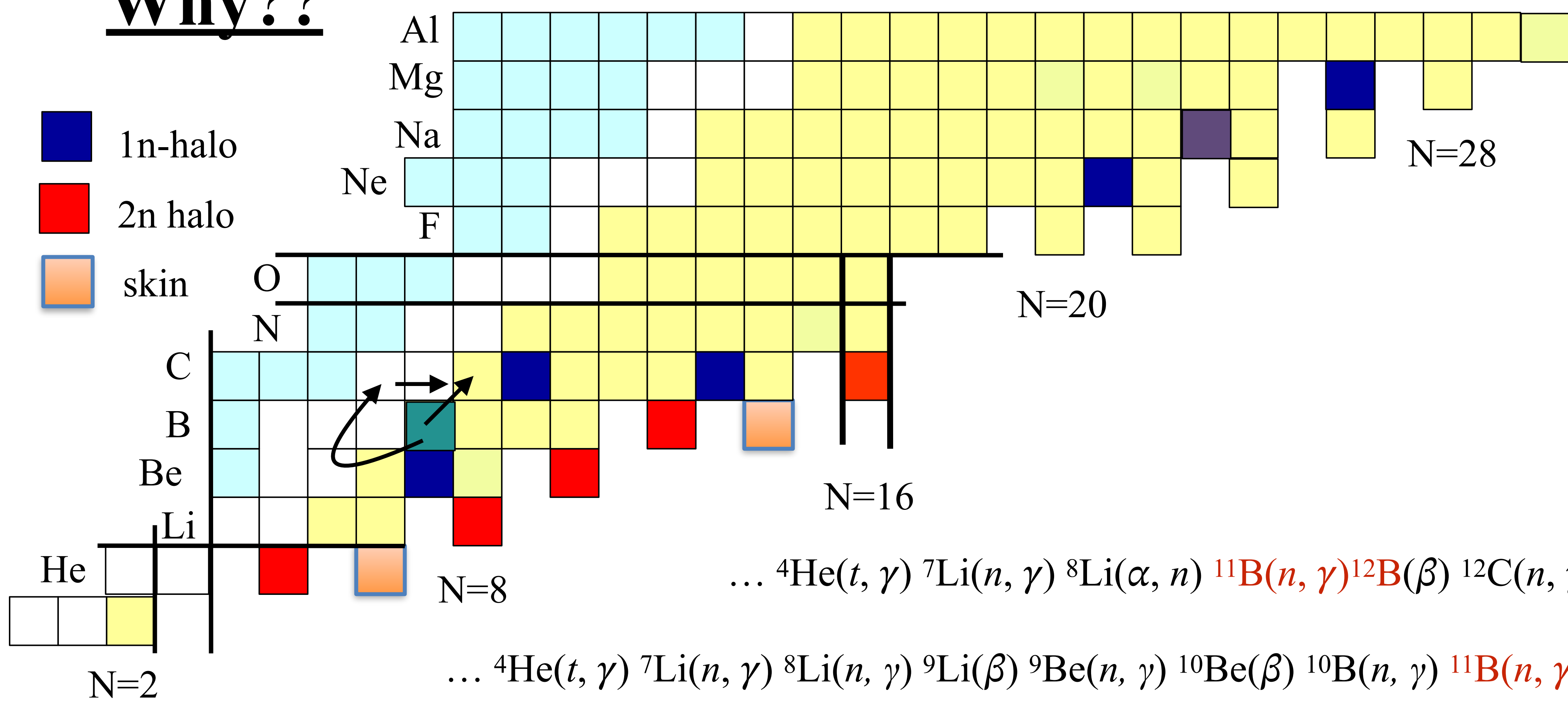
Why??



… ^{4}He(t, γ) ^{7}Li(n, γ) ^{8}Li(α, n) ^{11}B(n, γ)^{12}B(β) ^{12}C(n, γ) ^{13}C(n, γ)^{14}C…

… ^{4}He(t, γ) ^{7}Li(n, γ) ^{8}Li(n, γ) ^{9}Li(β) ^{9}Be(n, γ) ^{10}Be(β) ^{10}B(n, γ) ^{11}B(n, γ)^{12}B(β) ^{12}C…

… ^{4}He(t, γ) ^{7}Li(t, n) ^{9}Be(n, γ) ^{10}Be(β) ^{10}B(n, γ) ^{11}B(n, γ)^{12}B(β) ^{12}C(n, γ) ^{13}C(n, γ)^{14}C…

The ^{11}B(n, γ)^{12}B reaction is vital to all these chains…

^{12}B is also seems crucial to the formation of ^{12}C!!!

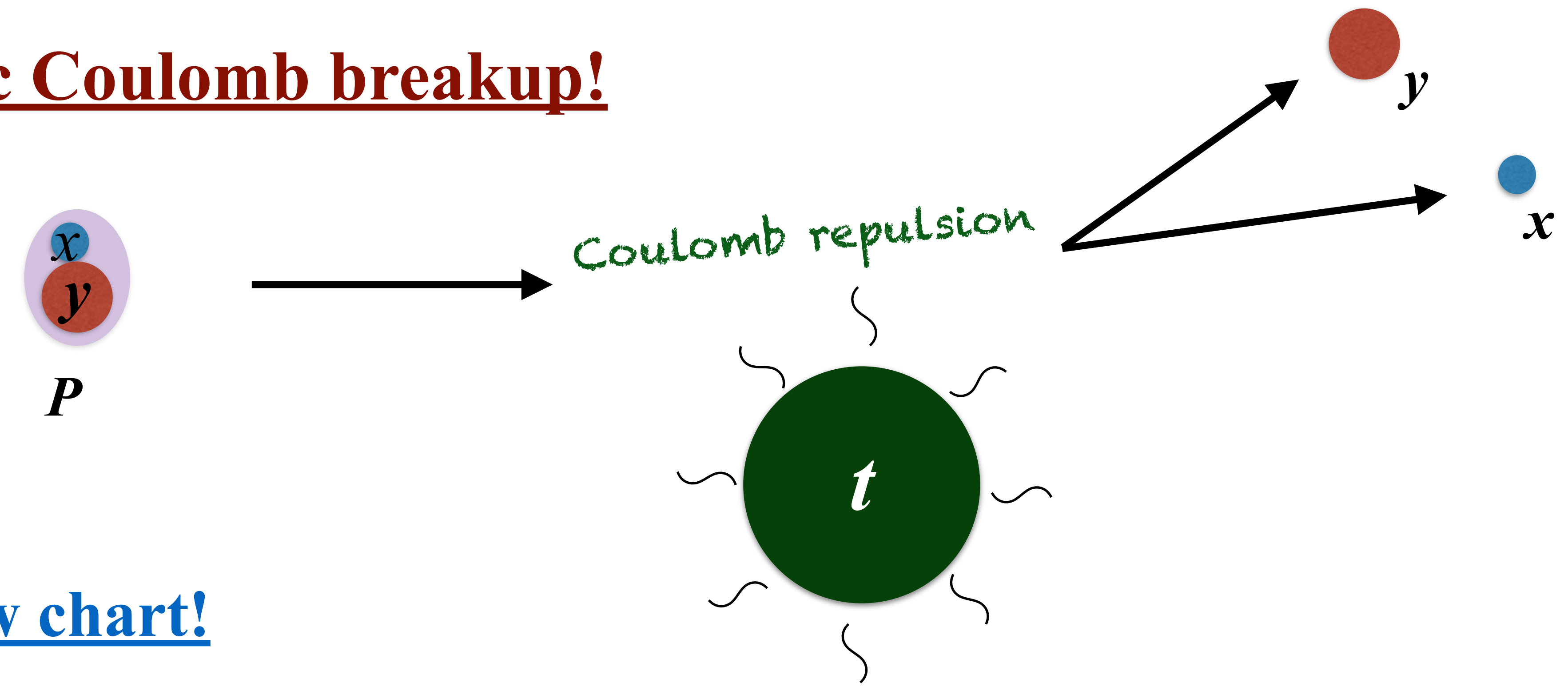
Resonance contribution?

Halo e.s. contribution??!!

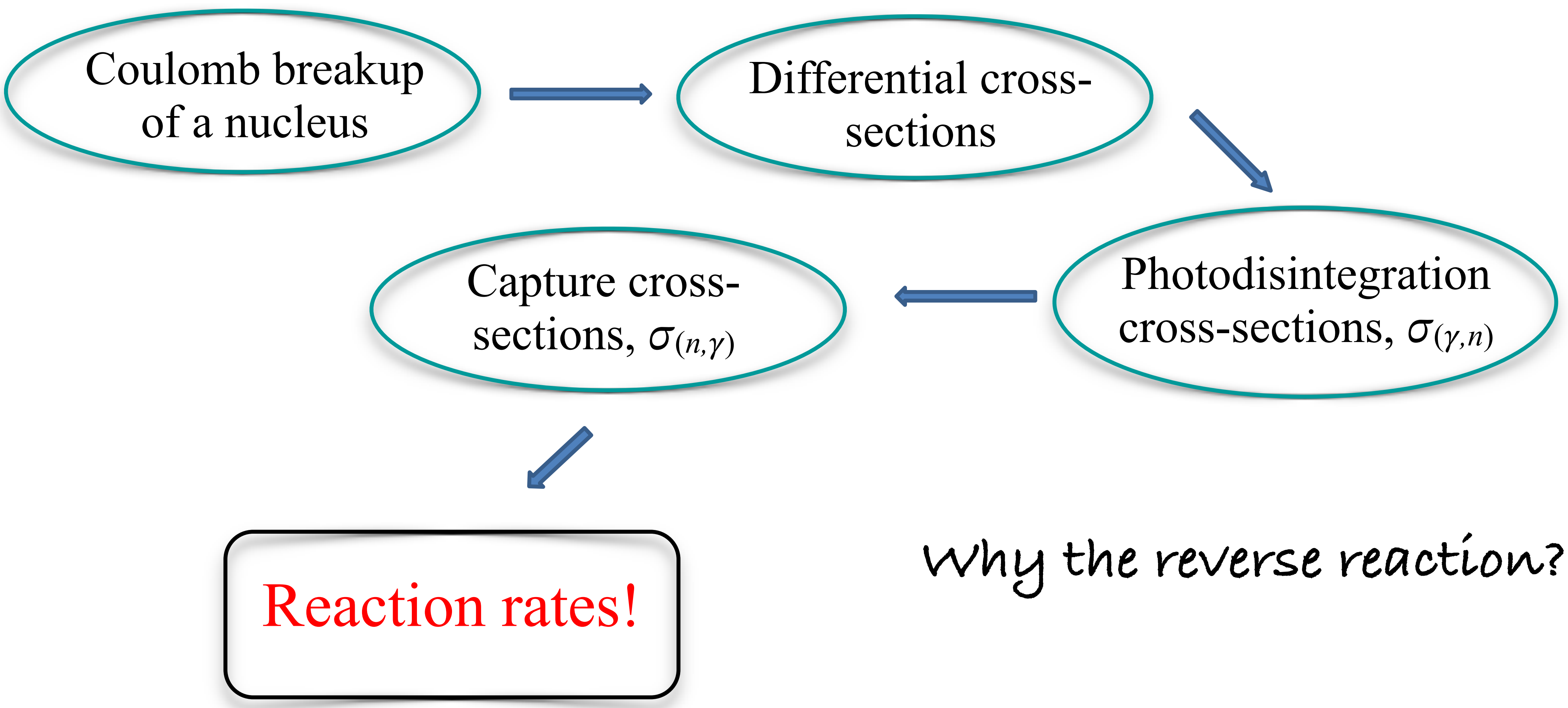
Dubovichenk S.B., *et al.*, Astropart. Phys. **123**, 102481 (2020).
Wang T.R., *et al.*, Phys. Rev. C **43**, 883 (1991).
Lee H.Y., *et al.*, Phys. Rev. C **81**, 015802 (2010).
Guimaraes V., and Bertulani C.A., AIP Conf. Proc. **1245**, 30 (2010).
Malaney R.A., and Fowler W. A., ApJ. **133**, 14 (1988).
Terasawa M, *et al.*, ApJ **562,** 470 (2001).

Strategy!

Elastic Coulomb breakup!



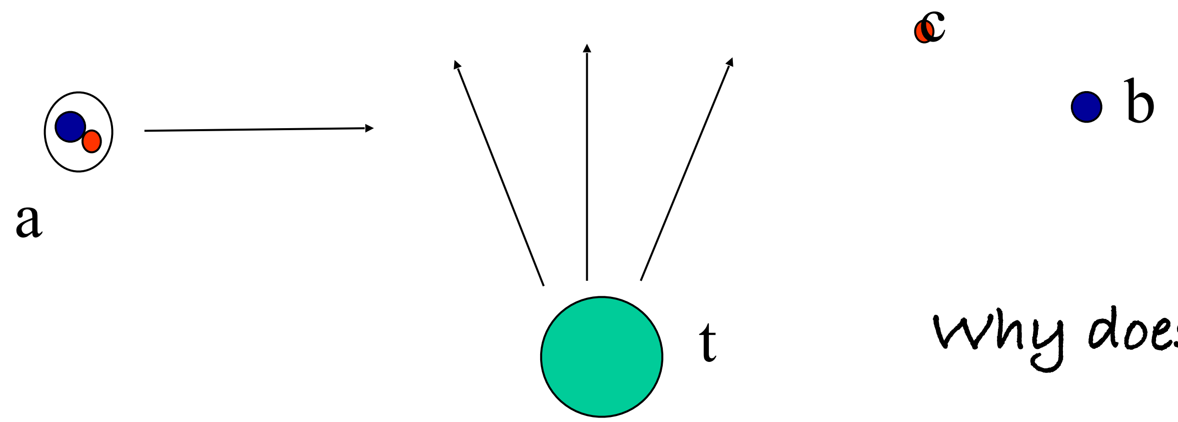
The flow chart!



Why the reverse reaction?!!

(^{12}B) Coulomb dissociation and the finite range distorted wave Born approximation (FRDWBA) theory:

Coulomb dissociation: an elegant method to study nuclear halos!!



Why does it work?

The triple differential cross-section:

Phase space factor

$$\frac{d^3\sigma}{dE_b d\Omega_b d\Omega_c} = \frac{2\pi}{\hbar v_{at}} \rho \sum_{lm} |\beta_{lm}|^2$$

Reduced transition matrix

For a neutron,

$$\chi_c^{(-)*}(\boldsymbol{q}_c, \boldsymbol{r}_c) = e^{-i(\boldsymbol{q}_c, \boldsymbol{r}_c)}$$

The reduced transition matrix under the FRDWBA theory:

Structure part! *Includes deformation!!*

Dynamics part!

$$\hat{l}\beta_{lm} = \int d\boldsymbol{r}_1 e^{-iW.\boldsymbol{r}_1} V_{bc}(\boldsymbol{r}_1)\phi_a^{lm}(\boldsymbol{r}_1) \int d\boldsymbol{r}_i e^{-i\delta \boldsymbol{q}_c.\boldsymbol{r}_i} \chi_b^{(-)*}(\boldsymbol{q}_b, \boldsymbol{r}_i)\chi_a^{(+)}(\boldsymbol{q}_a, \boldsymbol{r}_i)$$

Can be evaluated analytically in terms of the Bremsstrahlung integral. ☺

Chatterjee R, Banerjee P, and Shyam R, Nucl. Phys. A **675** (2000) 477.

Applications to astrophysics

For a **single multipole dominated reaction**,

$$\frac{d^3\sigma}{dE_b d\Omega_b d\Omega_c} = \frac{2\pi}{\hbar v_{at}} \rho \sum_{lm} |\beta_{lm}|^2$$

FRDWBA!!

$$\sigma_{\gamma,n}^{\pi\lambda} = \frac{E_\gamma}{n_{\pi\lambda}} \frac{d\sigma}{dE_{bc}}$$

Bertulani C A, and Baur G, Phys. Rep. **163,** 299 (1988).

But where is the Astrophysics application?

Achieved by invoking the principle of detailed balance relating the photodisintegration cross-section with its "radiative capture" counterpart via:

$$\sigma_{n,\gamma} = \frac{2\hat{j}_a^{\,2}}{\hat{j}_b^{\,2}\hat{j}_c^{\,2}} \frac{k_\gamma^2}{k_{bc}^2} \sigma_{\gamma,n}^{\pi\lambda}$$

$$\langle \sigma(v_{bc}) v_{bc} \rangle = \sqrt{\frac{8}{\pi\mu_{bc}(k_B T)^3}} \int_0^\infty dE_{bc}\, \sigma_{(n,\gamma)}(E_{bc}) E_{bc} \exp\left(-\frac{E_{bc}}{k_B T}\right)$$

Then, reaction rate,

$$R = N_A \langle \sigma(v_{bc}) v_{bc} \rangle$$

Rolfs, and Rodney, *Cauldrons in the Cosmos* (University of Chicago Press), 1988.

Method applied successfully in the past to study ^{33}Na(n,γ), ^{18}C(n,γ), ^{19}N(n,γ) reactions, among others!

Capture Cross-section

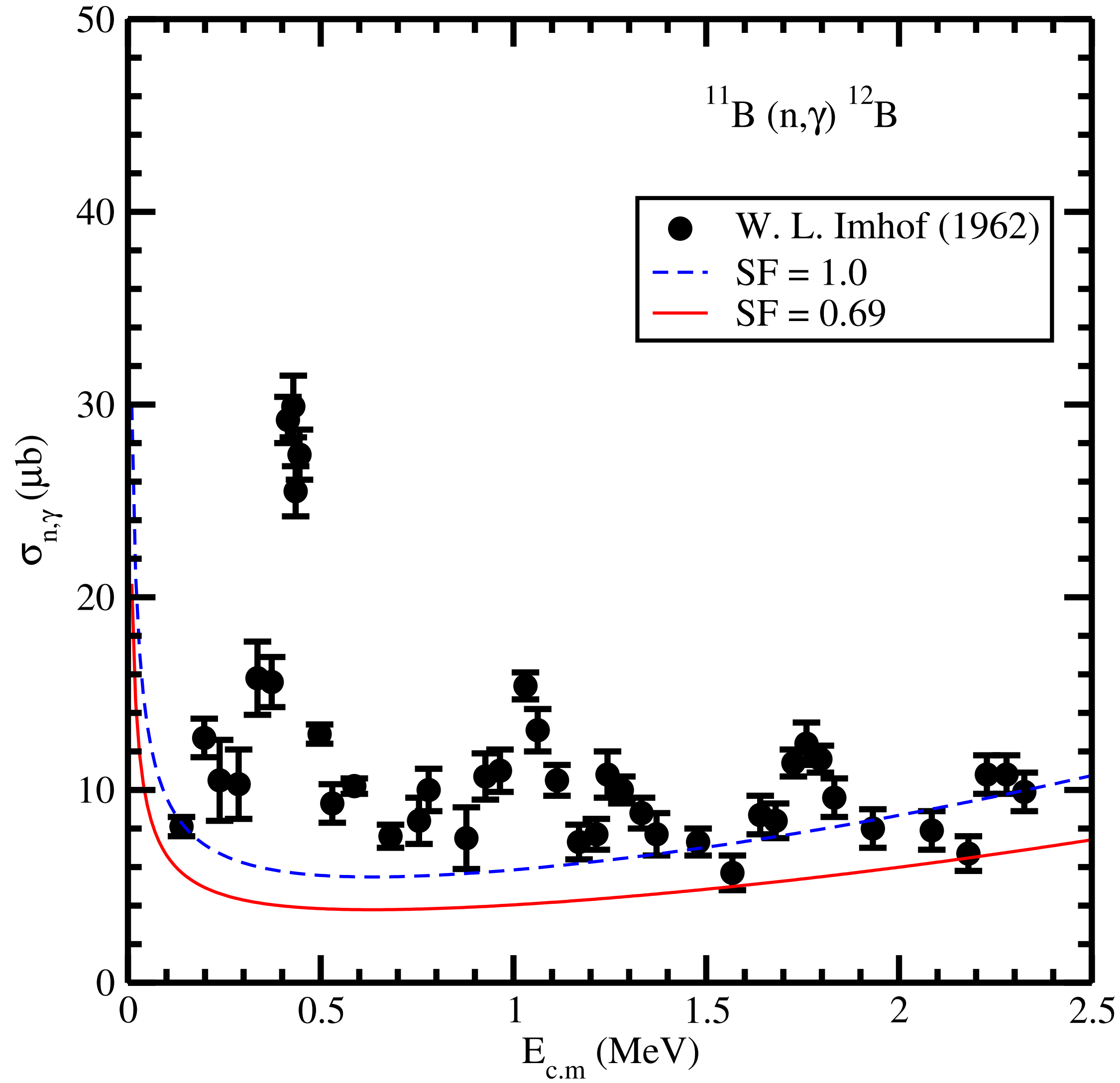
$^{12}B + ^{208}Pb \xrightarrow{60\ \text{MeV/u}} ^{11}B + ^{1}n + ^{208}Pb$

G.s.: E = 0.0 MeV, $J^\pi=1^+$, $\tau_{1/2}$ = 20.20 ms;
1st e.s.: E = 0.947 MeV, 2^+;
2nd e.s.: E = 1.674 MeV, $J^\pi=2^-$;
3rd e.s.: E = 2.618 MeV, $J^\pi=1^-$;
S_n = 3.368 MeV;
1st res: E_x = 3.389 MeV, $J^\pi=3^-$, Γ_n = 3.1 eV, E_R = 21keV;
2nd res: E_x = 3.764 MeV, $J^\pi=2^+$, Γ_n = 37 keV;
3rd res: E_x = 4.311 MeV, $J^\pi=1^-$, Γ_n = 9 keV;
4th res: E_x = 4.54 MeV, $J^\pi=4^-$, Γ_n = 130 keV;
5th res: E_x = 5.0 MeV, $J^\pi=1^+$, Γ_n = 60 keV.

We consider only the ground state at present!

Non-resonant capture cross-section from the FRDWBA theory.

What about the resonant contribution?



S.F. = 0.69 from Nucl. Phys. A **506**, 1 (1990).

One can parametric the resonances using a Breit-Wigner and just add.

Kelley J.H., Nucl. Phys. **968**, 71 (2017); Lee H.Y., *et al.*, Phys. Rev. C **81**, 015802 (2010); Belyaeva T.L., *et al.*, Phys. Rev. C **98**, 034602 (2018).

Imhof W.L., *et al.*, Phys. Rev. **125**, 1334 (1962).

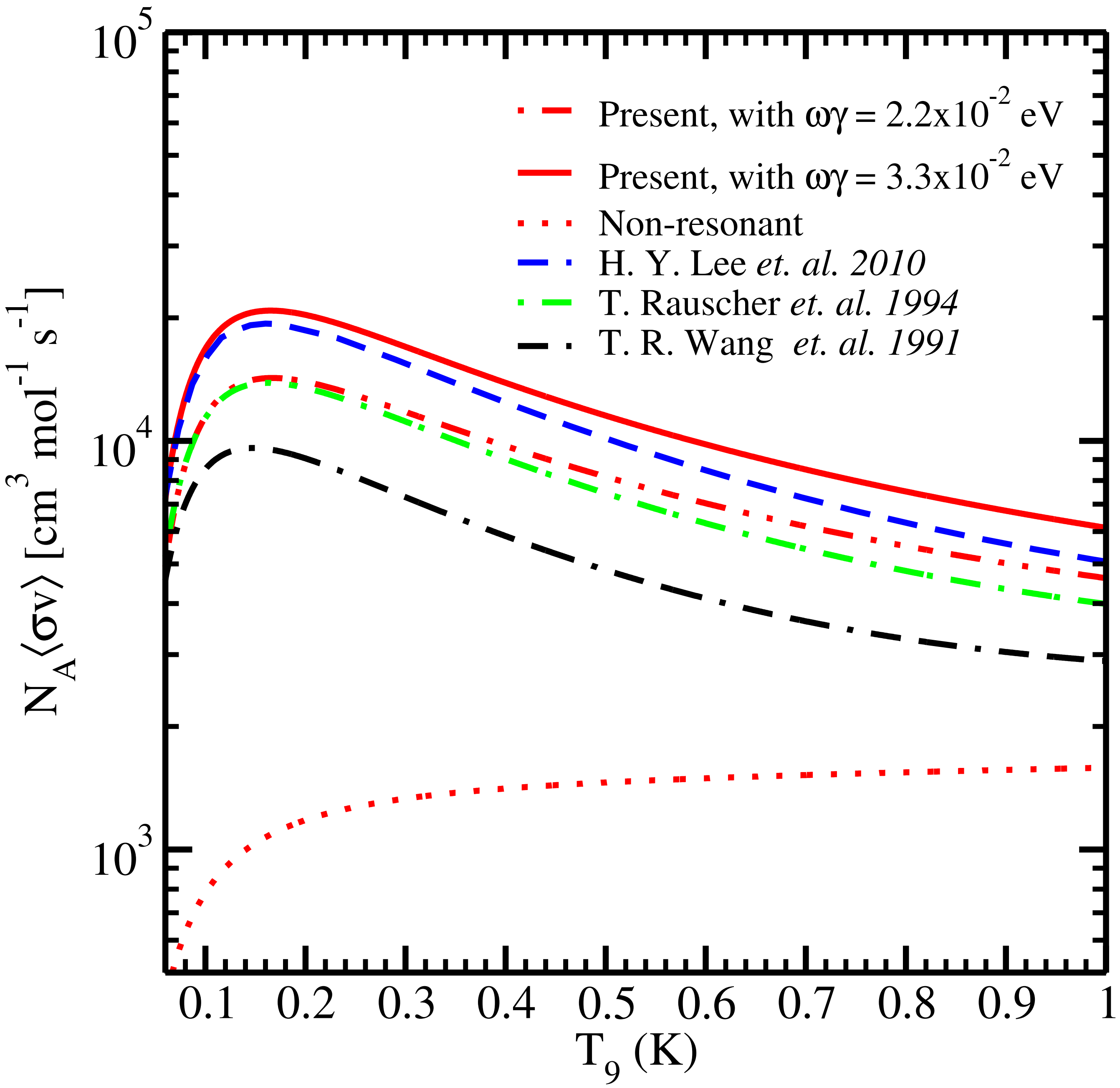
The Reaction Rates!

$^{11}B(n, \gamma)^{12}B$

- The reaction rates in agreement with previous predictions.

- The reaction rates here show only the contribution of the first and dominant resonance.

- The non resonant reaction rate is an order of magnitude lower, but becomes relevant at higher temperatures.



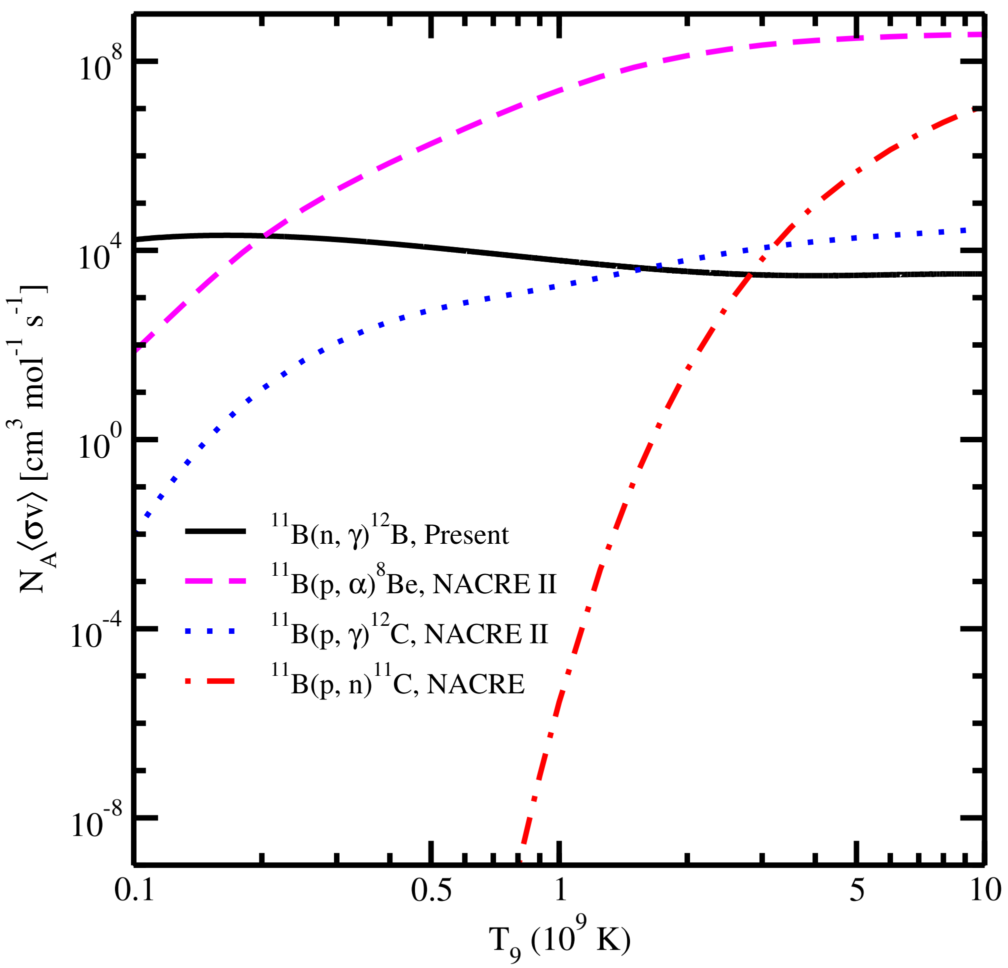
- The effect of excited halos states in ^{12}B as well as other resonances needs to be seen to be quantified.

The Reaction Rates!

Comparisons with other capture reactions!

$^{11}B(n, \gamma)^{12}B$

$^{11}B(p,*)$



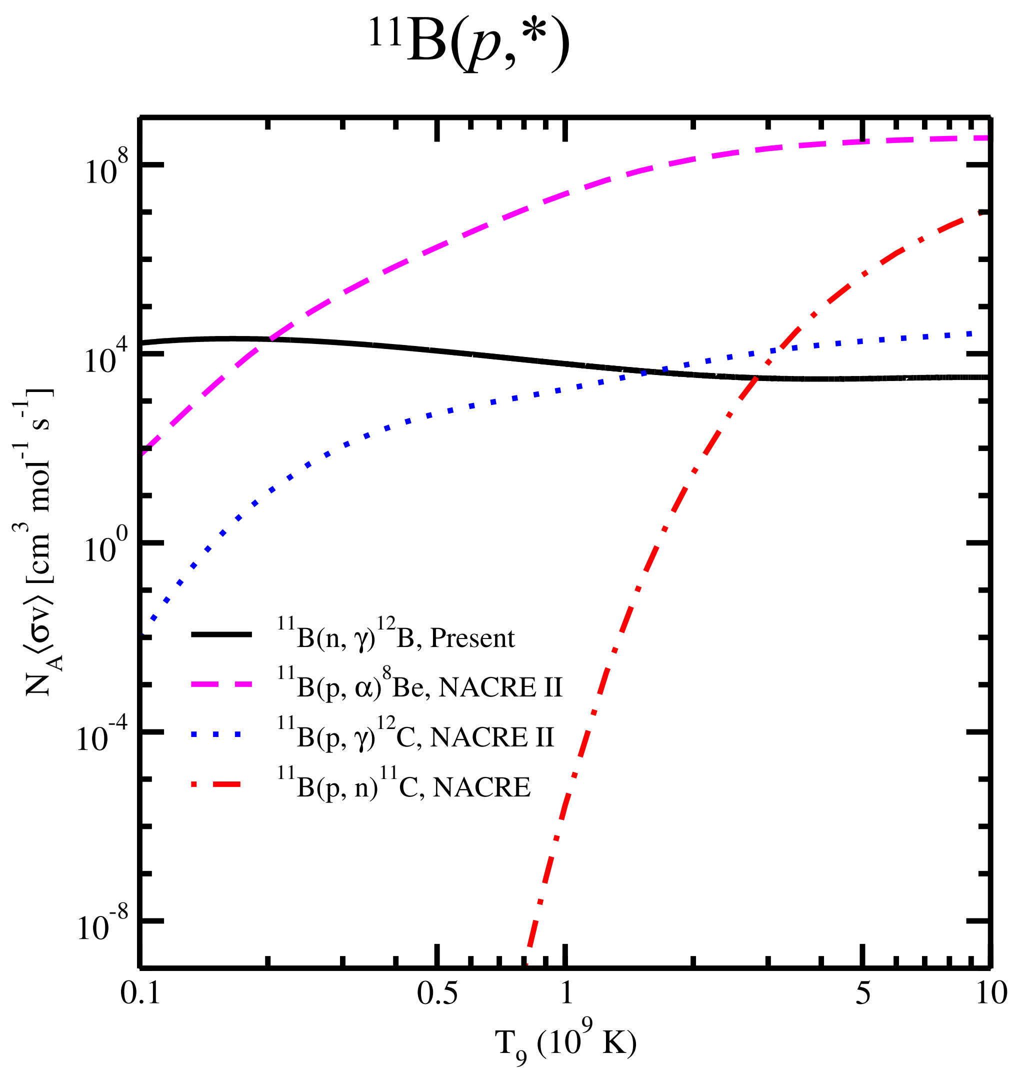
- The $^{11}B(n, \gamma)^{12}B$ dominates the $^{11}B(p,*)$ upto $T_9 = 0.2$.

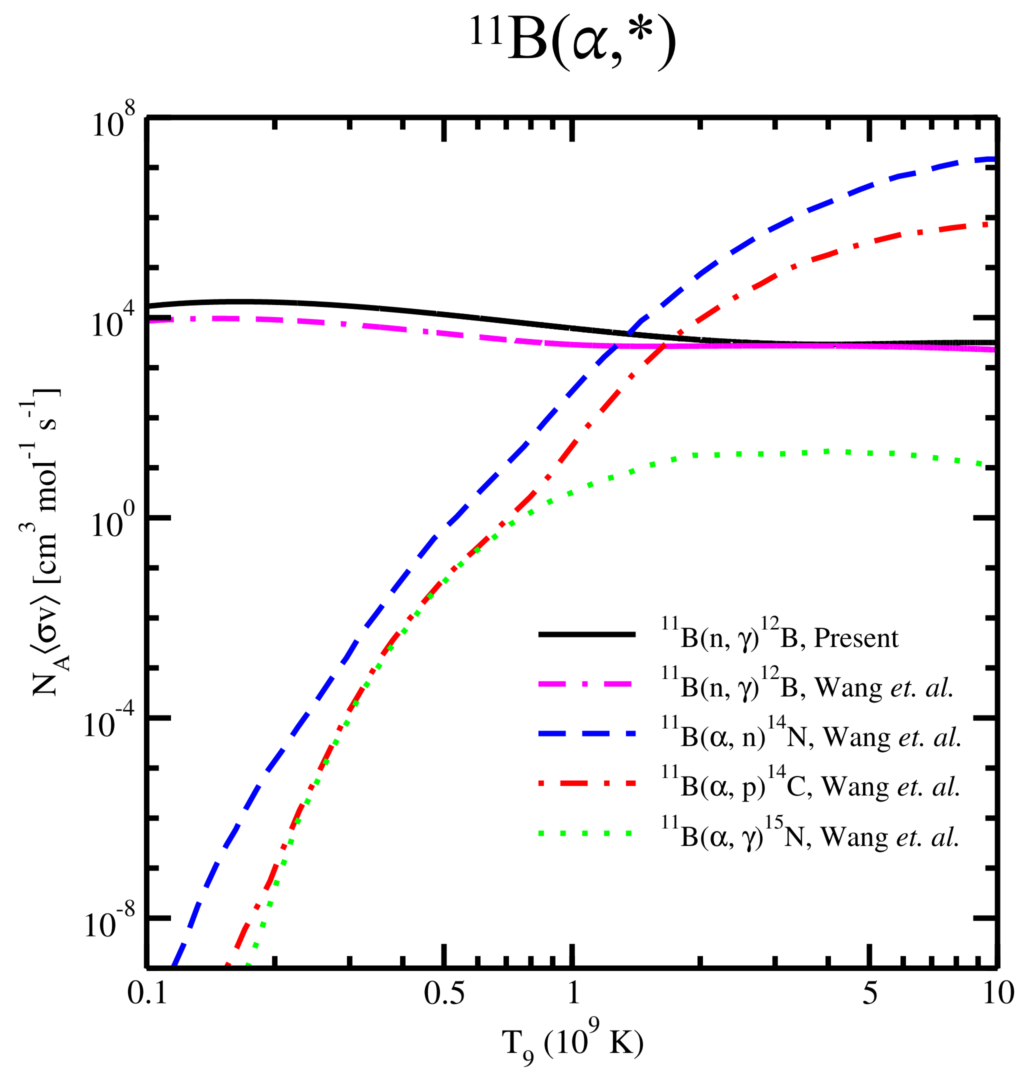
Xu Y., *et al.*, Nucl. Phys. A **918**, 61 (2013).

The Reaction Rates!

Comparisons with other capture reactions!

$^{11}B(n, \gamma)^{12}B$





- The $^{11}B(n, \gamma)^{12}B$ dominates the $^{11}B(p,*)$ upto $T_9 = 0.2$.
- The $^{11}B(n, \gamma)^{12}B$ dominates the $^{11}B(\alpha,*)$ upto $T_9 = 1.3$.
- This is consistent with most reaction sequence model predictions for formation of ^{12}B.

Xu Y., *et al.*, Nucl. Phys. A **918**, 61 (2013).

Wang T.R., *et al.*, Phys. Rev. C **43**, 883 (1991).

Conclusions and Future Outlook!

- ★ **The reaction rates for the $^{11}B(n, \gamma)^{12}B$ radiative neutron capture were computed for capture of the neutron to the ground state.**

- ★ The rates were found to be dominant than the $(p,*)$ and the $(\alpha,*)$ reactions in the relevant temperature range for reaction sequences.

- ★ The various resonances need to accounted for systematically in order to fully understand their contributions.

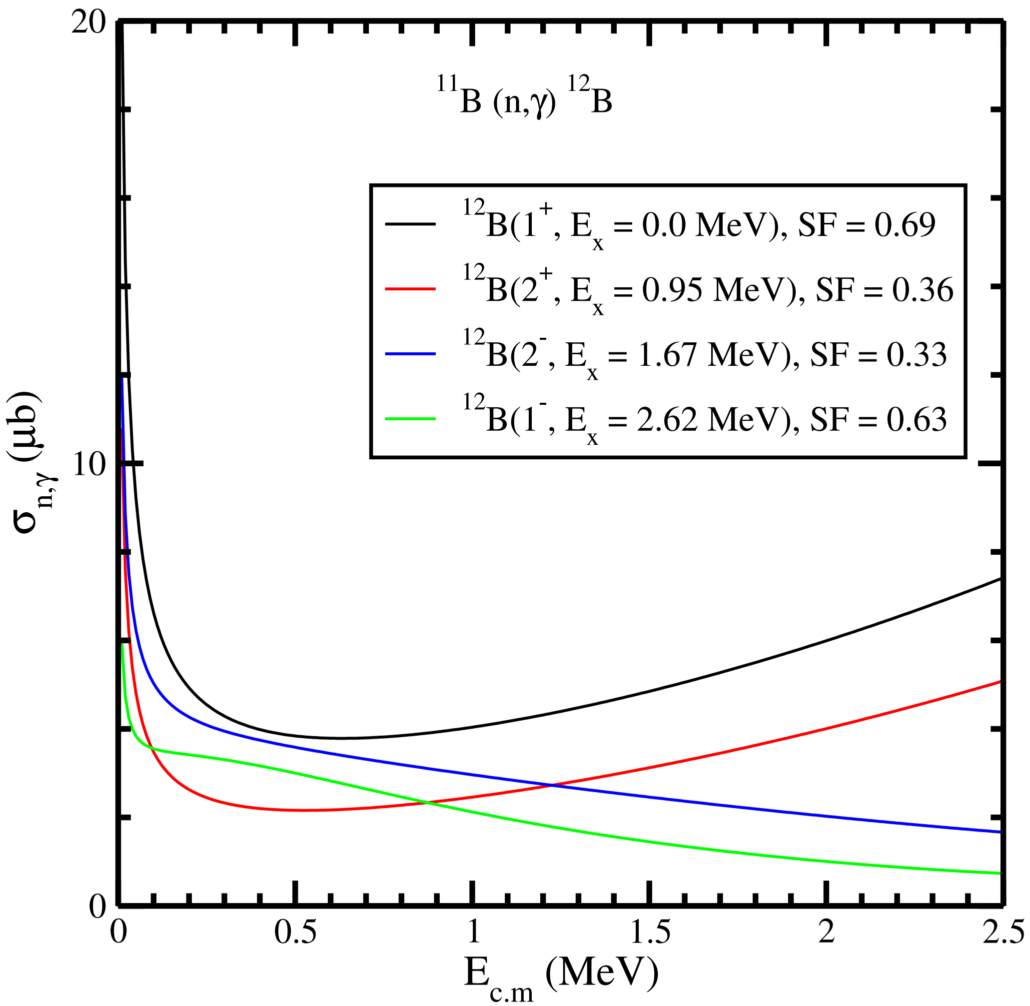
- ★ The consideration of excited state halos (2nd and 3rd e.s.) in ^{12}B in the total reaction rates is under progress.

The resonance at 3.389MeV is about 21 keV higher than the Sn at 3.368 MeV.
The Γ_n and Γ_γ are given to be 3.1 eV and 0.025 eV.
Phys. Rev. C **178**, 1612 (1969).

70% probability of E1 transition to the ground state from the Neutron separation threshold at 3.368 MeV.
Phys. Rev. C **93**, 054303 (2016).

Thermal neutron capture cross-section:

9.09 ± 0.1 mb (Phys. Rev. C **93**, 054303 (2016)).
5 ± 3 mb (Phys. Rev. **125**, 1334 (1962)).
5.5 ± 3.3 mb (Atlas of Neutron Resonances, 5th ed. (Elsevier, New York, 2006).



G.s.: E = 0.0 MeV, 1+, 20.20 ms;
1st e.s.: E = 0.947 MeV, 2+ (2+), < 10keV; M1 transition to g.s.
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3rd e.s.: E = 2.618 MeV, 1- (1-), <10keV;
4th e.s.: E = 2.723 MeV, 0+ (0+), <10keV;
1st res: E = 3.389 MeV, 3- (3-), Γ_n = 3.1 eV;
Nucl. Phys. **968**, 71 (2017); [Phys. Rev. C **81**, 015802 (2010)].