The 17th CNS International Summer School

MEAN-FIELD STUDY OF THE RADIATIVE CAPTURE $^{12}C(p,\gamma)^{13}N$ AND $^{13}C(p,\gamma)^{14}N$ REACTIONS

Speaker: **Le-Anh Nguyen**
Supervisor: **Prof. Dao Tien Khoa**

Ho Chi Minh City University of Education, Vietnam
Institute of Nuclear Science and Technology, VINATOM, Vietnam

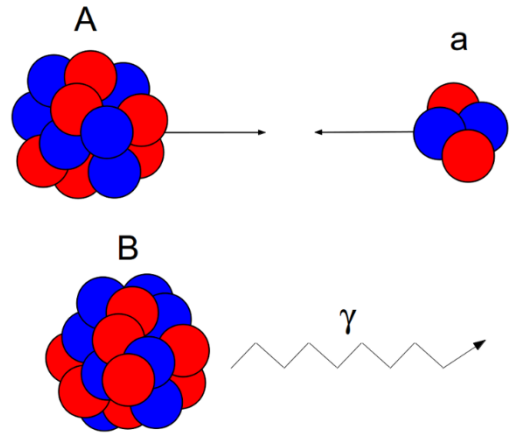
25/8/2018

CONTENT

I. Radiative capture
II. Nuclear mean-field potential
III. Mean-field description of the $^{12}C(p,\gamma)^{13}N$ and $^{13}C(p,\gamma)^{14}N$ reactions
IV. Summary

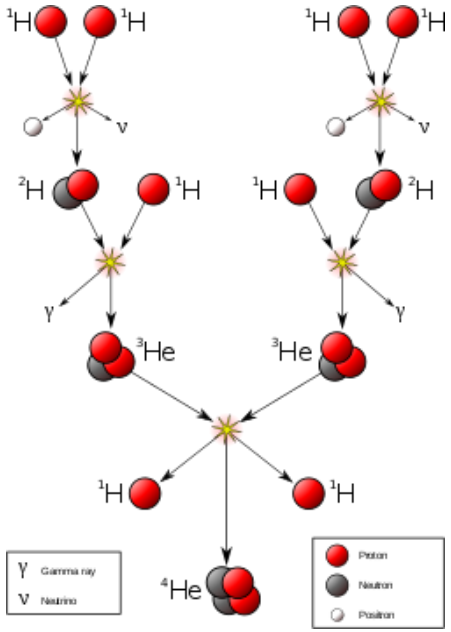
RADIATIVE CAPTURE

Radiative capture is an important process due to its astrophysical applications.

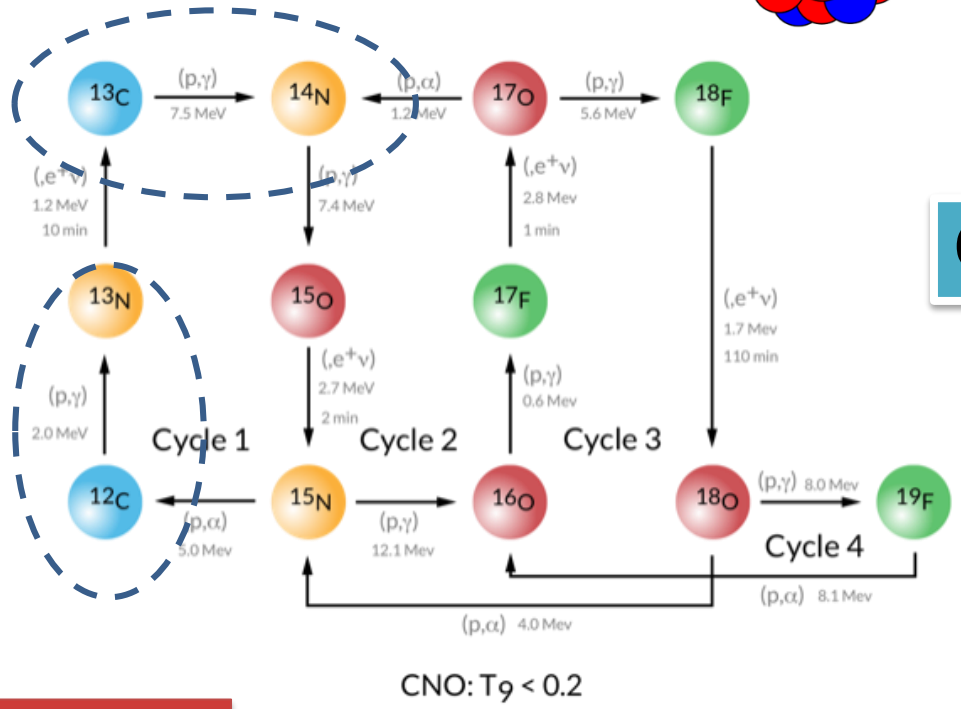


BBN, stellar evolution, element synthesis, X-ray bursts, etc.

pp chain

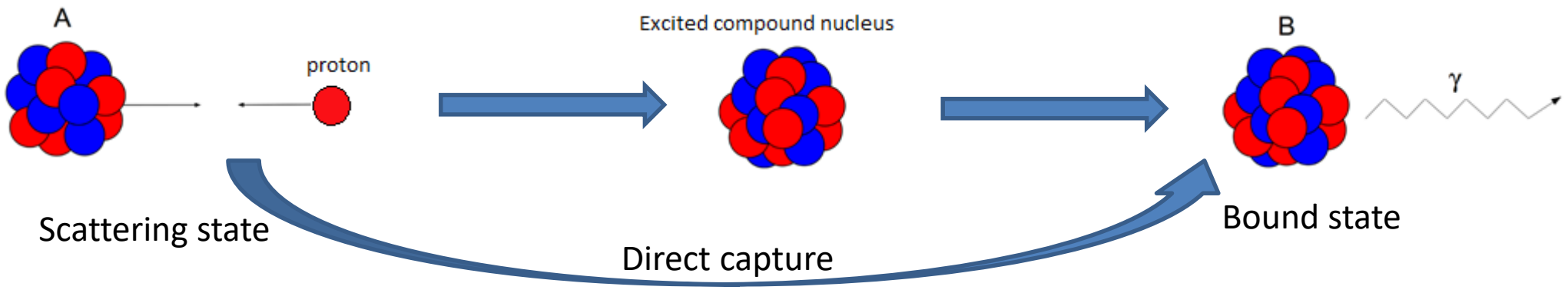


CNO cycle



Hydrogen burning

RADIATIVE CAPTURE

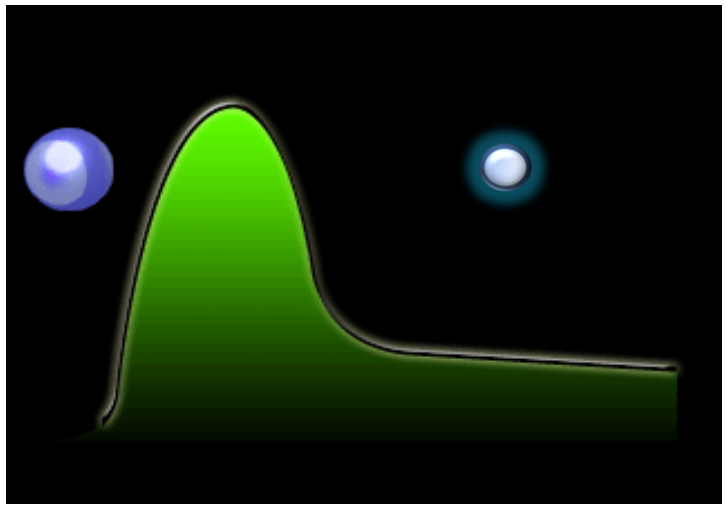


The radial Schrödinger equation:

$$\frac{\hbar^2}{2\mu}\left[\frac{d^2}{dr^2} - \frac{l(l+1)}{r^2}\right]u(r) + V(r)u(r) = Eu(r)$$

- Bound state
- Scattering state

Coulomb pot. Nuclear pot. Spin-orbit pot.



Normalization

- Bound state: $u_J(r) \to C\exp(-k_B r)$
- Scattering state: $u_J(r) \to F_J(kr)\cos\delta_J + G_J(kr)\sin\delta_J$

RADIATIVE CAPTURE

Using the balanced detail, the cross section for the radiative capture A(p;γ)B reaction is determined as

$$\sigma(J_f, E) \sim \sum_{\sigma\lambda} \left(\frac{E_\gamma}{\hbar c}\right)^{2\lambda-1} \left|\langle \Psi^{J_f} \| M^{\sigma\lambda} \| \Psi(E) \rangle\right|^2$$

Photon — Nucleon

Matrix elements needed for electromagnetic transitions

$$\langle \Psi^{J_f} \| M^{\sigma\lambda} \| \Psi(E) \rangle = eZ_{eff} \langle J_f \lambda M_f \mu | J_i M_i \rangle \sqrt{\frac{(2J_i+1)(2\lambda+1)}{4\pi(2J_f+1)}} \int_0^\infty u_i(E,r) r^\lambda u_f(r) dr$$

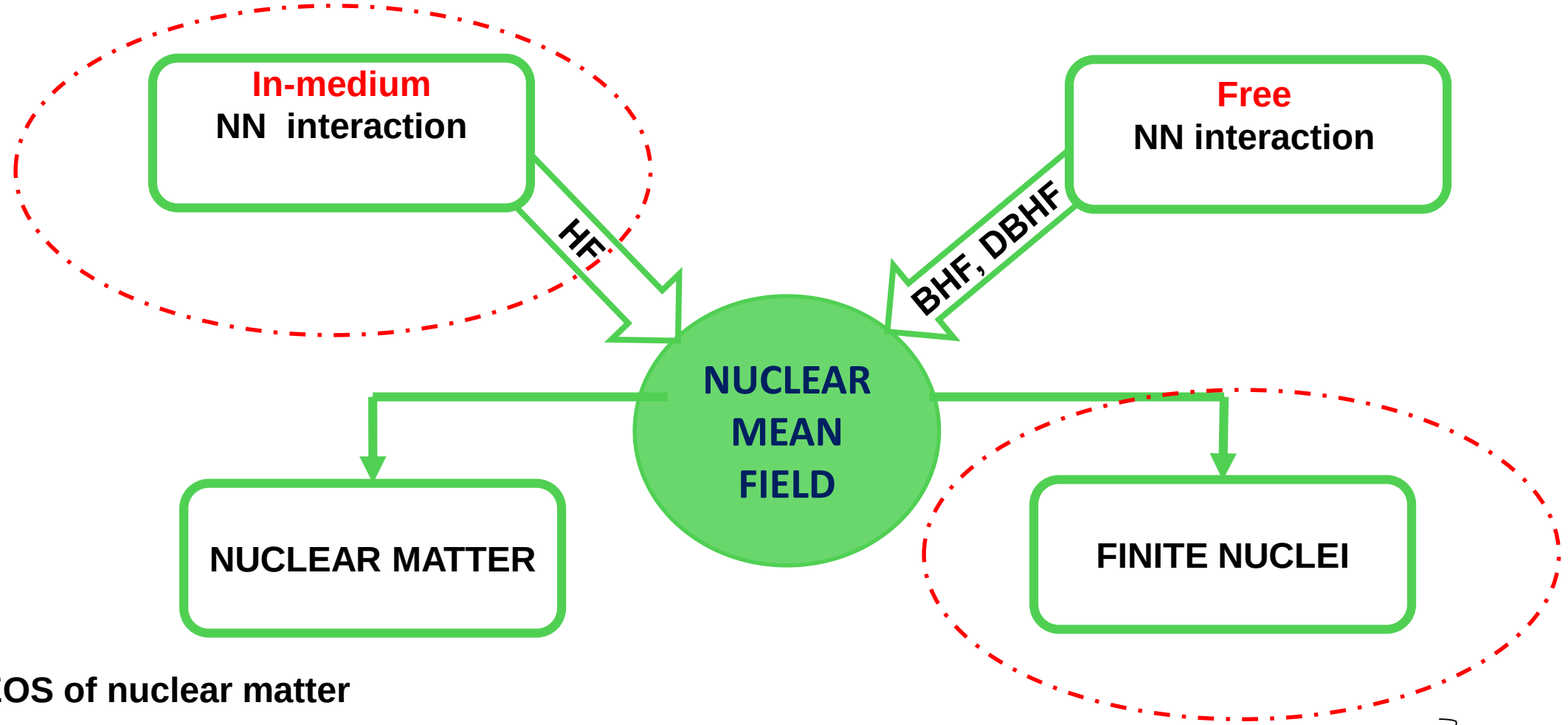
Scattering state — Bound state

Coupling coefficient — Overlap integral

Long wavelength approximation

$$\sigma\lambda = E_1 \gg E_2 \approx M_1 \gg E_3 \approx M_2, \ldots$$

NUCLEAR MEAN-FIELD POTENTIAL



- ✓ **EOS of nuclear matter**
- ✓ **Single particle potential**
- ✓ **Symmetry energy**
- ✓ **Neutron star**

Ngo Hai Tan *et al, Phys. Rev. C 93, 035806*

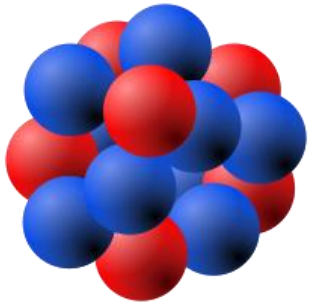
Doan Thi Loan *et al, Phys. Rev. C 92, 034304*

Dao T. Khoa *et al, Phys. Rev. C 94, 034612*

- ✓ **Bound problems**
- ✓ **Scattering problems**

Radiative capture

NUCLEAR MEAN-FIELD POTENTIAL



Fermions

Antisymmetry of wave functions (Slater's determinant) + HF Approximation

$$v = v^D + v^{EX}$$

M3Y

In-medium (density dependent) NN interaction

$$v^{D(EX)}(\rho, s) = F_0(\rho) v_{00}^{D(EX)}(s) + F_1(\rho) v_{01}^{D(EX)}(s) \overrightarrow{\tau_1} \cdot \overrightarrow{\tau_2} \quad \text{with} \quad s = |\vec{r}_1 - \vec{r}_2|$$

Density dependence

D.T. Khoa, G.R. Satchler and W. von Oertzen, *Phys. Rev.* C 56, 954 (1997);
D.T. Loan, B.M. Loc, and D.T. Khoa, *Phys. Rev.* C 92, 034304 (2015).

G-matrix based on M3Y interaction

N. Anantaraman, H. Toki, G.F. Bertsch, *Nucl. Phys*. A 398, 269 (1983).

HF calculation → HvH theorem → **Extended HF (HF + RT) calculation**

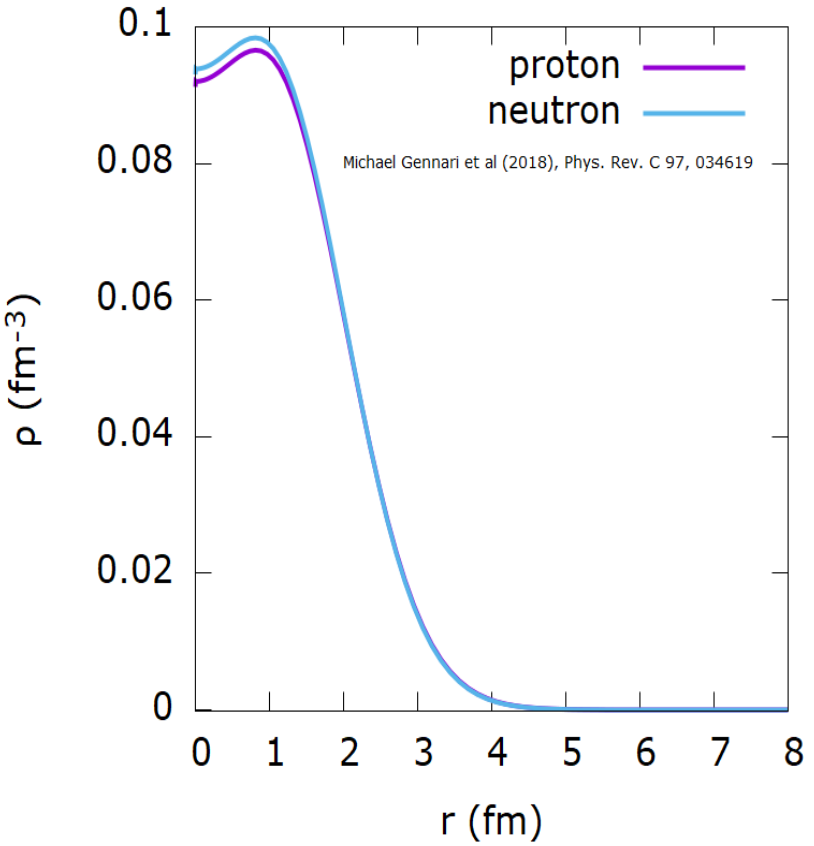
Doan Thi Loan, Bui Minh Loc, and Dao T. Khoa, *Phys. Rev.* C 92, 034304 (2015)

Dao T. Khoa, Nguyen Hoang Phuc, Doan Thi Loan, and Bui Minh Loc, *Phys. Rev.* C 94, 034612 (2016)

NUCLEAR MEAN-FIELD POTENTIAL

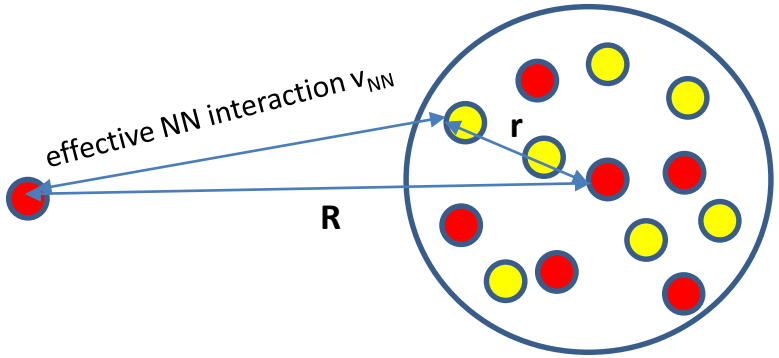
Single folding model

Nucleon density of ^{12}C at ground state



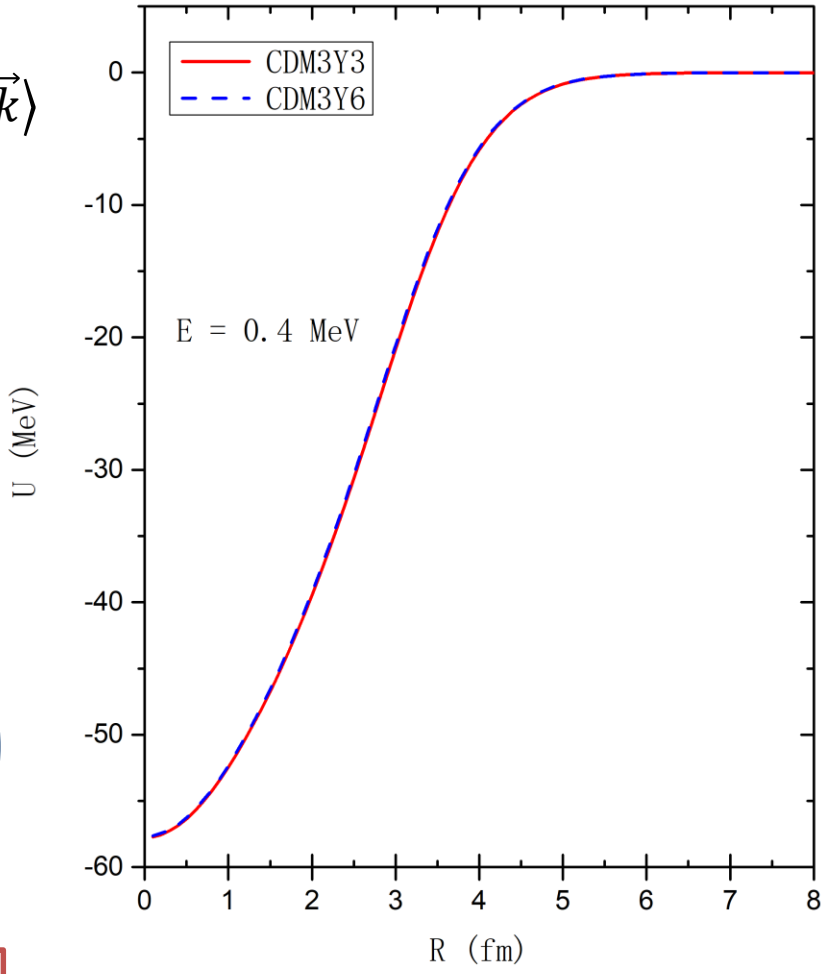
$$U = \sum_{j \in A} \langle \vec{k}, j | v_c^D | \vec{k}, j \rangle + \langle \vec{k}, j | v_c^{EX} | j, \vec{k} \rangle$$

$$U(\vec{R}) = \int dr \rho_A(\vec{r}) v_{NN}(\vec{r} - \vec{R}, \rho)$$



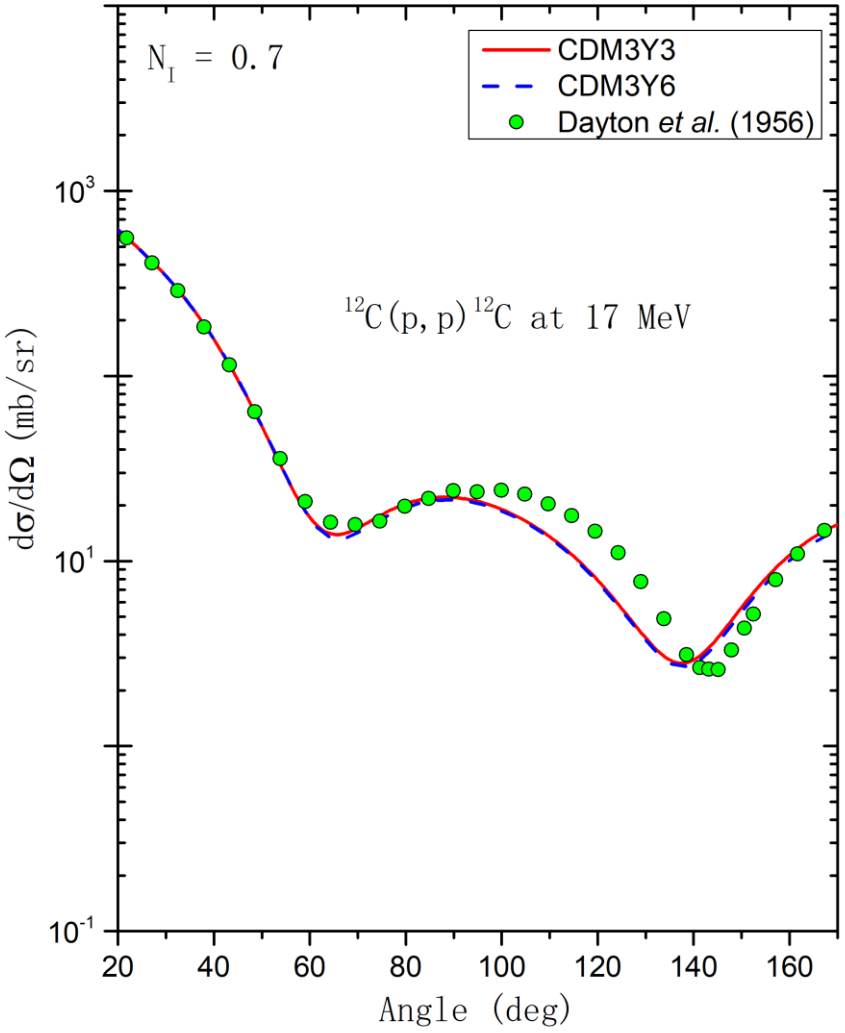
mean-field

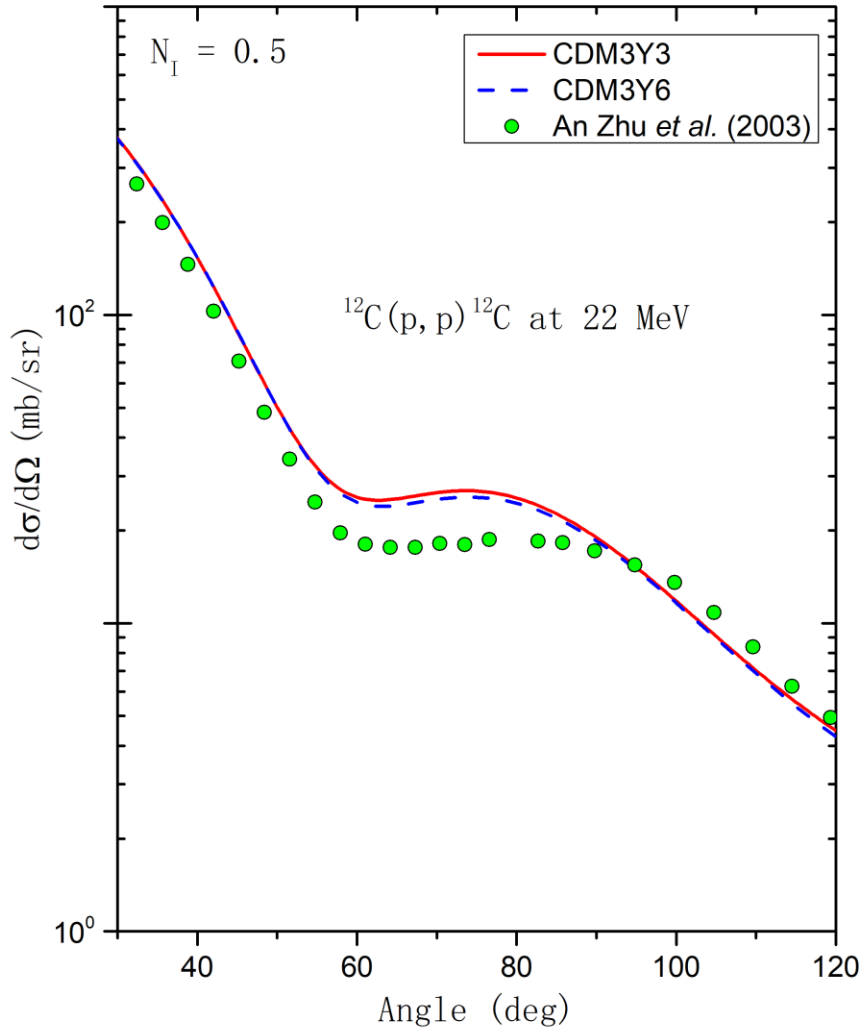
Folding model potential of p + 12C scattering



NUCLEAR MEAN-FIELD POTENTIAL

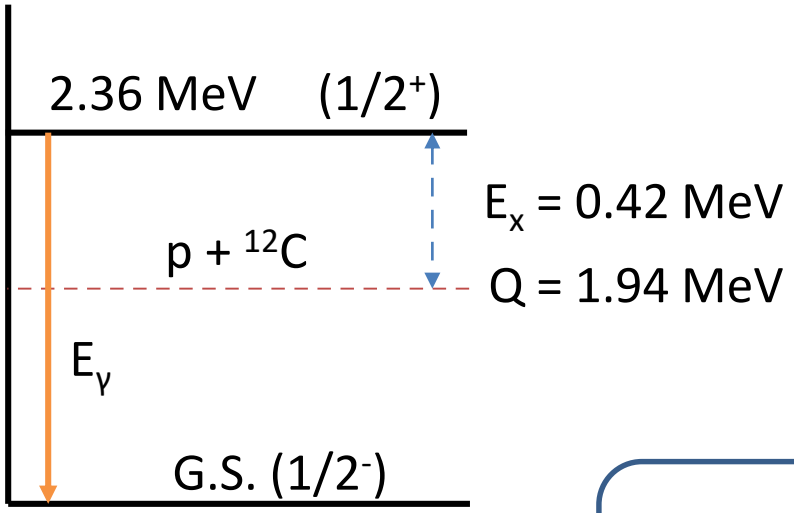
Elastic (p + ^{12}C) scattering





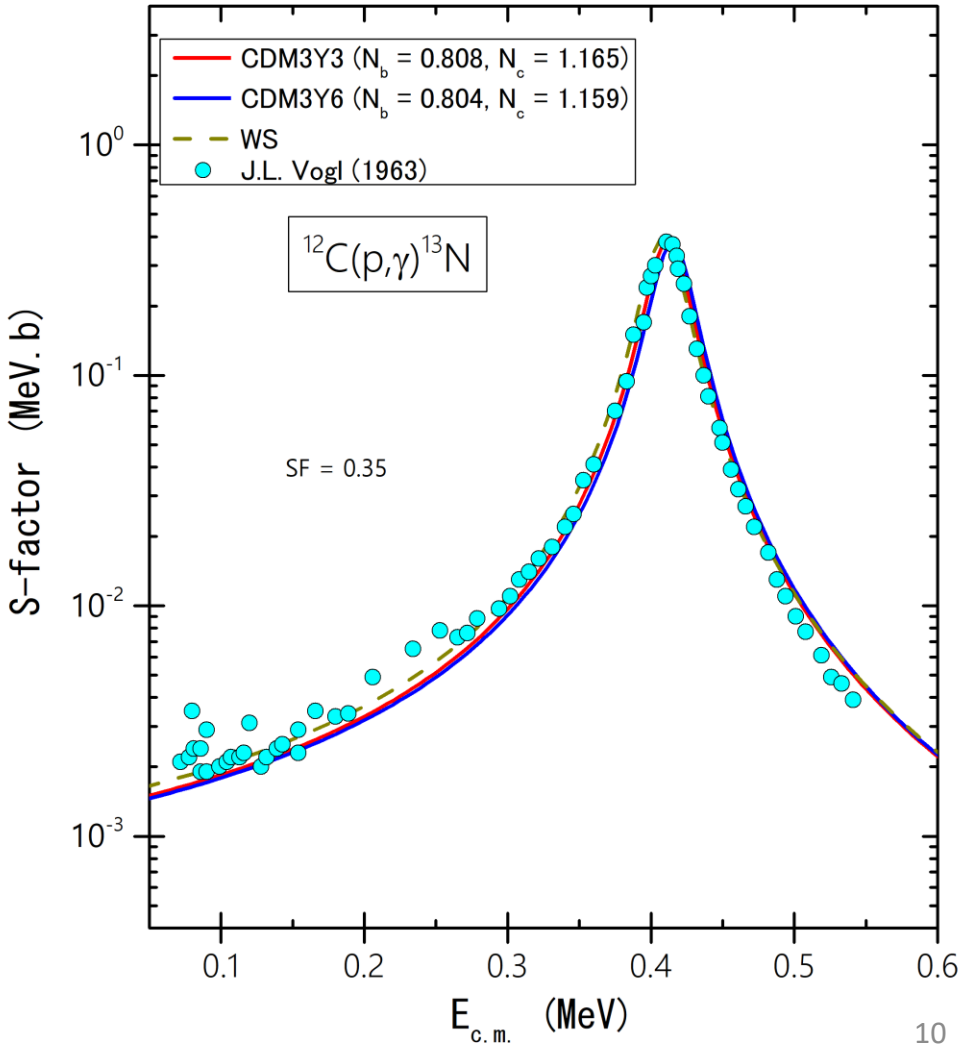
MEAN-FIELD DESCRIPTION OF THE $^{12}C(p,\gamma)^{13}N$ AND $^{13}C(p,\gamma)^{14}N$ REACTIONS

$^{12}C(p,\gamma)^{13}N$



S-factor

$$S(E) = E\exp(2\pi\eta)\,\sigma(E)$$

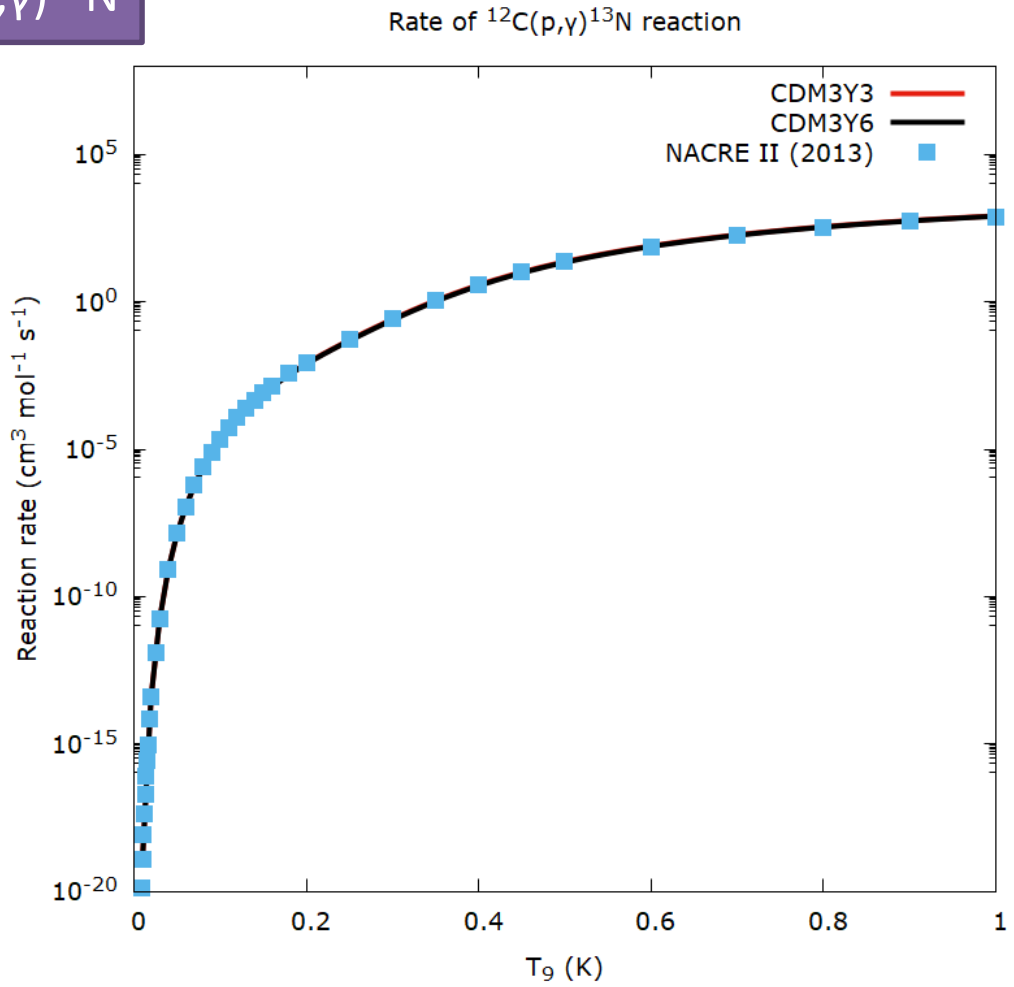


MEAN-FIELD DESCRIPTION OF THE $^{12}C(p,\gamma)^{13}N$ AND $^{13}C(p,\gamma)^{14}N$ REACTIONS

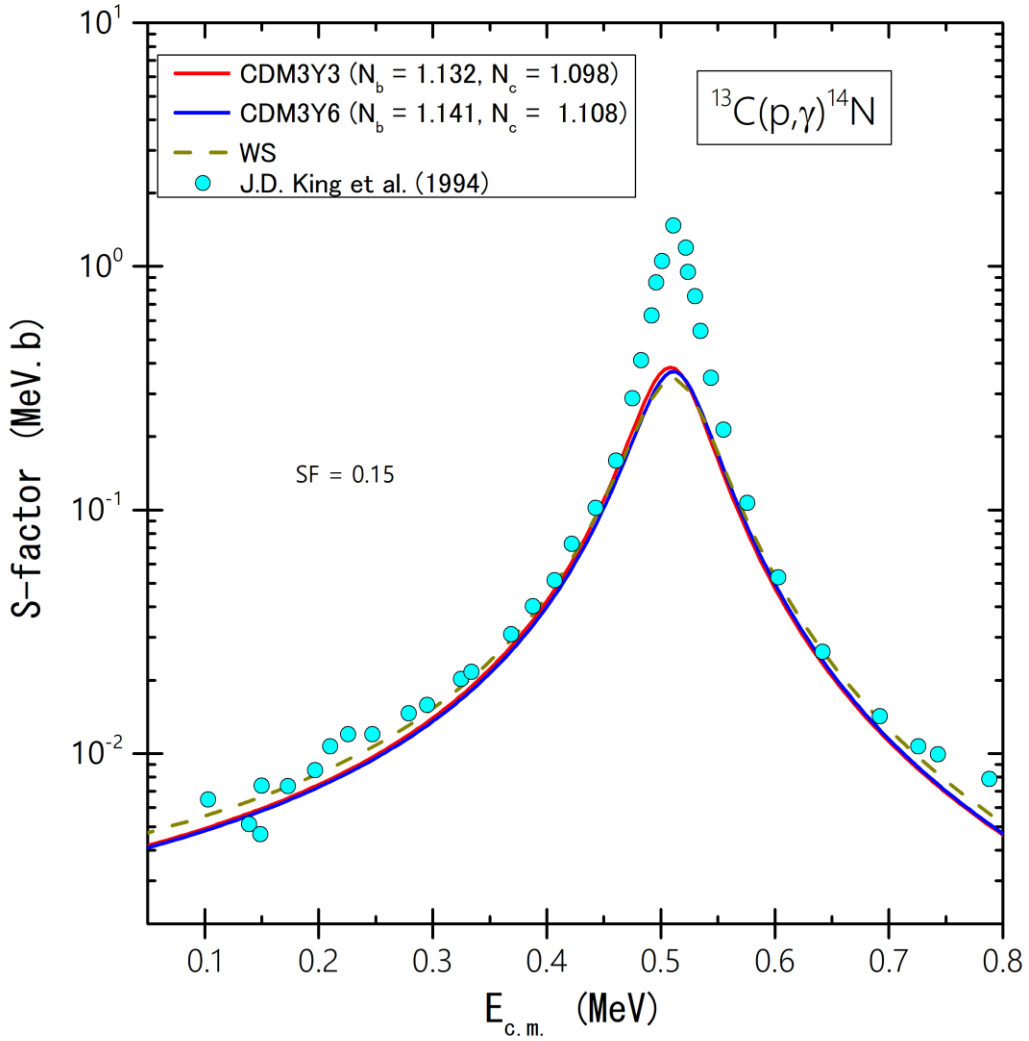
Reaction rate

$$\langle \sigma v \rangle = \left(\frac{8}{\pi\mu}\right)^{\frac{1}{2}} \frac{1}{(k_B T)^{\frac{3}{2}}} \int_0^\infty \sigma(E) E \exp\left(-\frac{E}{k_B T}\right) dE$$

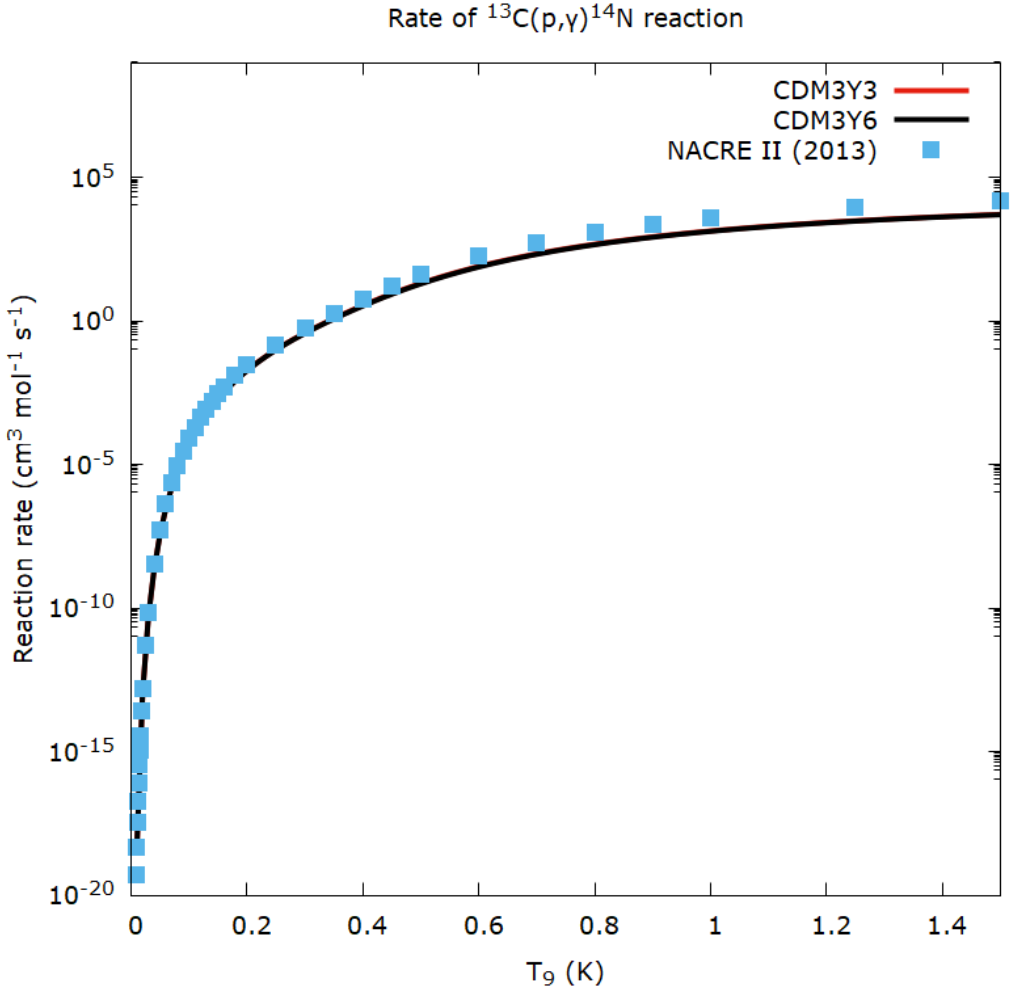
$^{12}C(p,\gamma)^{13}N$



MEAN-FIELD DESCRIPTION OF THE $^{12}C(p,\gamma)^{13}N$ AND $^{13}C(p,\gamma)^{14}N$ REACTIONS



$^{13}C(p,\gamma)^{14}N$



J. T. Huang et al. Atom.Data Nucl.Data Tabl. 96 (2010)

SUMMARY

The folded potential gives a good OM description of the elastic p+^{12}C scattering at several energies.

This SFM approach is further used to calculate the nuclear mean-field potential for the study of the astrophysical S factor of the ^{12}C(p,γ)^{13}N and ^{13}C(p,γ)^{14}N reactions.

Reaction rates of the radiative capture reactions which are an importantly astrophysical quantity are produced to describe effectively the experimental data.

THANK YOU FOR YOUR ATTENTION!