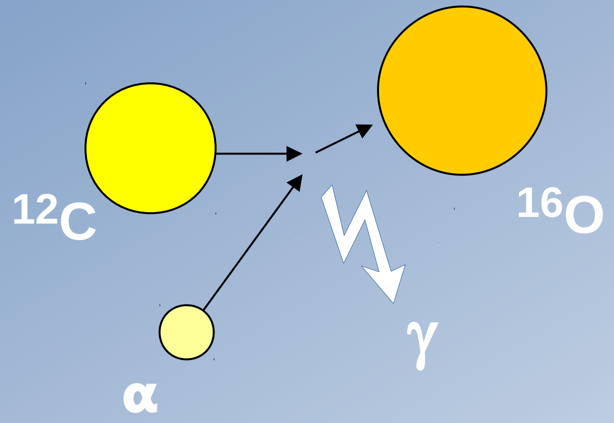
International Workshop on Neutrino Nuclear Responses for Double Beta Decays and Astro-Neutrino Interactions (NNR16)
RCNP, Osaka, 30 September, 2016

Reaction Mechanism in the stellar $^{12}C(\alpha,\gamma)^{16}O$ reaction



M Katsuma

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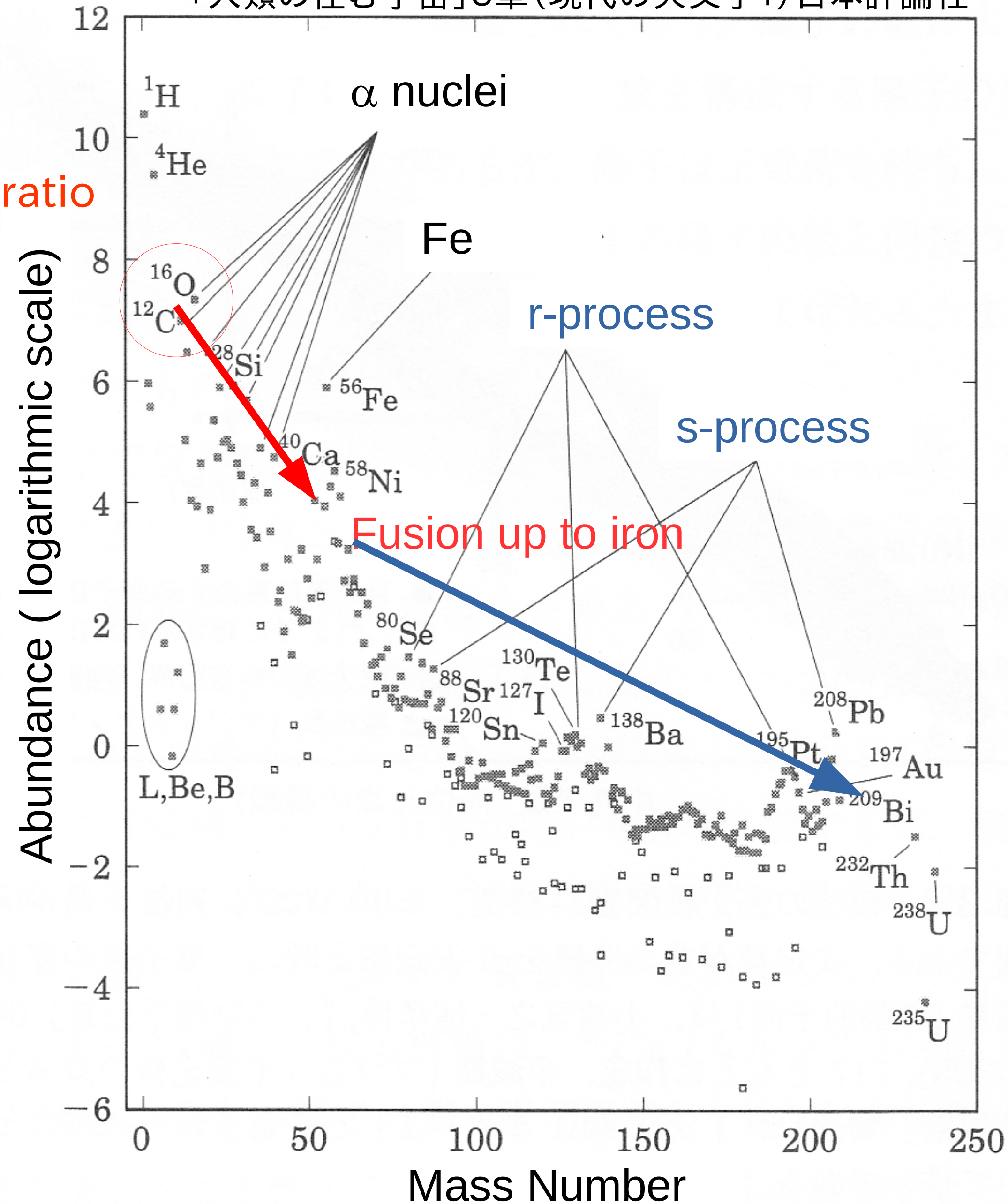
Nucleosynthesis of elements

- Oxygen is the third abundant nuclei and the product of stars.

^{1}H	70.7%	Mostly come from BBN
^{4}He	27.4%	

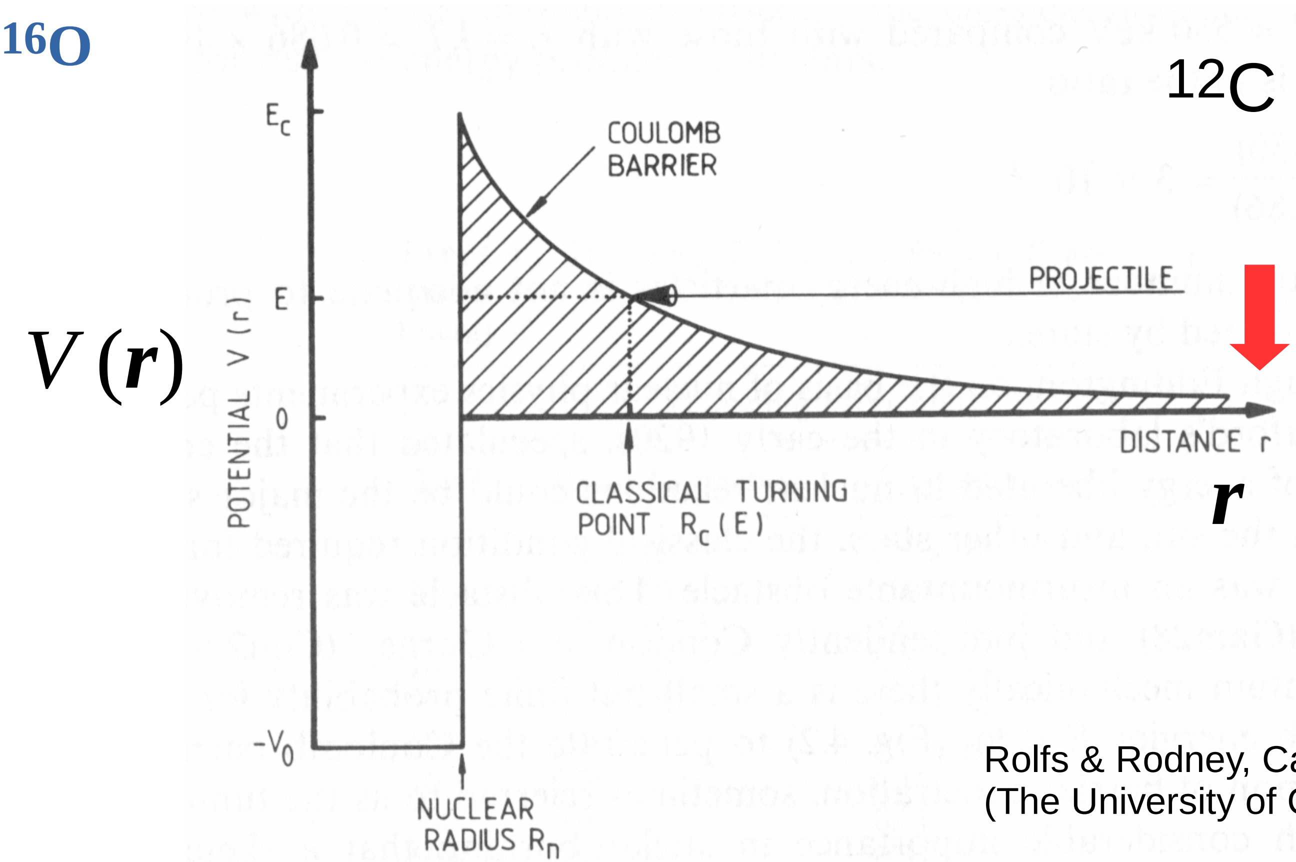
- ^{12}C(α,γ)^{16}O is the most important nuclear reaction in the nucleosynthesis of heavy elements.
  - 3α reaction is known by the Hoyle state.
- The C/O ratio is determined by ^{12}C(α,γ)^{16}O at the end of the Helium burning phase.
  - Stellar evolution
  - Concomitant nucleosynthesis
- ^{12}C(α,γ)^{16}O has the experimental difficulty due to the Coulomb barrier.

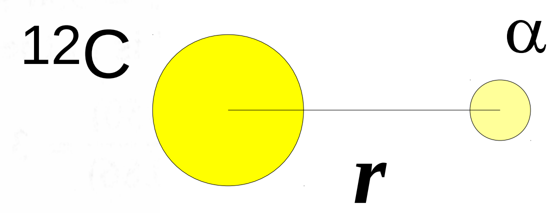
「人類の住む宇宙」3章（現代の天文学1）日本評論社



Coulomb barrier

- $^{12}C(\alpha,\gamma)^{16}O$

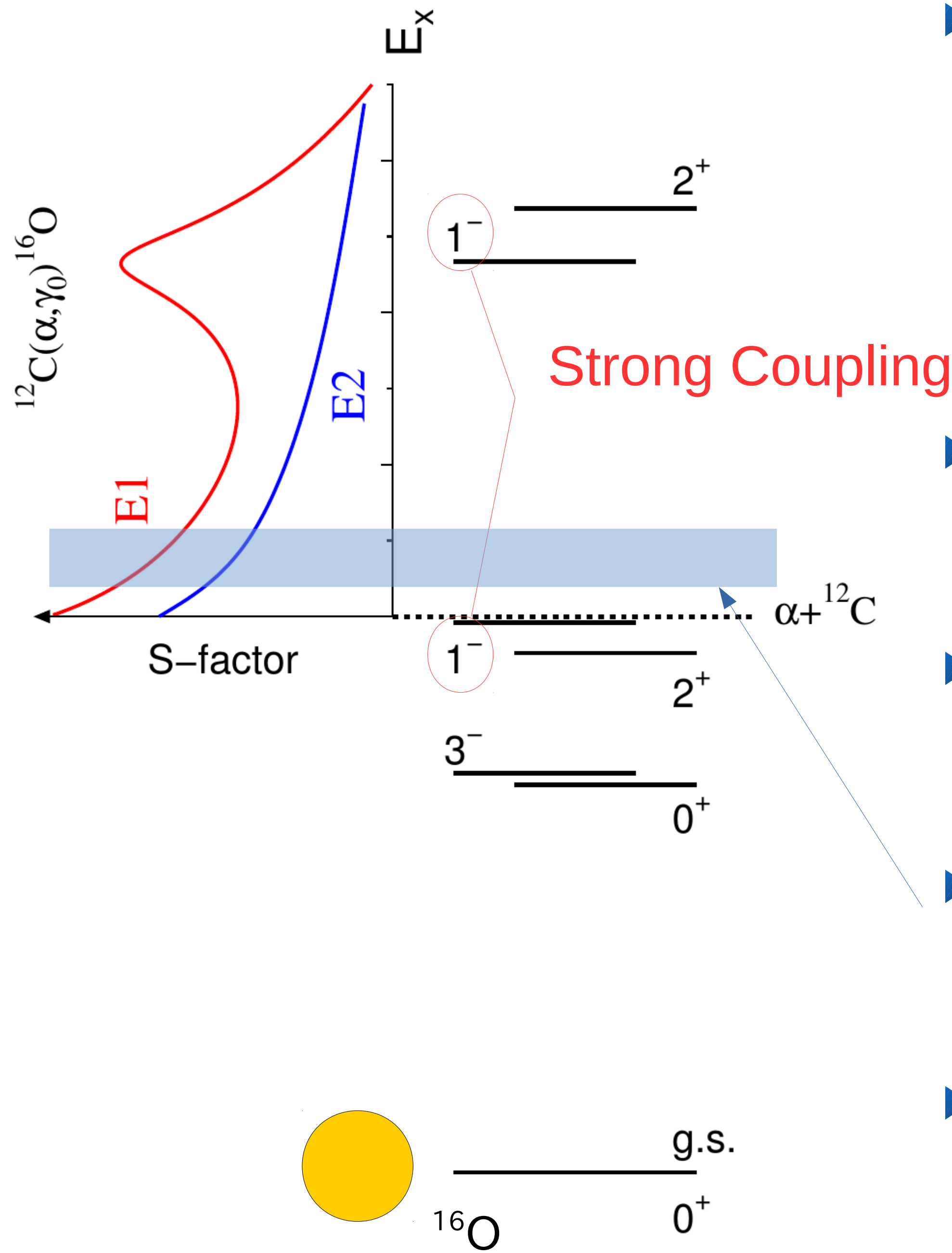




Rolfs & Rodney, Cauldrons in the Cosmos
(The University of Chicago Press 1988)

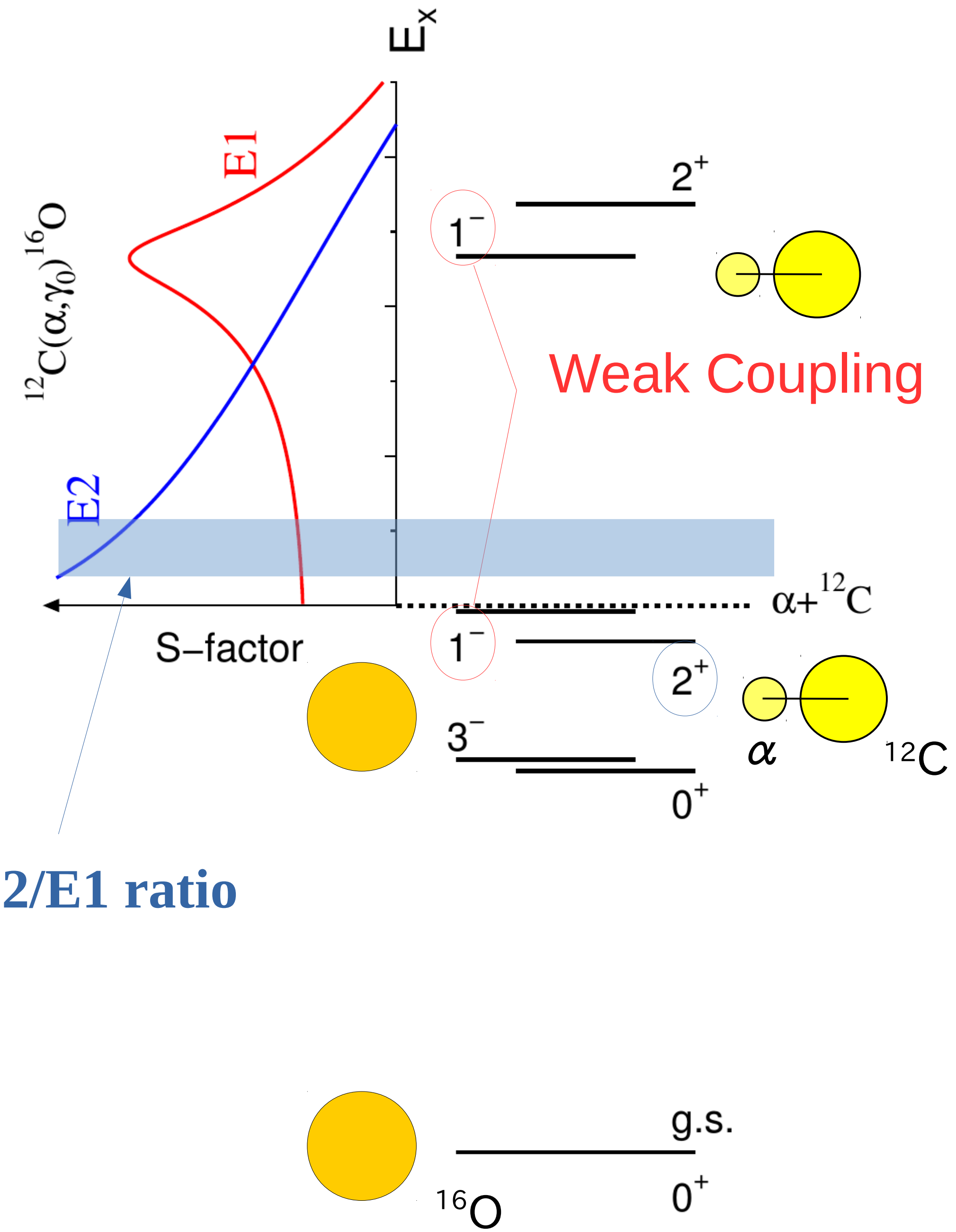
- The cross sections are very small due to the Coulomb barrier.
- Cross section at $E_{c.m.} = 300$ keV (Helium burning temperature)
  - The lowest energy of the experimental work is approximately 1.2 MeV.
  - The cross section is inferred from the indirect measurements.
  - The extrapolation to low energies is made by the theoretical model.

Reaction Mechanism



- The 1^-_1(E_x= 7.12 MeV) and 1^-_2 (E_x= 9.59 MeV) states play an important role in the extrapolation of the low-energy cross section.
- Complicated process of the compound nucleus
- The strong interference between two 1^- states.
- **E1 transition** is predominant in the strong coupling mechanism.
- At present, this interference has been believed to describe the cross section at $E_{c.m.}$= 300 keV.

Reaction Mechanism (this work)

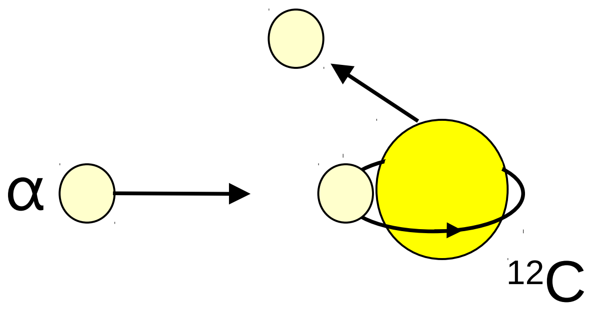


E2/E1 ratio

- **E2 transition** plays the important role in the extrapolation.
- This is caused by the 2^+_1 state. (E_x= 6.92 MeV)
- **$\alpha+^{12}C$ molecular (cluster) state**
- The 1^-_2 state is different from the subthreshold 1^-_1 state.
- Weak coupling is expected between two 1- states.
- E1 is negligible, compared with the contribution from the $\alpha+^{12}C$ molecular state.

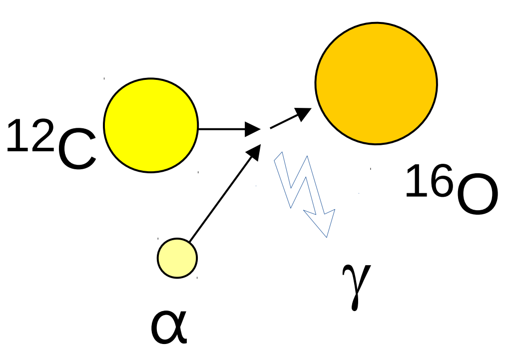
Present report

Theoretical result based on the **potential model**, describing the fundamental process of the nuclear reaction in the weak coupling.



α+^{12}C cluster states in ^{16}O

- Entrance channel of $^{12}C(\alpha,\gamma)^{16}O$
- Molecular resonances and rotational bands in ^{16}O



$^{12}C(\alpha,\gamma)^{16}O$ with the potential model

- E2 transition dominates the low-energy cross section.
- Discuss the weak coupling, the reduced E1 component, and the derived reaction rates.
- Recent experimental data of γ-ray angular distribution

$$\sigma_{\gamma\alpha} > \sigma_{\alpha\gamma}$$

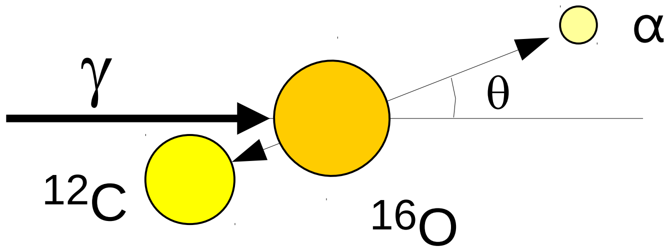
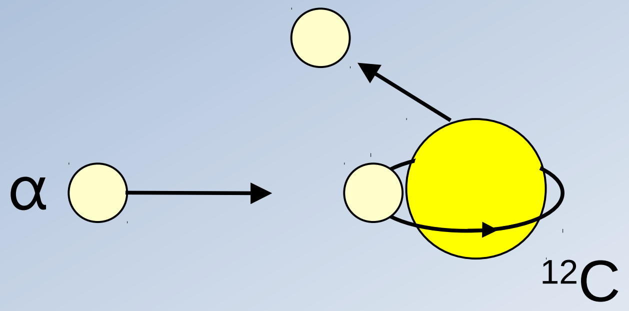


Photo-disintegration of ^{16}O

- The photo-disintegration is expected to provide more accurate experimental information.
- Inverse reaction of $^{12}C(\alpha,\gamma)^{16}O$

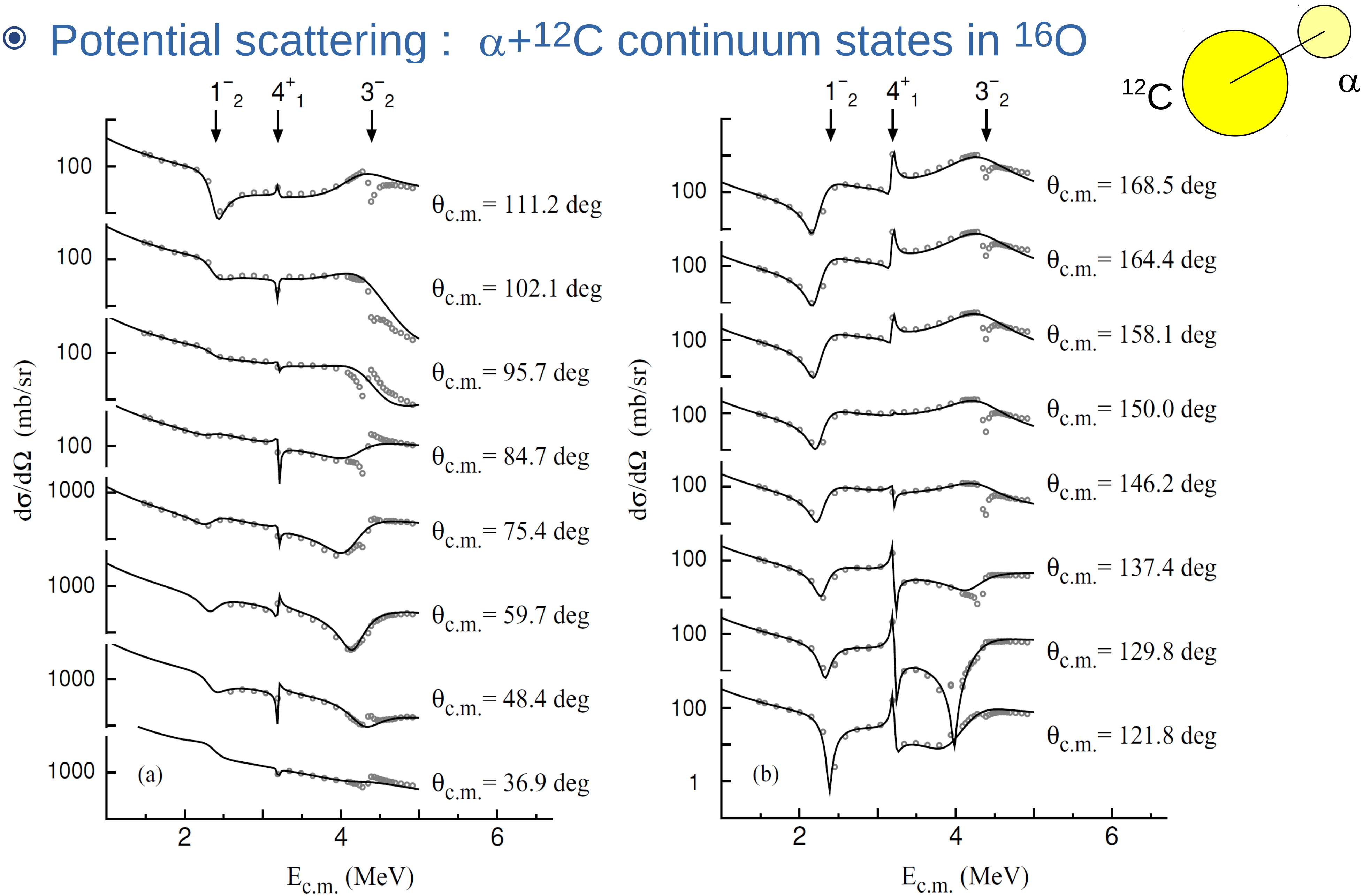
α+^{12}C cluster states in ^{16}O



Potential scattering of α-particle

Excitation functions of α+^{12}C elastic scattering

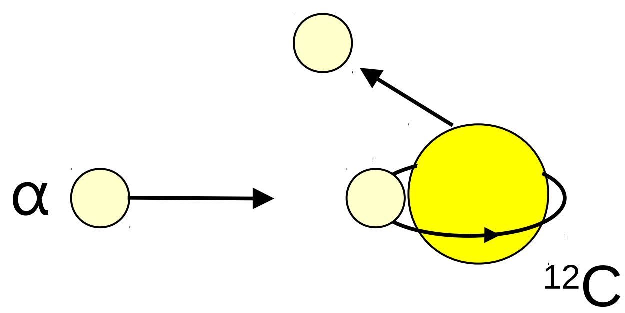
- Potential scattering : α+^{12}C continuum states in ^{16}O



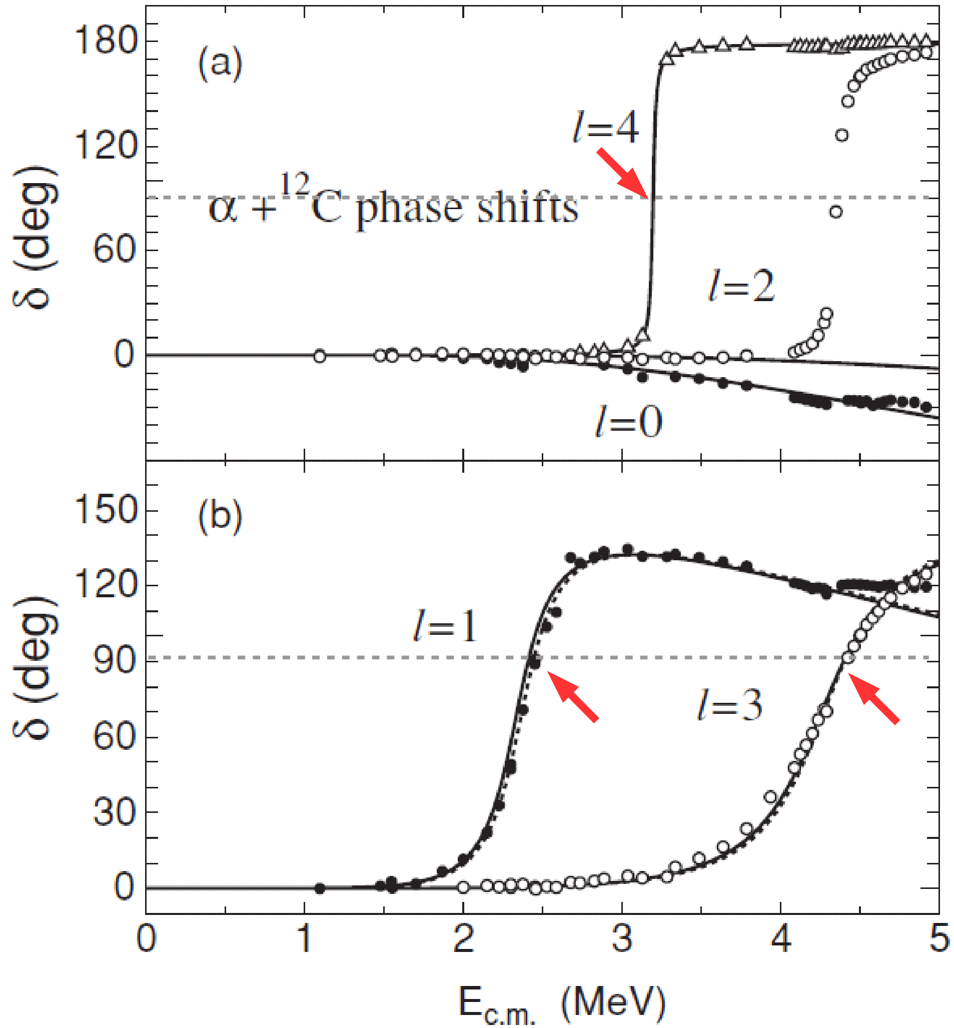
Exp.: R. Plaga *et. al.*, NPA465, 291 (1987)

Phase shifts of α+^{12}C elastic scattering

- α+^{12}C molecular resonances
  - δ = 90 deg.
  - p-, f-, g-waves (l = 1,3,4)



Exp.: R. Plaga *et. al.*, NPA465, 291 (1987)



- Woods-Saxon (WS) potentials
  - Parity-dependence

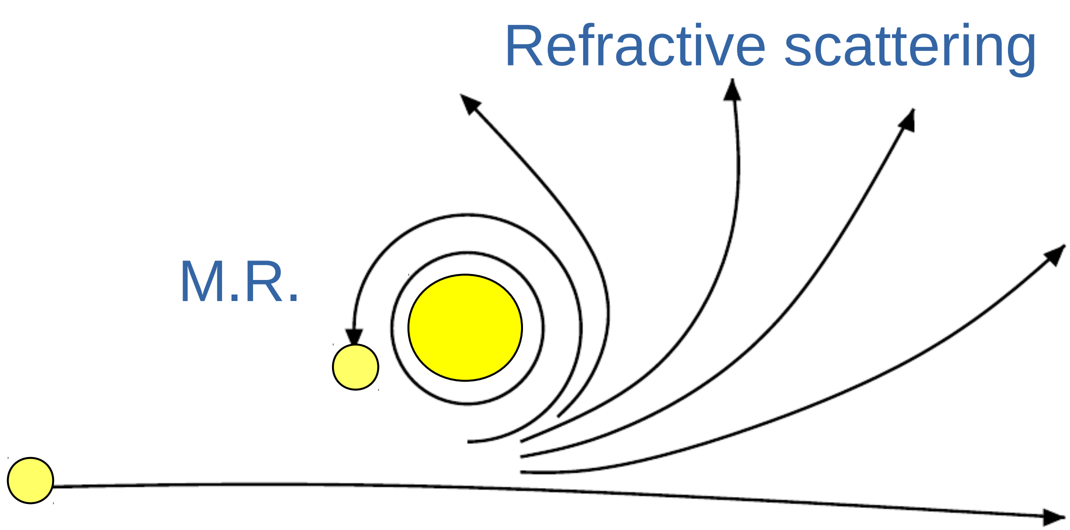
$$V(r) = -\frac{V_\xi}{1 + \exp[(r - R_\xi)/a_\xi]}$$

  - The potential used in the present study does not have the absorption, and it is transparent in the entire region.
  - The α+^{12}C system can be treated in the weak coupling.

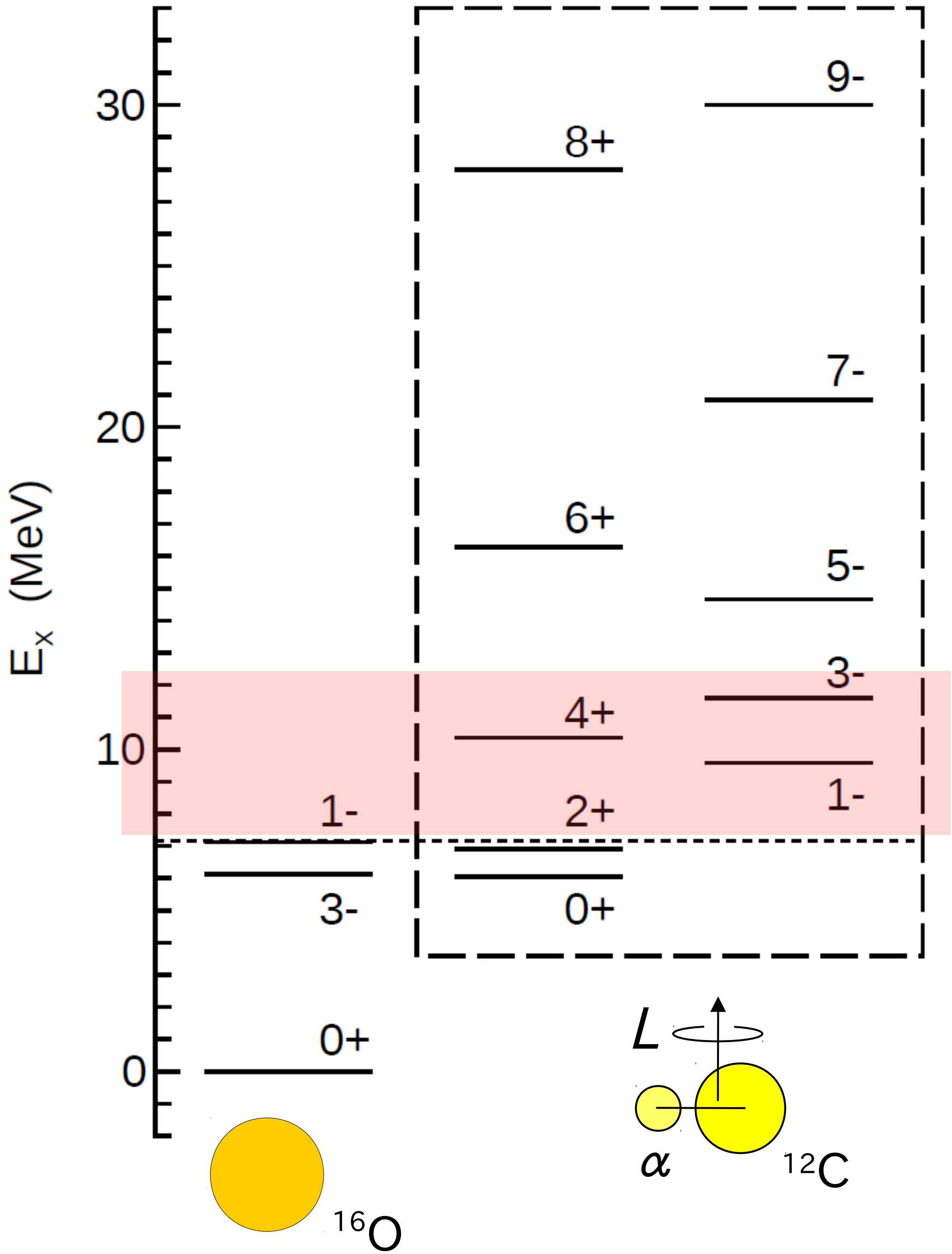
Rotational Bands in ^{16}O

- The used potential makes the sequence of the rotational excitation mode.
  - N=8 (even), N=9 (odd)

- Optical potentials for α-particle elastic scattering at high energies.
  - α-particle can go round in circles at low energies.
  - α-particle tends to go straight as the energy increases.



Trajectory of the incident α-particle.

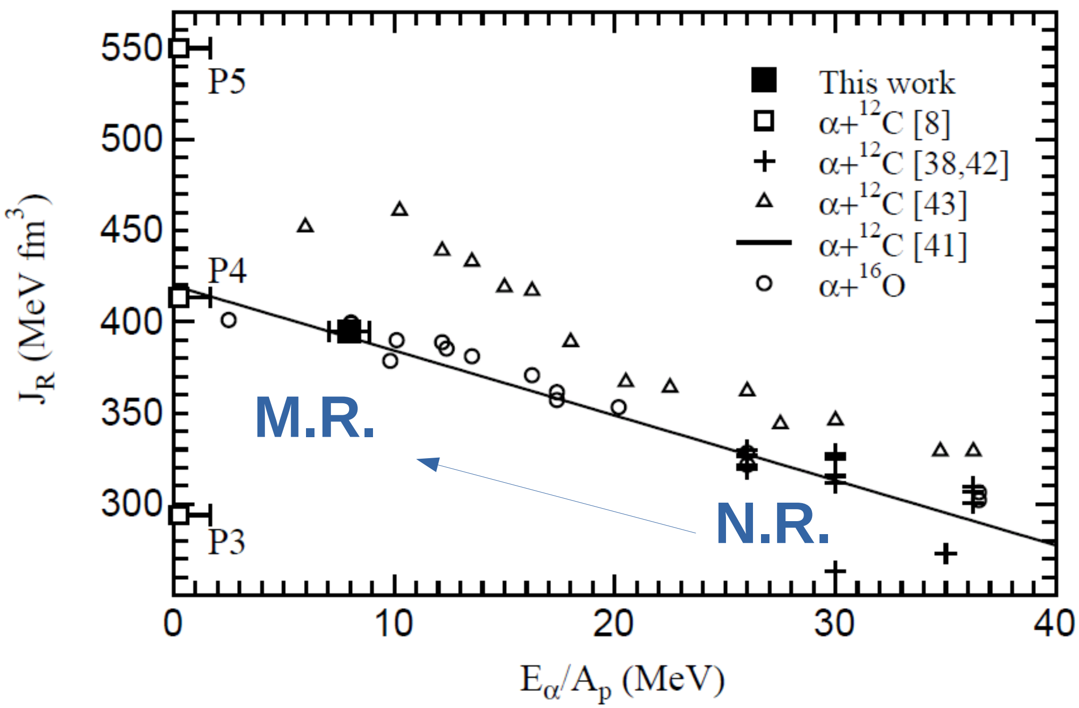


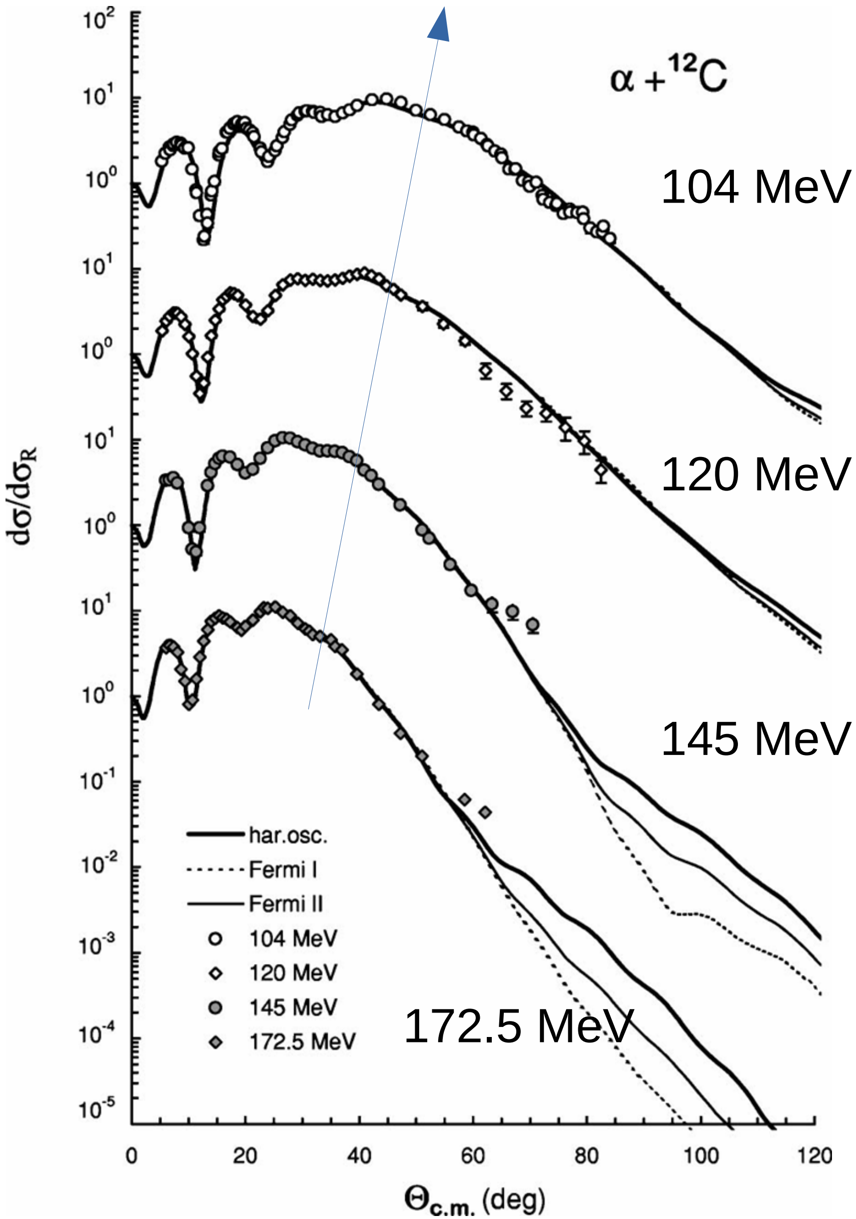
Refractive scattering (Nuclear rainbow)

- Elastic scattering at high energies
  - Backward angles: Dark region
  - determine the strength of the nuclear potential at low energies
- Volume integrals of the potential

$$J_R = \frac{4\pi}{A_p A_t} \int |V(r)| r^2 dr,$$

  - The smooth energy variation



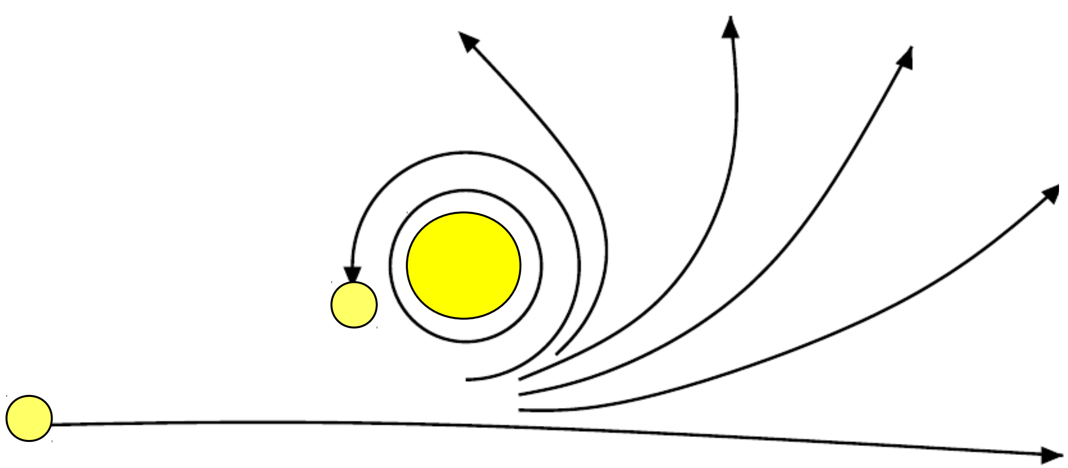


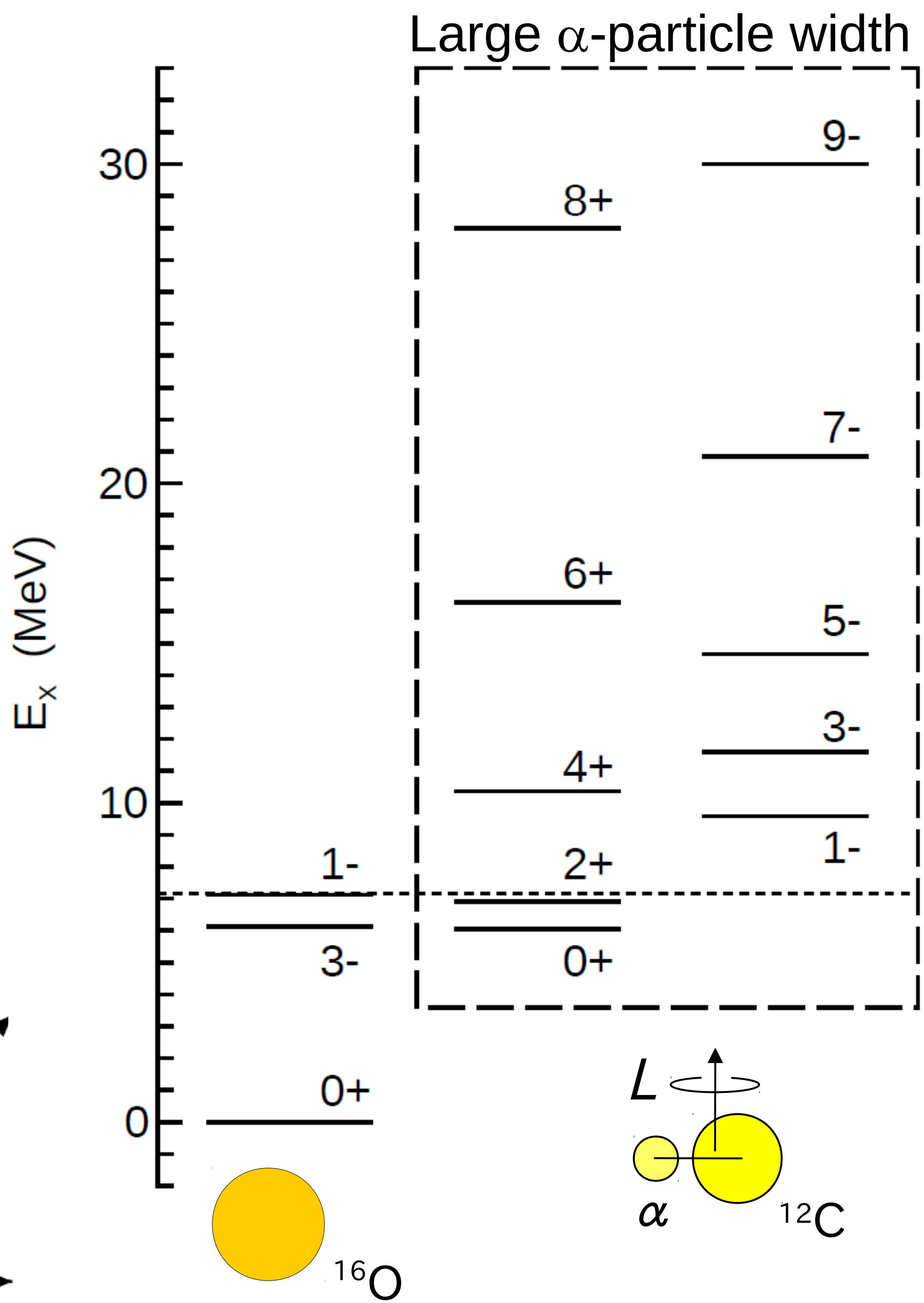
Right: D.T. Khoa, PRC **63**, 034007 (2001)

Left: M. Katsuma, J Phys. G40, 025107 (2013)

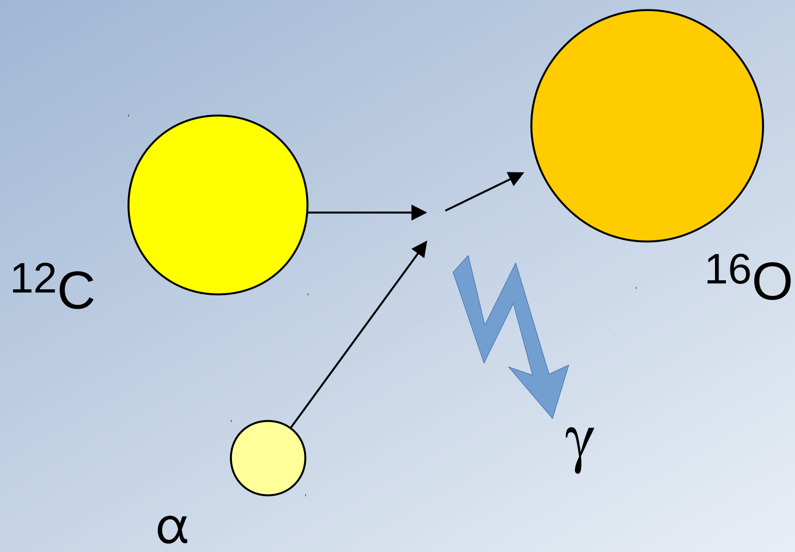
Summary: α+^{12}C cluster states in ^{16}O

- Good wavefunction of the α+^{12}C cluster states in ^{16}O through the study of elastic scattering.
- The resulting α+^{12}C molecular states satisfy the semi-classical limit of the quantum system.
- The **weak coupling** can be expected from non-absorption.
- Large α-particle width
- The subthreshold 1^-_1 state is not a member of the molecular bands.





$^{12}C(\alpha,\gamma)^{16}O$



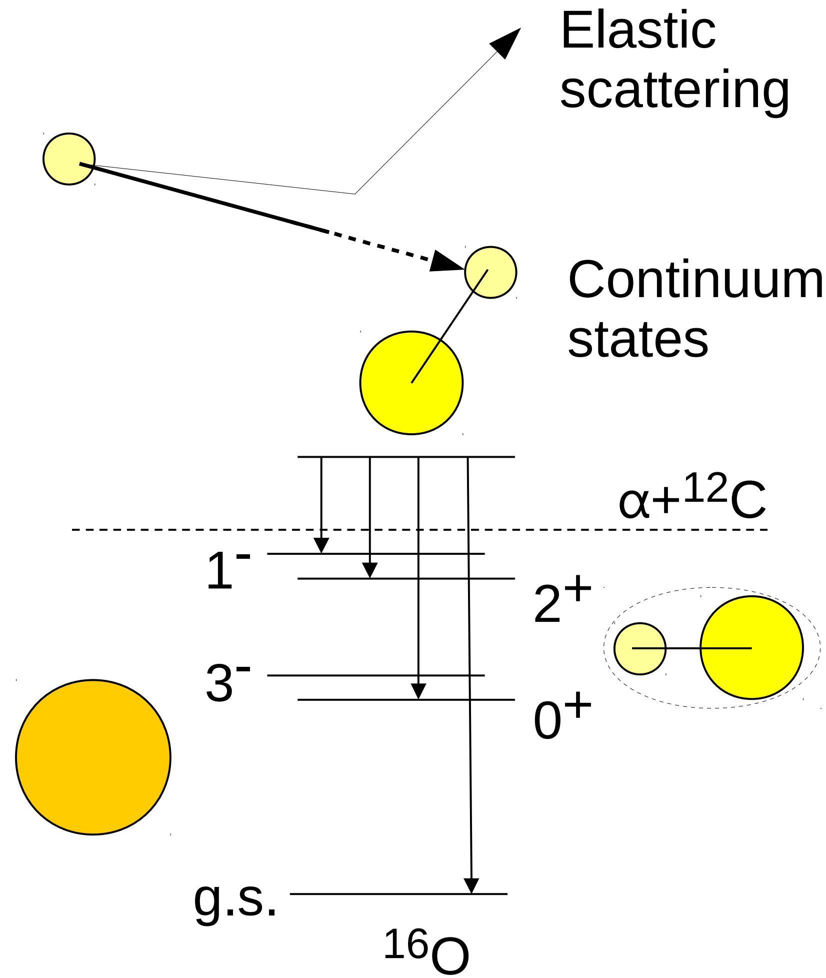
Radiative capture cross sections

$$\sigma \propto \left| \langle \varphi_f | \, e \, M_\lambda^E | \varphi_i \rangle \right|^2$$

Input: (1) Potentials
(2) Effective charge

- **Initial waves**
  - Generated from the potential describing elastic scattering.
- **Bound states**
  - α+^{12}C molecular states (0^+ and 2^+ states)
    - The potential is the same as that for the scattering states.
  - Shell model states (g.s., 3^- and 1^- states)
    - Separation energy method:

      The potential strength is adjusted to reproduce the α-particle separation energy. This method gives appropriate wavefunction in the peripheral region.
- **Effective charges**
  - obtained phenomenologically.



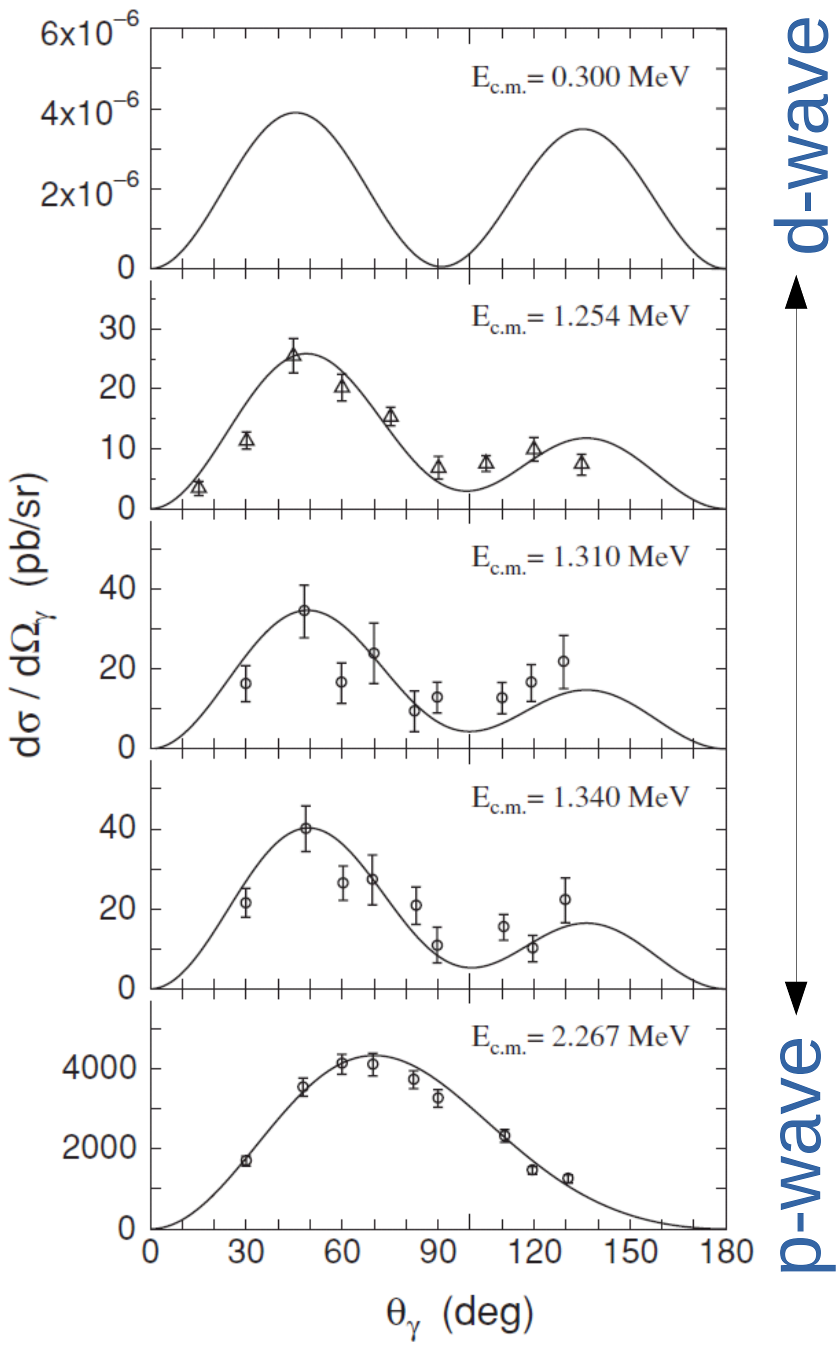
γ-ray angular distributions of $^{12}C(\alpha,\gamma_0)^{16}O$

- Potential model

$$\frac{d\sigma}{d\Omega_\gamma}(\theta_\gamma, E_{\text{c.m.}}) = \sum_{j=0}^{4} c_j P_j(\cos\theta_\gamma),$$

$$c_j = \sum_{\lambda\lambda' f f' i i'} d_j \frac{k_\gamma^{\lambda+\lambda'+1}}{\hbar v} \langle \phi_f || M_\lambda^E || \phi_i \rangle \langle \phi_{f'} || M_{\lambda'}^E || \phi_{i'} \rangle^*.$$

  - The reproduction of the data looks good.
  - p-wave at 2.267 MeV.
  - d-wave becomes important at lower energies.



- Cross sections

$$\sigma(E_{\text{c.m.}}) = 4\pi c_0$$
$$= \sigma_{E1}(E_{\text{c.m.}}) + \sigma_{E2}(E_{\text{c.m.}})$$

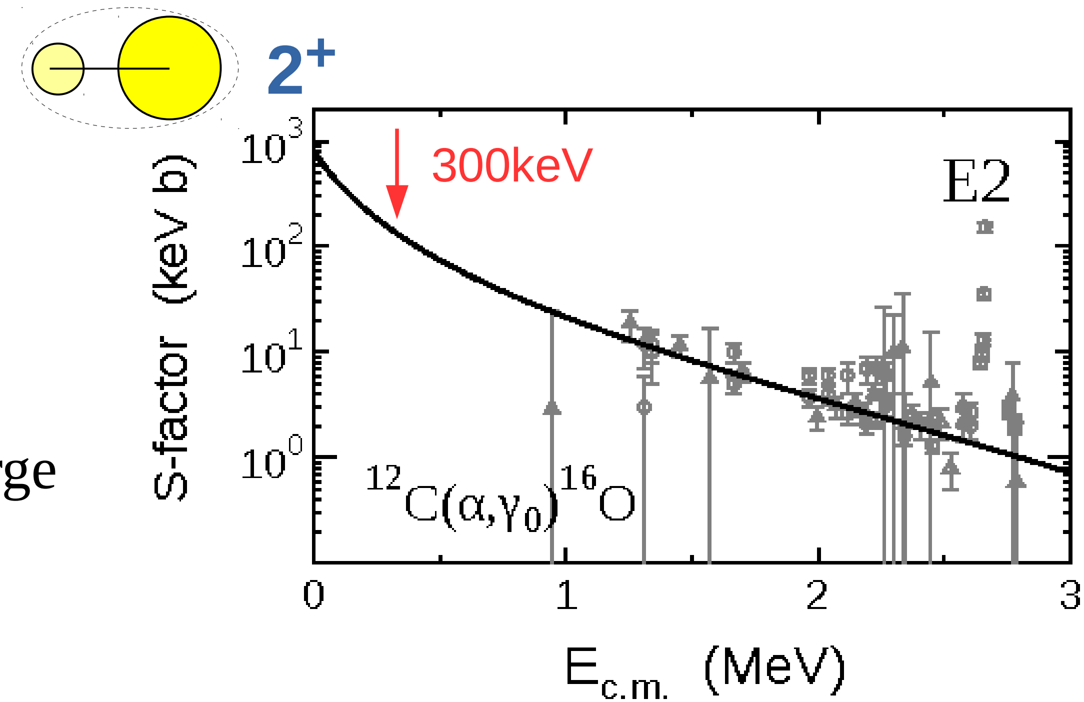
Exp.: M. Assunção, *et. al.*, PRC73, 055801 (2006)
R. Kunz, *et. al.*, PRL86,3244 (2001)

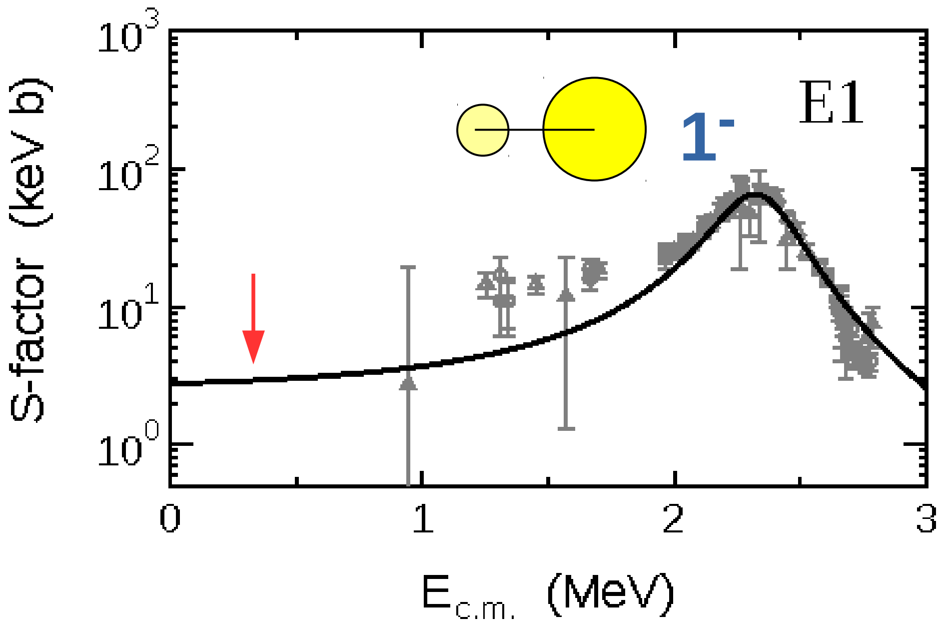
Astrophysical S-factors – Cross sections

$$S(E_{\rm c.m.}) = E_{\rm c.m.} \exp(2\pi\eta)\,\sigma(E_{\rm c.m.}),$$

$$\eta = Z_1 Z_2 e^2/\hbar v$$

- Strong enhancement of E2.
  - Two molecular states have the large width in the electric transition.
    - 2^+ state below the threshold
    - 1^- resonance at 2.4 MeV
  - The theoretical E1 value slightly deviate from the experimental one.
  - The separation of E1 and E2 is performed by the analysis of the γ-ray angular distribution, that looks good in the present model.



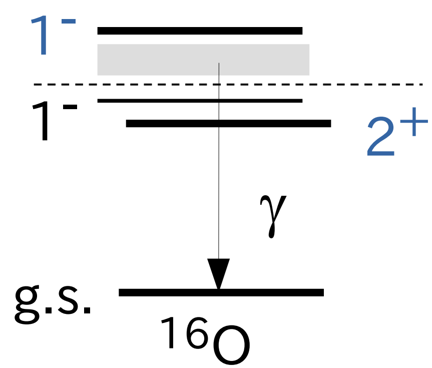


Exp.: M. Assunção, *et. al.*, PRC73, 055801 (2006)
R. Kunz, *et. al.*, PRL86,3244 (2001)

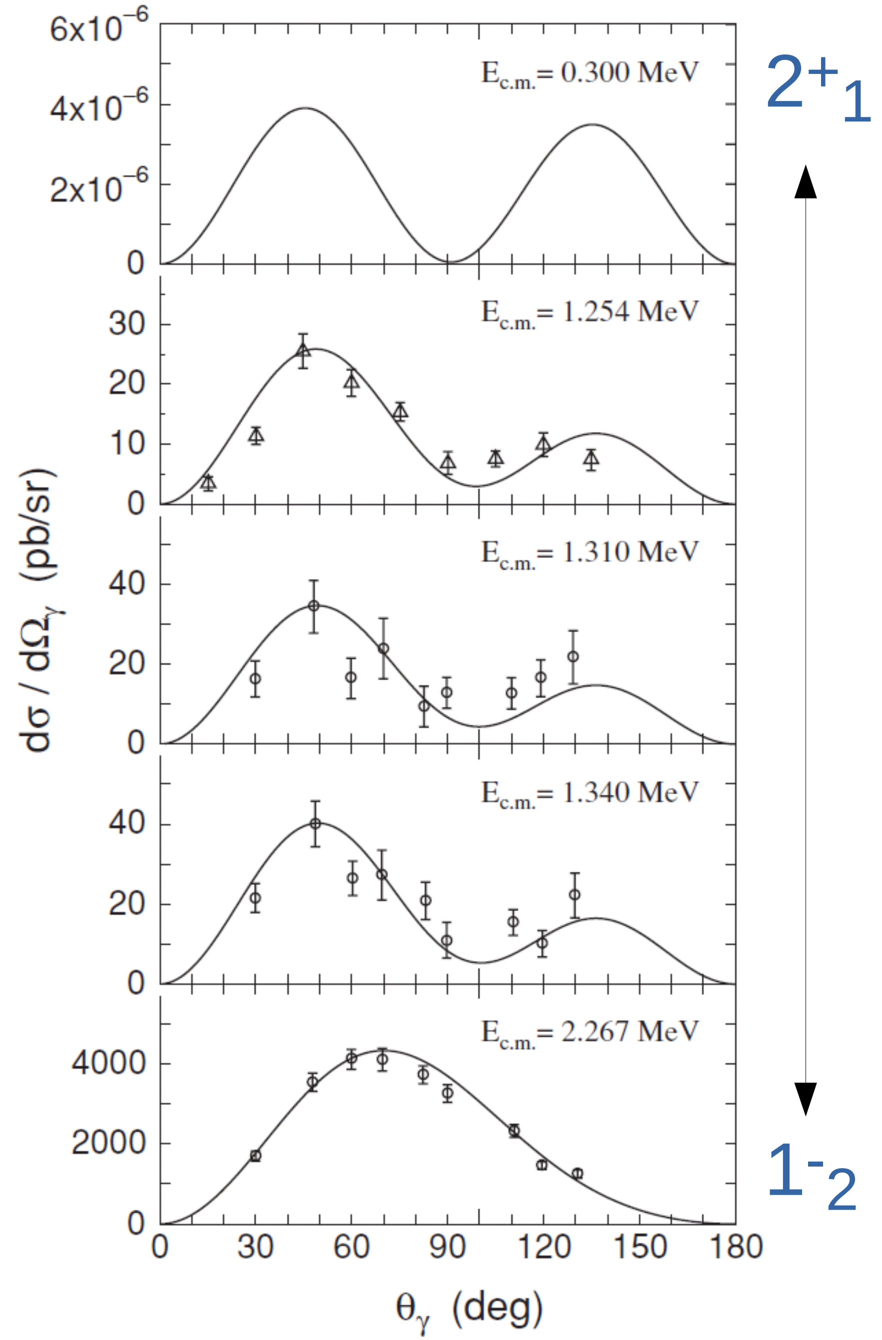
Interference between two molecular states

- The experimental S-factor is reproduced by the potential model with the reduced E1 S-factor.

- The angular distribution appears to be made from the interference between the 1^-_2 and 2^+_1 molecular states.
  - d-wave: 2^+_1
  - p-wave: 1^-_2



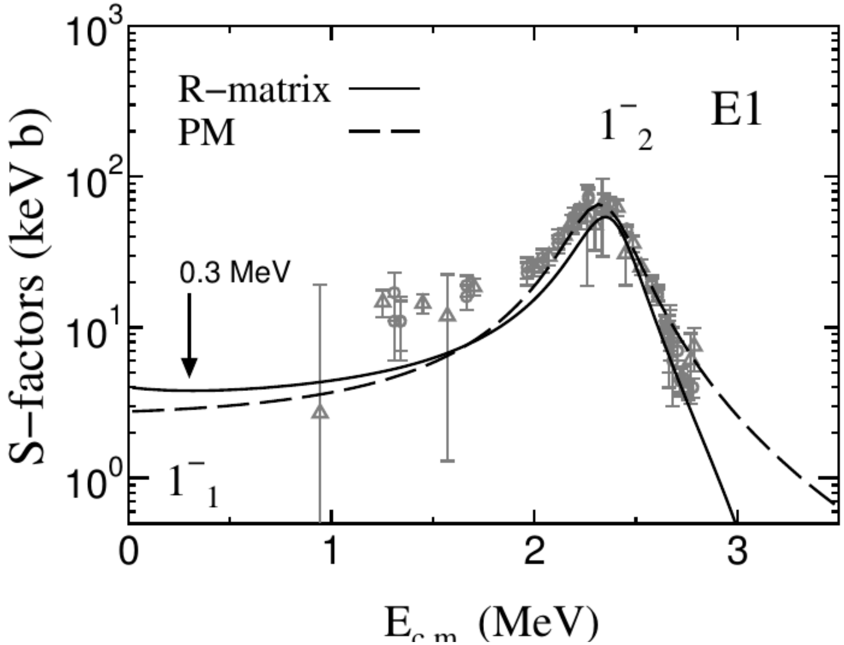
- The **weak coupling** between 1^-_1 and 1^-_2 seems to be advocated.
  - The E1 contribution from the subthreshold 1^- state is not necessarily required.

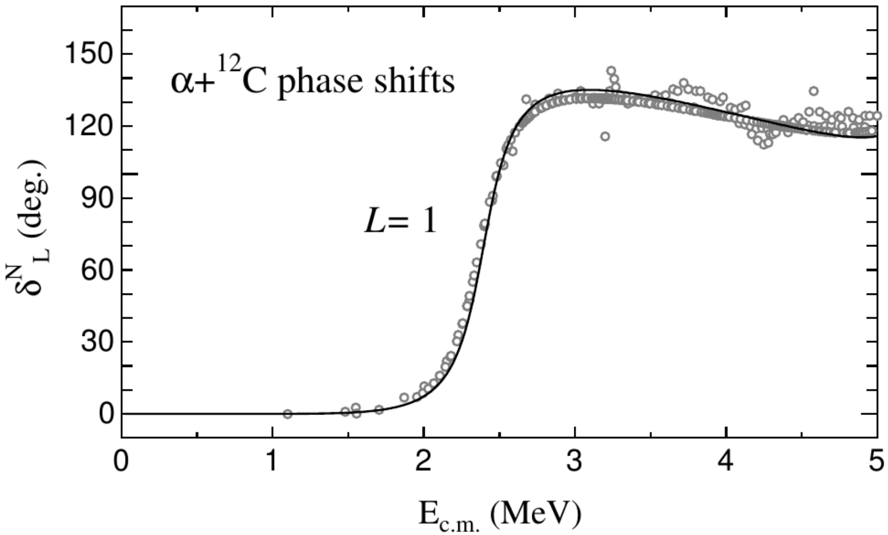


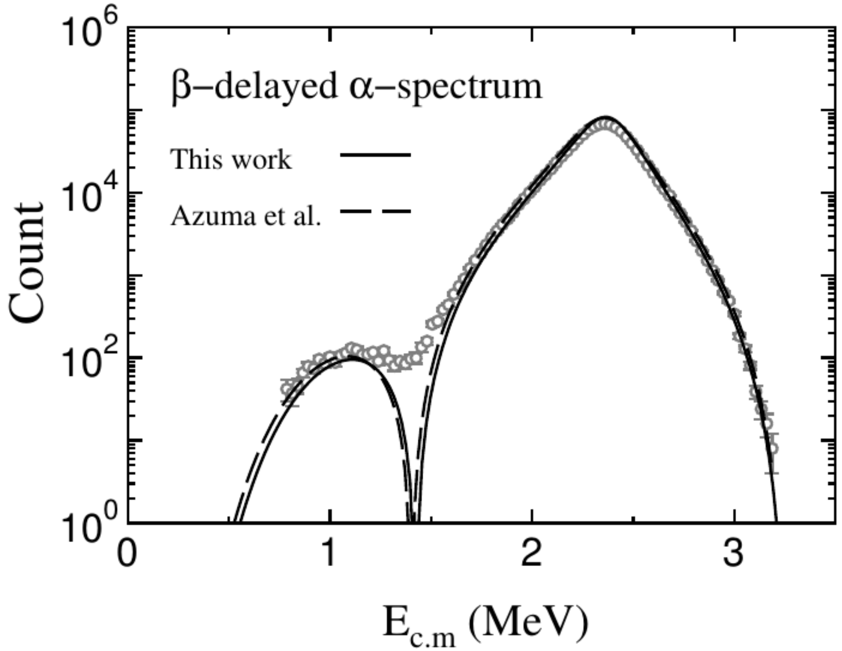
Exp.: M. Assunção, *et. al.*, PRC73, 055801 (2006)
R. Kunz, *et. al.*, PRL86,3244 (2001)

Reduced E1 S-factor

- R-matrix
  - The compatible calculation of E1 transition is obtained from R-matrix.
  - α-particle width and ANC from the potential model.
  - Channel radius: 4.5 fm
- E1 is not enhanced at low energies.
  - β-delayed α-spectrum of ^{16}N is reproduced in the same quality of fits. (p-wave)



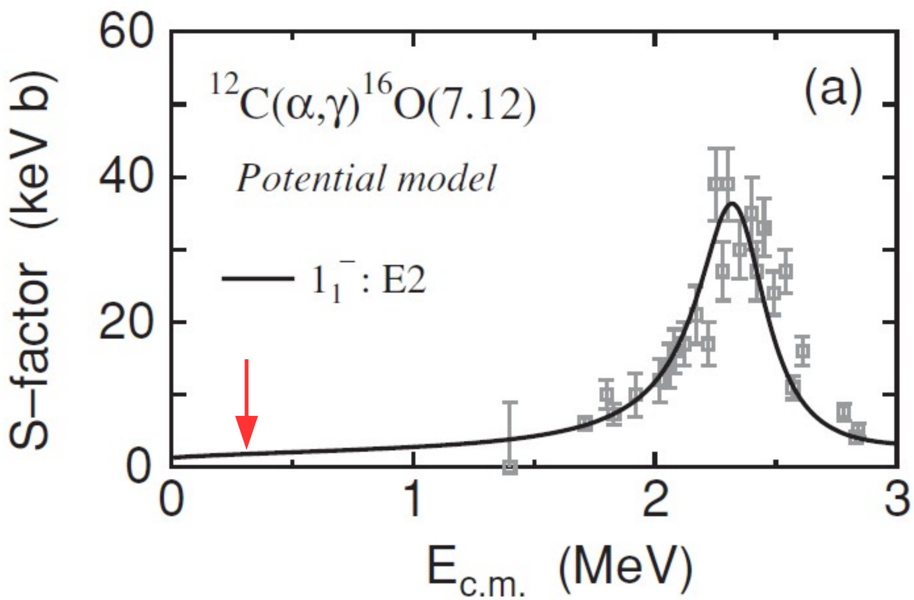


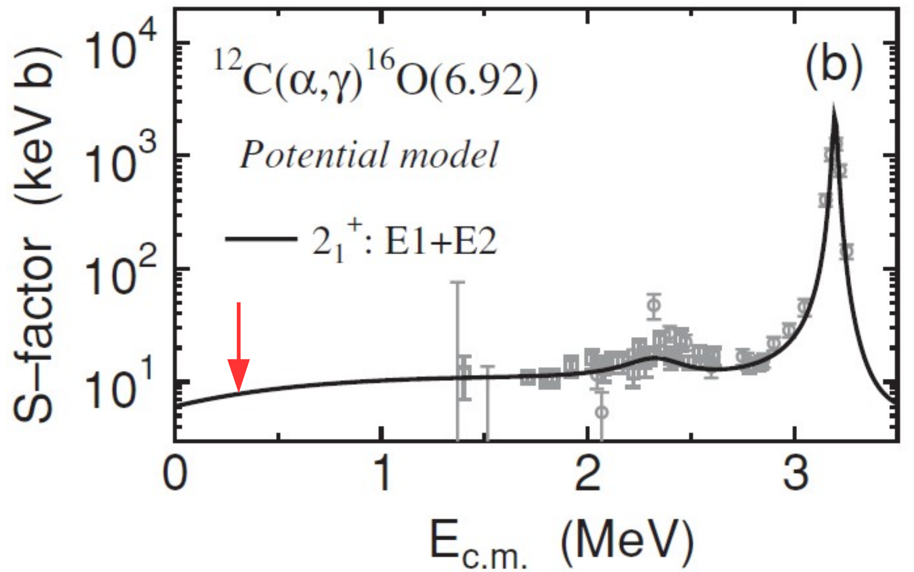


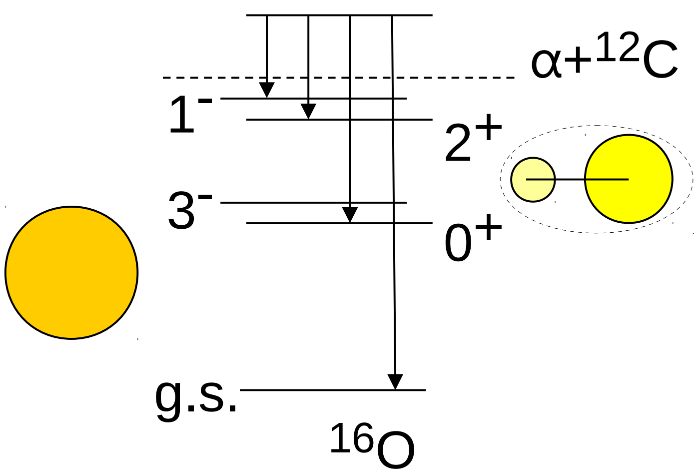
Exp: R.E. Azuma et al., PRC50, 1194 (1994).
P. Tischhauser et al., PRC79, 055803 (2009)

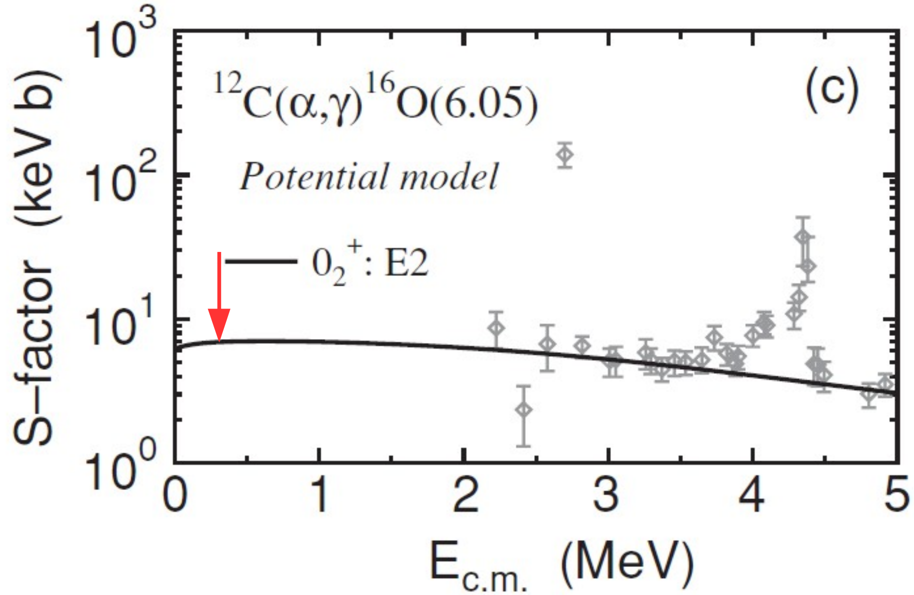
Cascade transitions

- Not important below $E_{\mathrm{c.m.}}$ = 1 MeV (≈ 18 keVb at $E_{\mathrm{c.m.}}$= 300 keV)









Exp.: K.L. Kettner, *et. al.*, Z.Phys. A308,73 (1982)
C. Matei, *et. al.*, PRL97, 242503 (2006)
A. Redder, *et. al.*, NPA462, 385 (1987)

Astrophysical S-factors at 300 keV

(S-factors are in unit of keV b.)

	This work	KU02	NACRE	BU96
E1	**3**	76±20	79±21	79±21
E2	**150^{+41}_{-17}**	85±30	120 ± 60	70±70
Cascade	**18±4.5**	4±4	-	16±16
Total	**171^{+46}_{-22}**	165±54	199±81	165±107

- Total S-factor from the potential model is consistent with the previous studies.
- The present results of E1 and E2 are different from the previous studies.
- The difference originates from the assumed reaction mechanism in the model.

[NACRE] (Brussels, Belgium)
Reaction rate compilation

[KU02] (Stuttgart, Germany)
γ-ray angular distributions measurements.

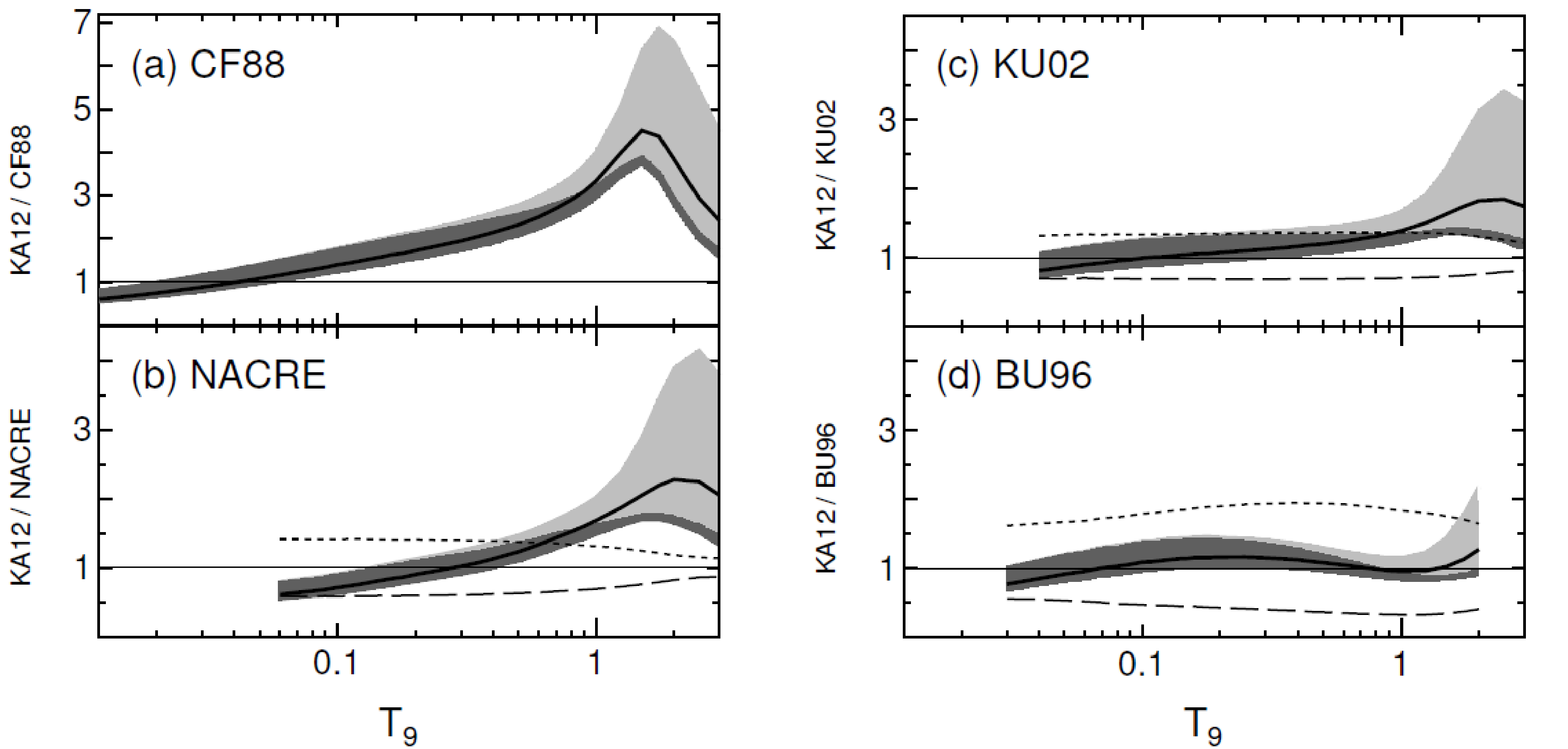
[BU96] (TRIUMF, Canada)
β-delayed α-spectrum of ^{16}N

Comparison of the reaction rates

- The reaction rates (KA12)

[KA12] M. Katsuma, Astrophys. J. **745**, 192 (2012)

  - Reaction rates from the potential model
  - Uncertainties of the rates from the variation of the model parameters

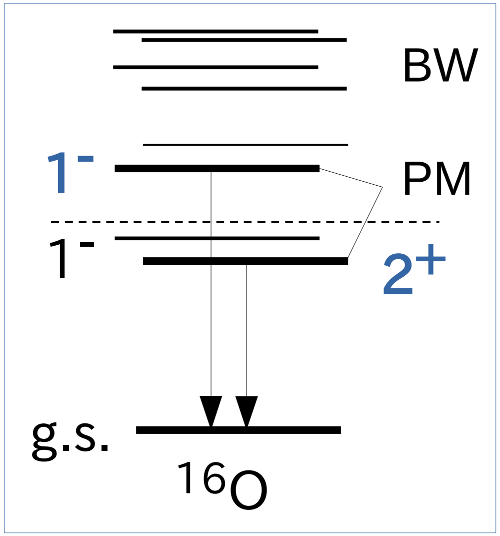


The derived rates are consistent with the published rates. ($T_9 < 1$)

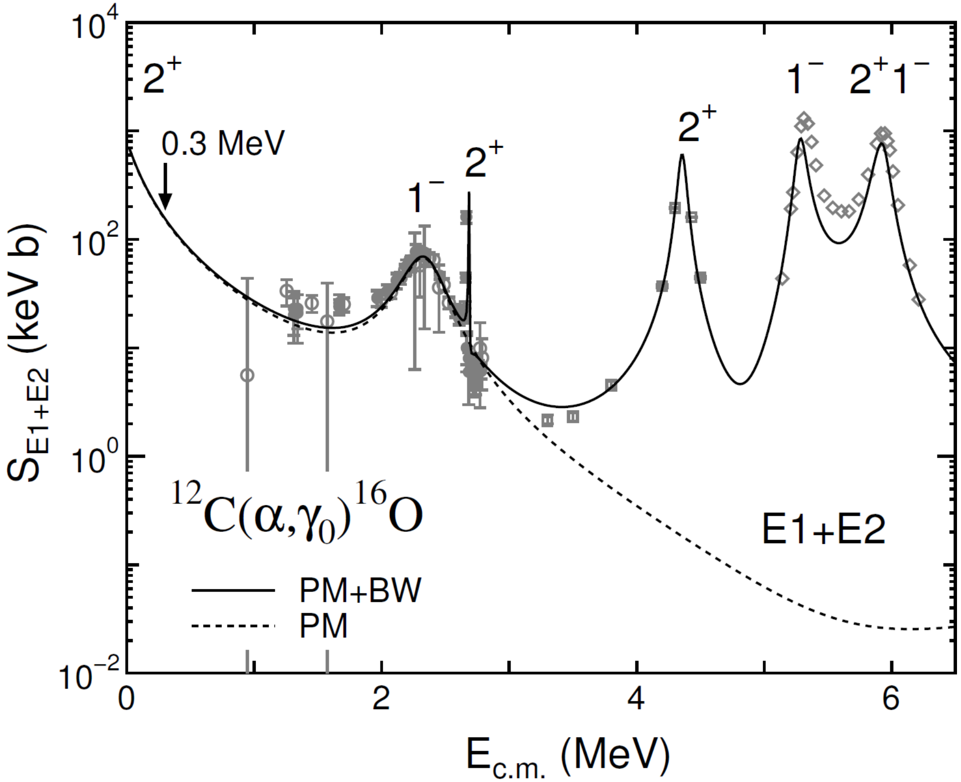
  - The total S-factor is comparable.

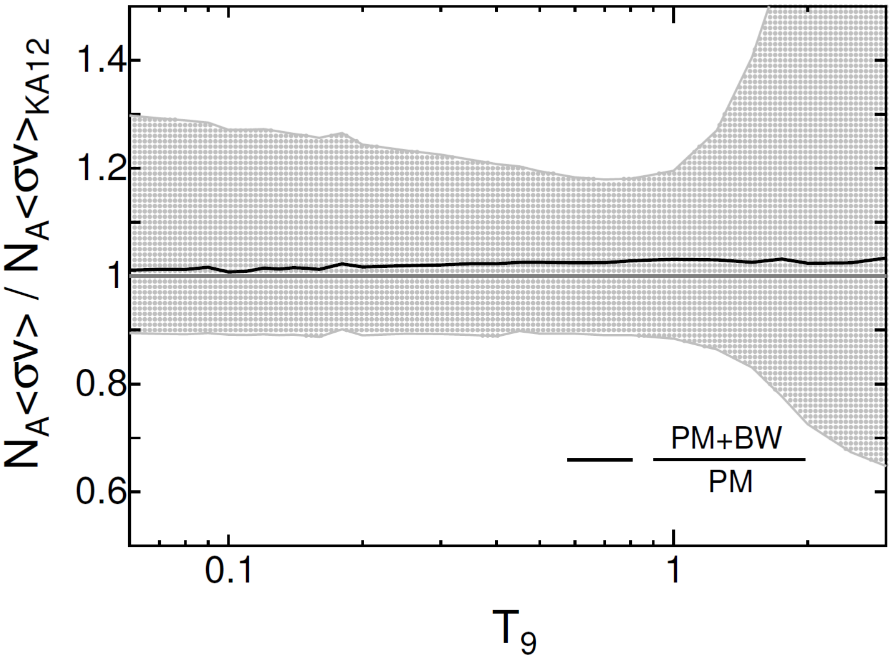
Additional resonant contribution

- To examine the effect of other resonances, the Breit-Wigner type of resonances is appended to the potential model.



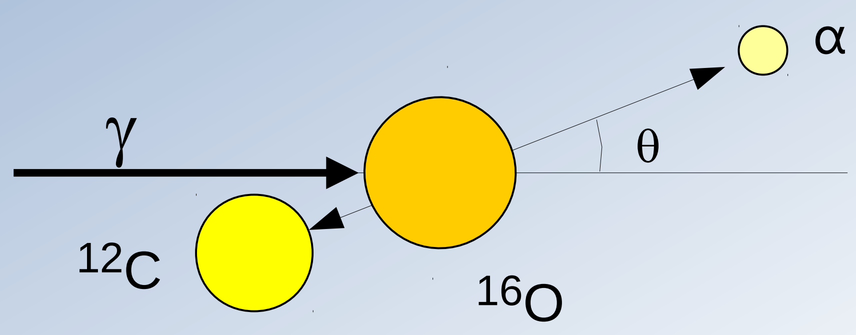
The additional contribution in the reaction rates is found to be small. (< 4%)





Exp.: D. Schurmann, *et. al.*, PLB711, 35 (2012); R. Plag, *et. al.*, PRC86, 015805 (2012)
H. Makii, *et. al.*, PRC80, 065802 (2009); M. Assunção, *et. al.*, PRC73, 055801 (2006)
R. Kunz, *et. al.*, PRL86,3244 (2001); G. Roters, *et. al.*, EPJA6, 451 (1999)

Photo-disintegration of ^{16}O



Potential model (Direct Nuclear Reaction Model)

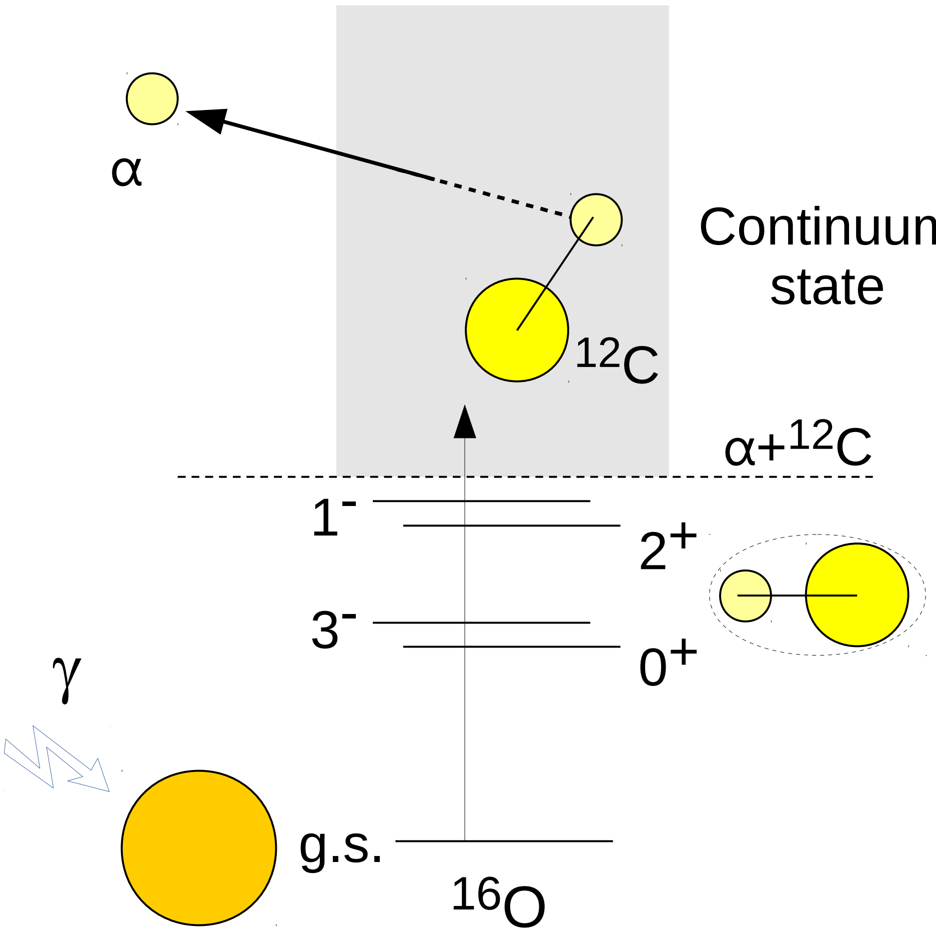
$^{16}O(\gamma,\alpha)^{12}C$ cross sections

$$\sigma_{\gamma\alpha} = \frac{k_\alpha^2}{2\,k_\gamma^2}\,\sigma_{\alpha\gamma}$$

- The wavenumber k_γ of photon is smaller than k_α of α-particle.
- The cross section of the photodisintegration is expected to be larger than that of $^{12}C(\alpha,\gamma)^{16}O$.

$$\sigma_{\gamma\alpha} > \sigma_{\alpha\gamma}$$

- In advance of the experiments, the photoelectric cross section is predicted from the available result of $^{12}C(\alpha,\gamma)^{16}O$.

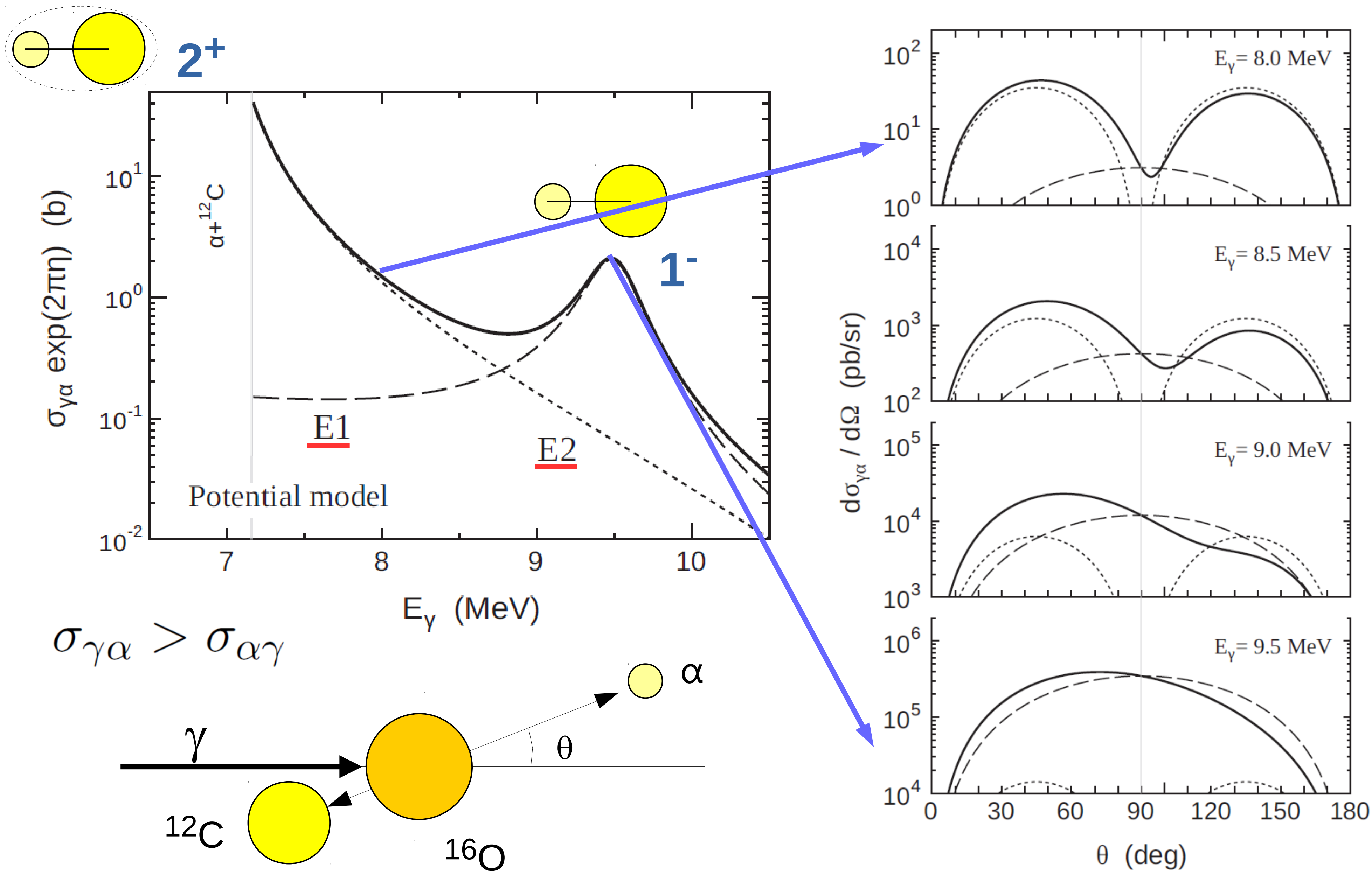


Statistical equilibrium of the capture reaction and photo-disintegration

$$\gamma + {}^{16}O \rightleftharpoons \alpha + {}^{12}C$$

Photodisintegration of ^{16}O – $^{16}O(\gamma,\alpha)^{12}C$

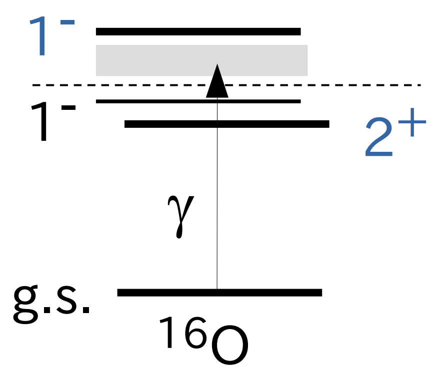
- E2 excitation dominates the reaction in the vicinity of the threshold.

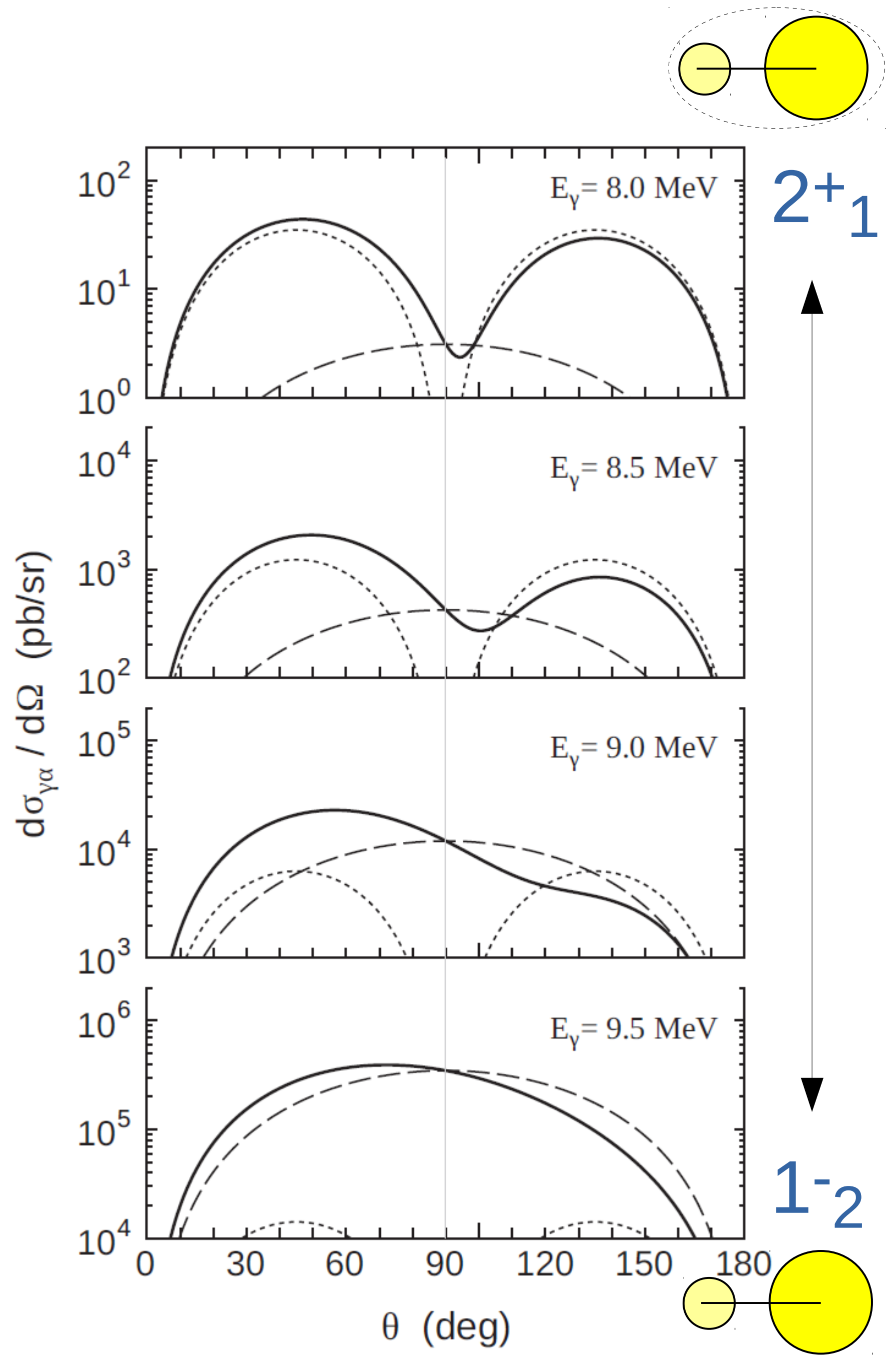


$$\sigma_{\gamma\alpha} > \sigma_{\alpha\gamma}$$

Photodisintegration of ^{16}O – $^{16}O(\gamma,\alpha)^{12}C$

- α-particle angular distribution
  - The interference between two $\alpha+^{12}C$ molecular states is predicted.
  - The interference makes the asymmetric angular distribution.





- E2/E1 ratio from the potential model

Eγ (MeV)	8.0	8.5	9.0	9.5
E2/E1	9.0	2.3	0.42	0.03

Summary

- The **$^{12}C(\alpha,\gamma)^{16}O$** reaction has been described with the potential model.

  - The cross section at $E_{c.m.}$= 300 keV is confirmed to be enhanced by **E2** transition, the tail of the subthreshold 2^+ state.
  - The γ-ray angular distribution appears to be made from the interference between **two α+^{12}C molecular states**.
  - The weak coupling feature apparently works in the α+^{12}C system.

  - The reaction rates are given by the direct capture component below the barrier.
    - The total S-factor at 300 keV and reaction rates are consistent with the previous studies, so the astrophysical impact of the present work may be small.
    - The cascade transitions through the excited states are not so important.
    - The other resonances are negligible.

- The **photodisintegration of ^{16}O** is also dominated by **E2** excitation.

  - The E2/E1 ratio and the reaction mechanism will be determined more accurately by the future experiments.