Transfer reactions to the continuum involving exotic nuclei

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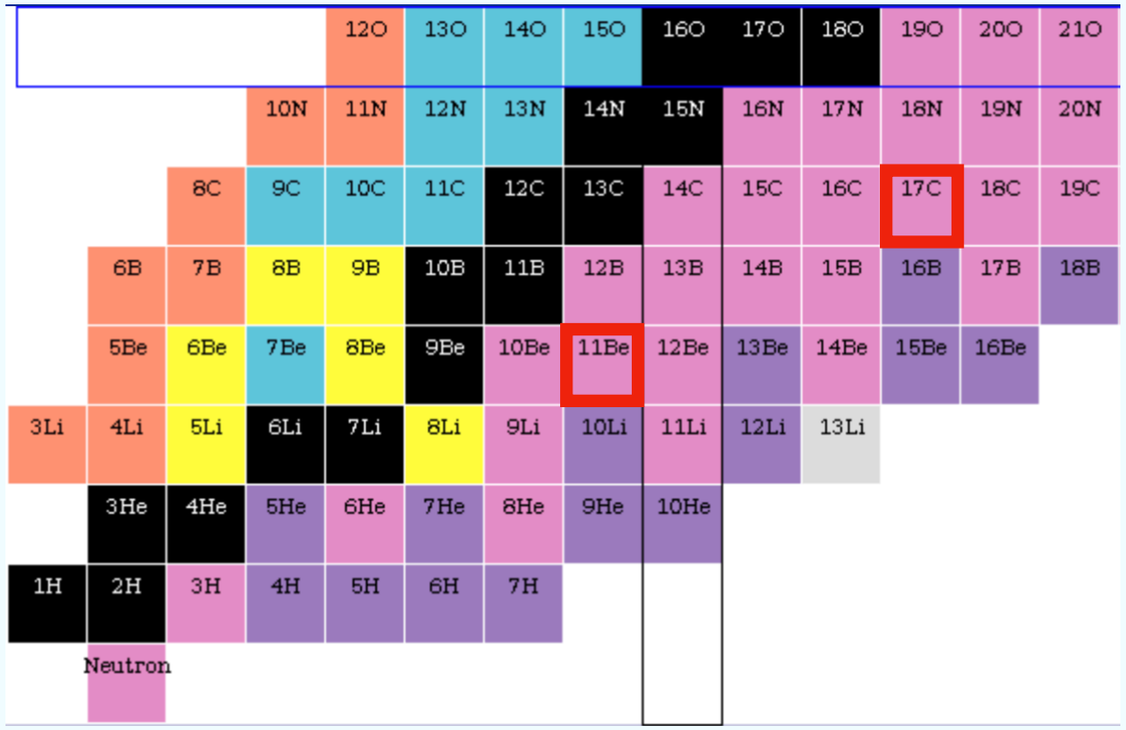
Introduction

- Exotic nuclei
  Different properties
  - Shell closure
  - Halo nature

- Transfer reactions with exotic nuclei
  Advances in radioactive beam facilities

- Few-body models
  Significant effect of deformation

- ^{11}Be and ^{17}C
  deformed core + neutron structure



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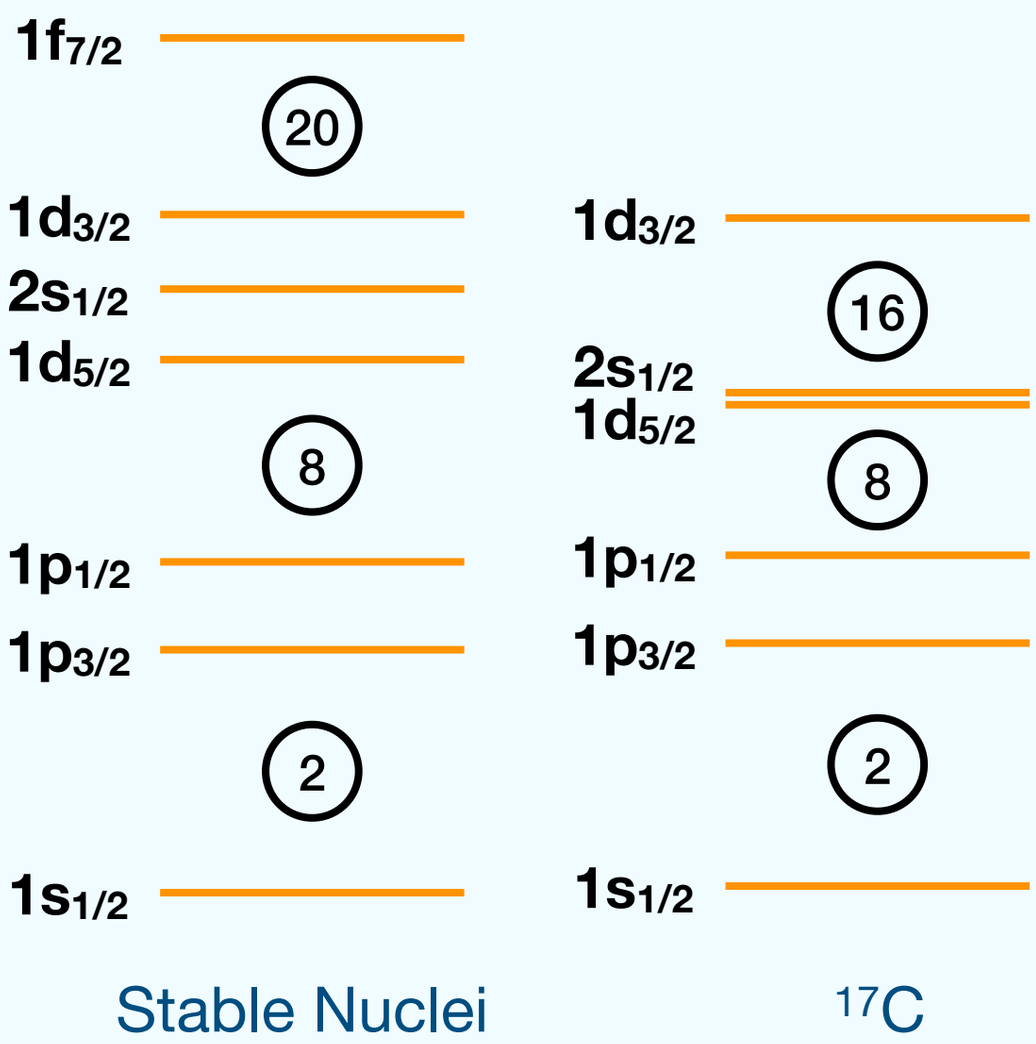

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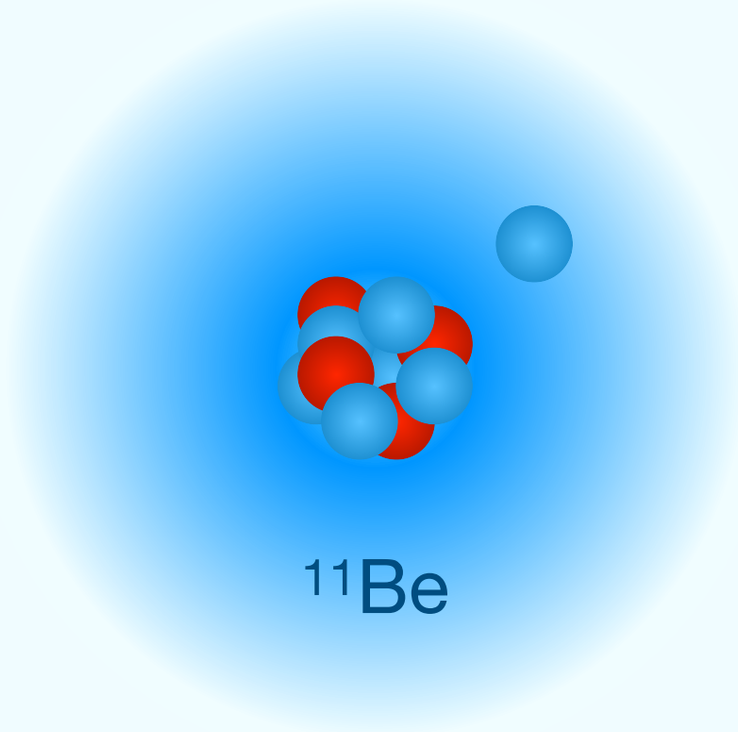

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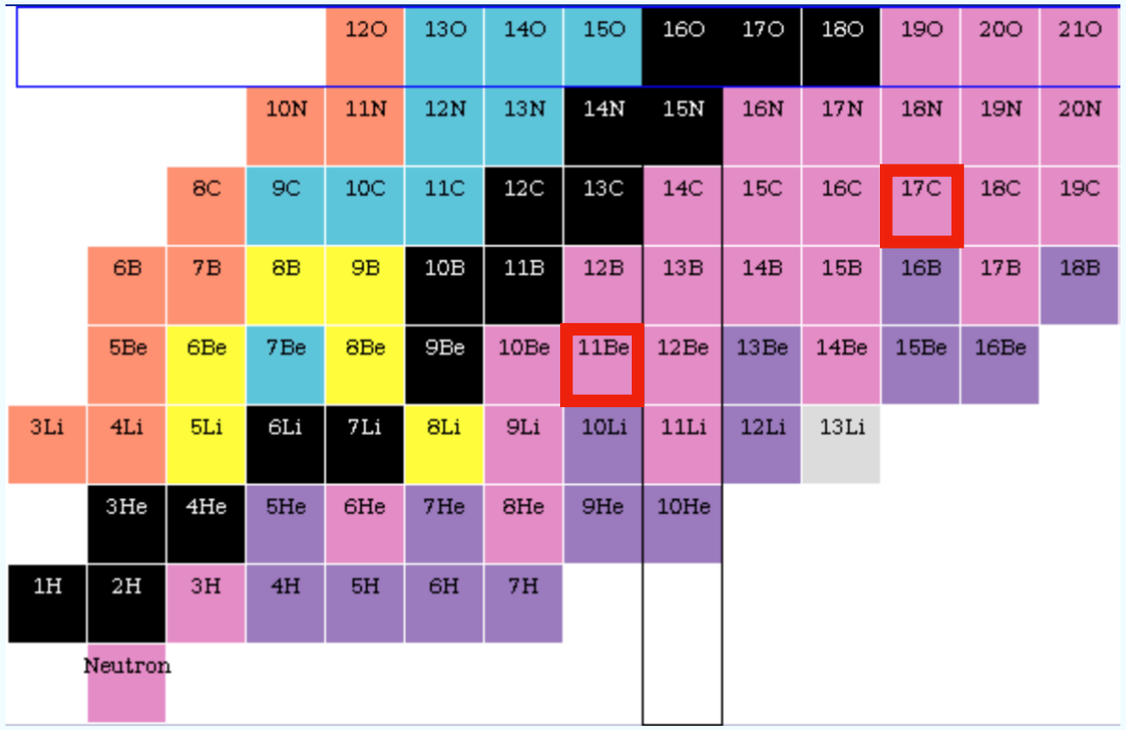
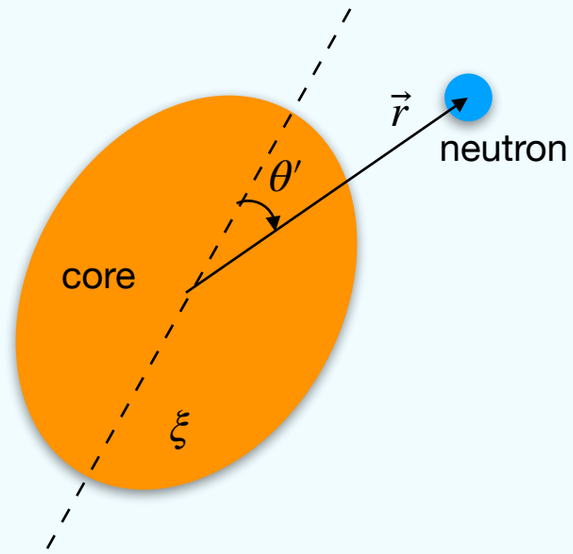


Structure models

- Deformed 2-body models (neutron+core)
  - Nilsson model

$$H = -\frac{\hbar^2}{2\mu}\nabla^2 + V_{ls}(r)(\vec{l}\cdot\vec{s}) + V_c(r) - r\beta\frac{dV_c(r)}{dr}Y_{20}(\theta') + \frac{\hbar^2}{2\mathcal{J}}\vec{I}^2$$



  - PAMD [PRC**89** (2014) 014333]

$$H = -\frac{\hbar^2}{2\mu}\nabla^2 + V_{ls}(r)(\vec{l}\cdot\vec{s}) + V_{vc}^{AMD}(\vec{r},\xi) + h_{core}(\xi)$$

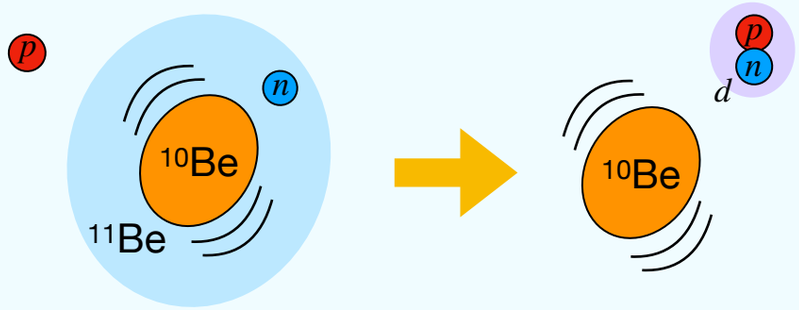
- Eigenstates from diagonalization in THO basis

$$\phi_{nl}^{THO}(r) = \sqrt{\frac{ds}{dr}}\phi_{nl}^{HO}[s(r)]$$

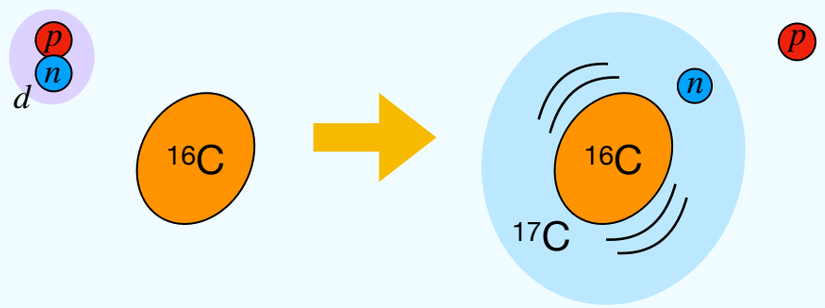
Neutron transfer reactions

- (*p*,*d*) and (*d*,*p*) reactions are studied applying the Adiabatic Distorted Wave Approximation (ADWA).

^{11}Be(*p*,*d*)^{10}Be



^{16}C(*d*,*p*)^{17}C



Neutron transfer reactions

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- These calculations require the $\langle {}^{10}\mathrm{Be}|{}^{11}\mathrm{Be}\rangle$ and $\langle {}^{17}\mathrm{C}|{}^{16}\mathrm{C}\rangle$ overlaps.

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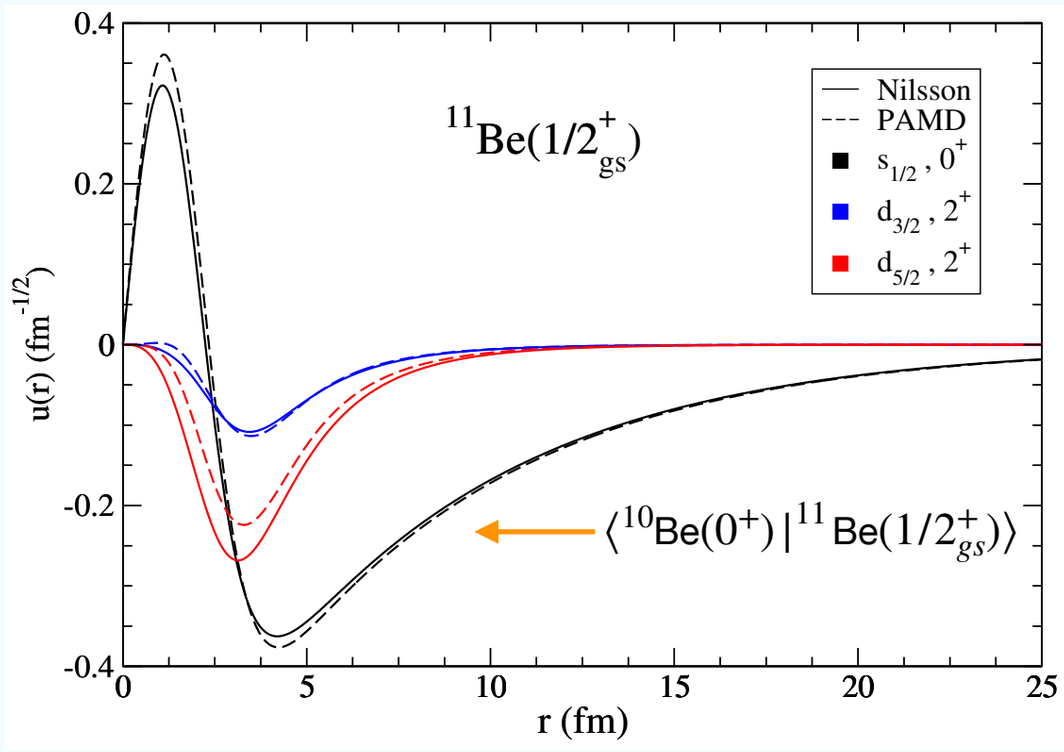

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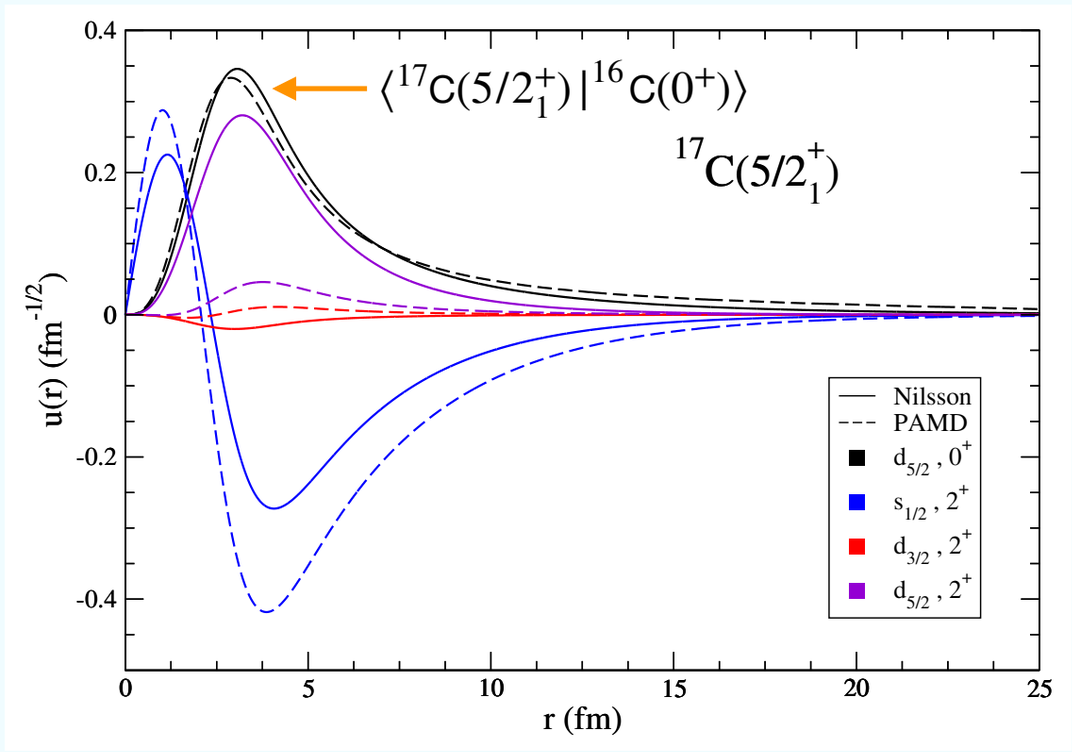

Neutron transfer reactions

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- These calculations require the $\langle {}^{10}\mathrm{Be} | {}^{11}\mathrm{Be} \rangle$ and $\langle {}^{17}\mathrm{C} | {}^{16}\mathrm{C} \rangle$ overlaps.
- Calculations are compared with recent experimental data.

^{11}Be(*p*,*d*)^{10}Be

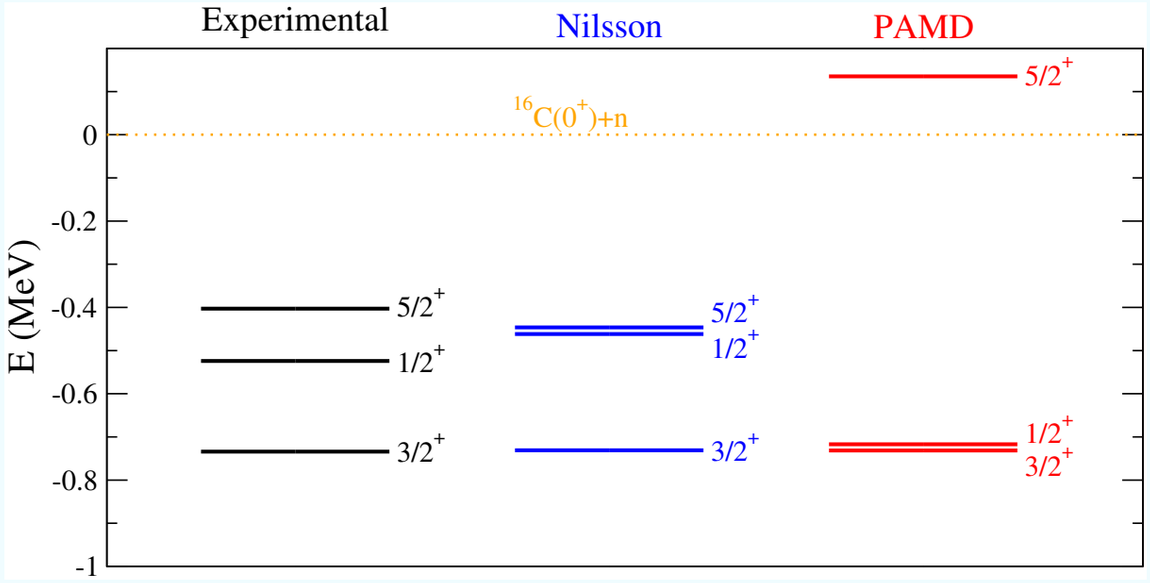
- GANIL, 35.3 MeV/nucleon beam [NPA**683** (2001) 48]
- RCNP, 26.9 MeV/nucleon beam [Chinese P. L. **35** (2018) 082501]

^{16}C(*d*,*p*)^{17}C

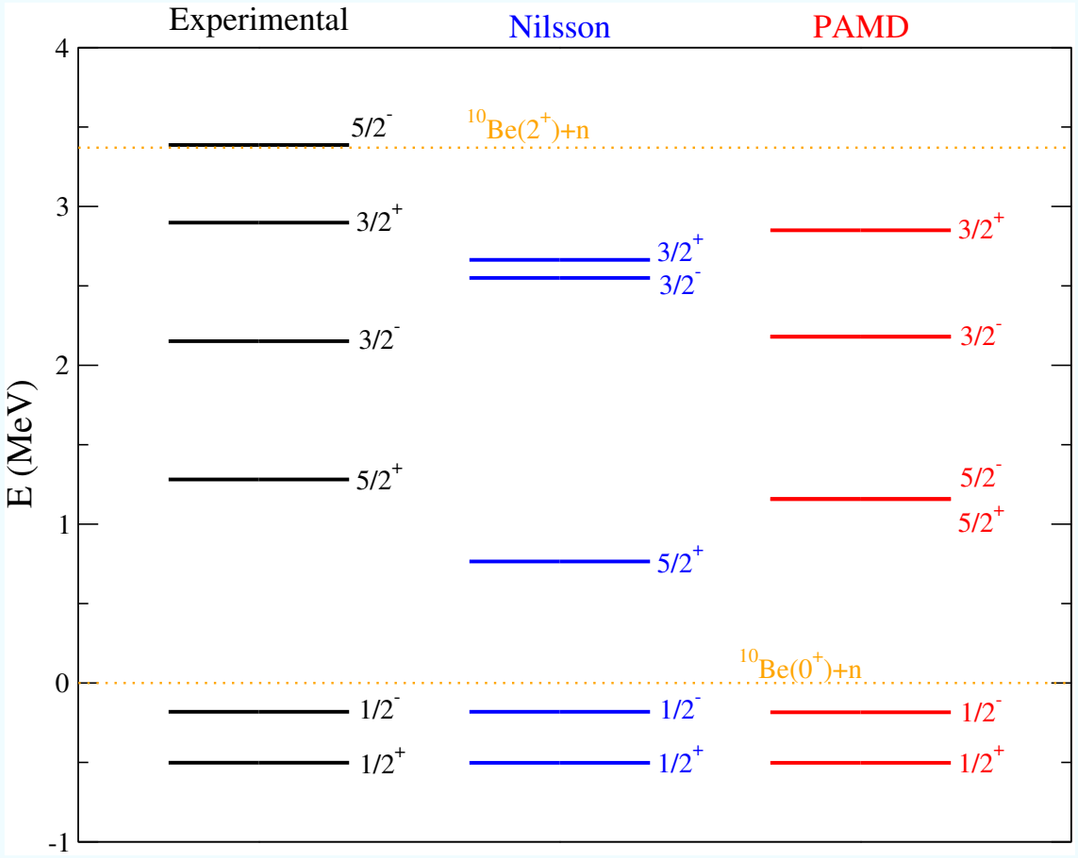
- GANIL, 17.2 MeV/nucleon beam [PLB**811** (2020) 135939]

Application to ^{17}C and ^{11}Be

^{17}C

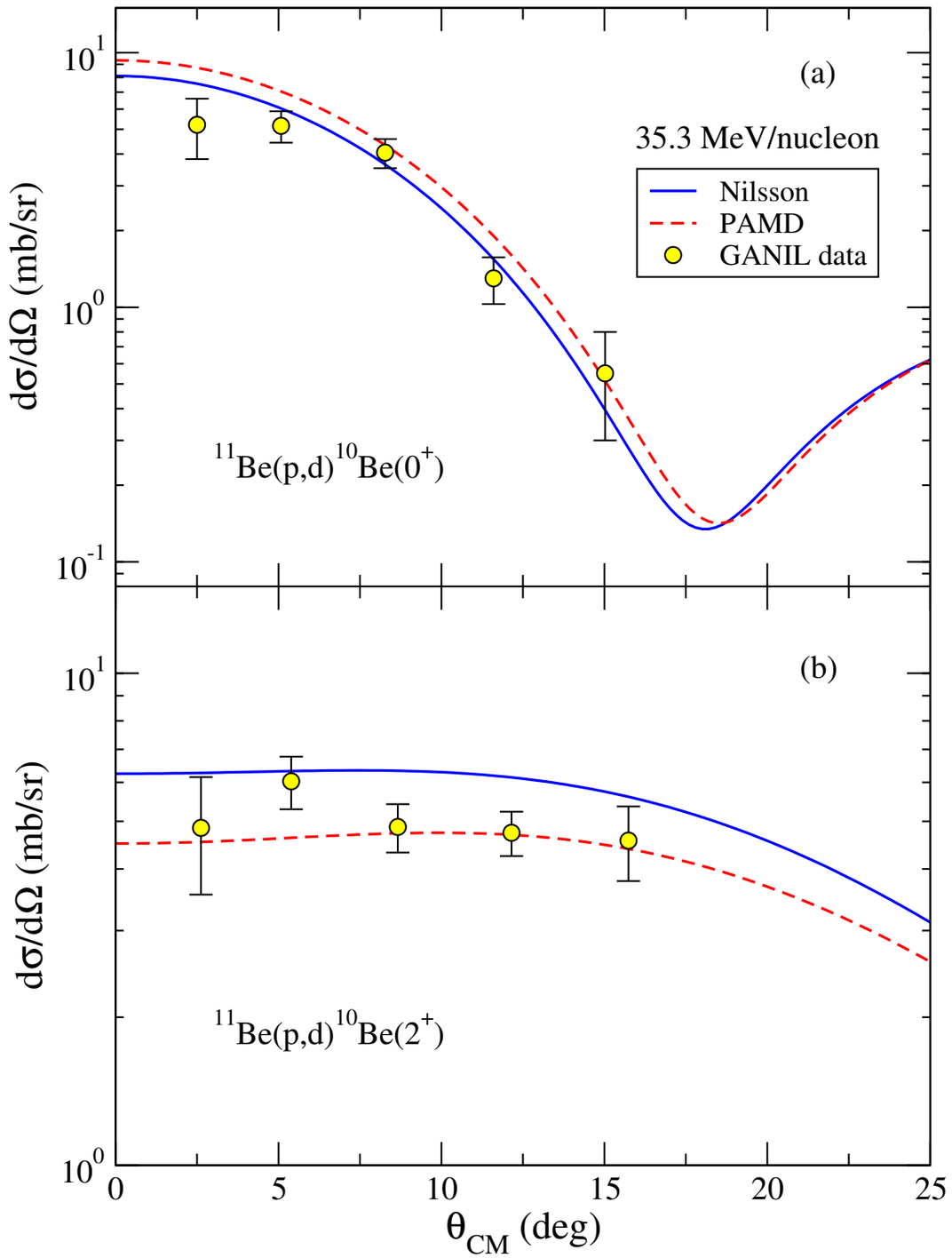


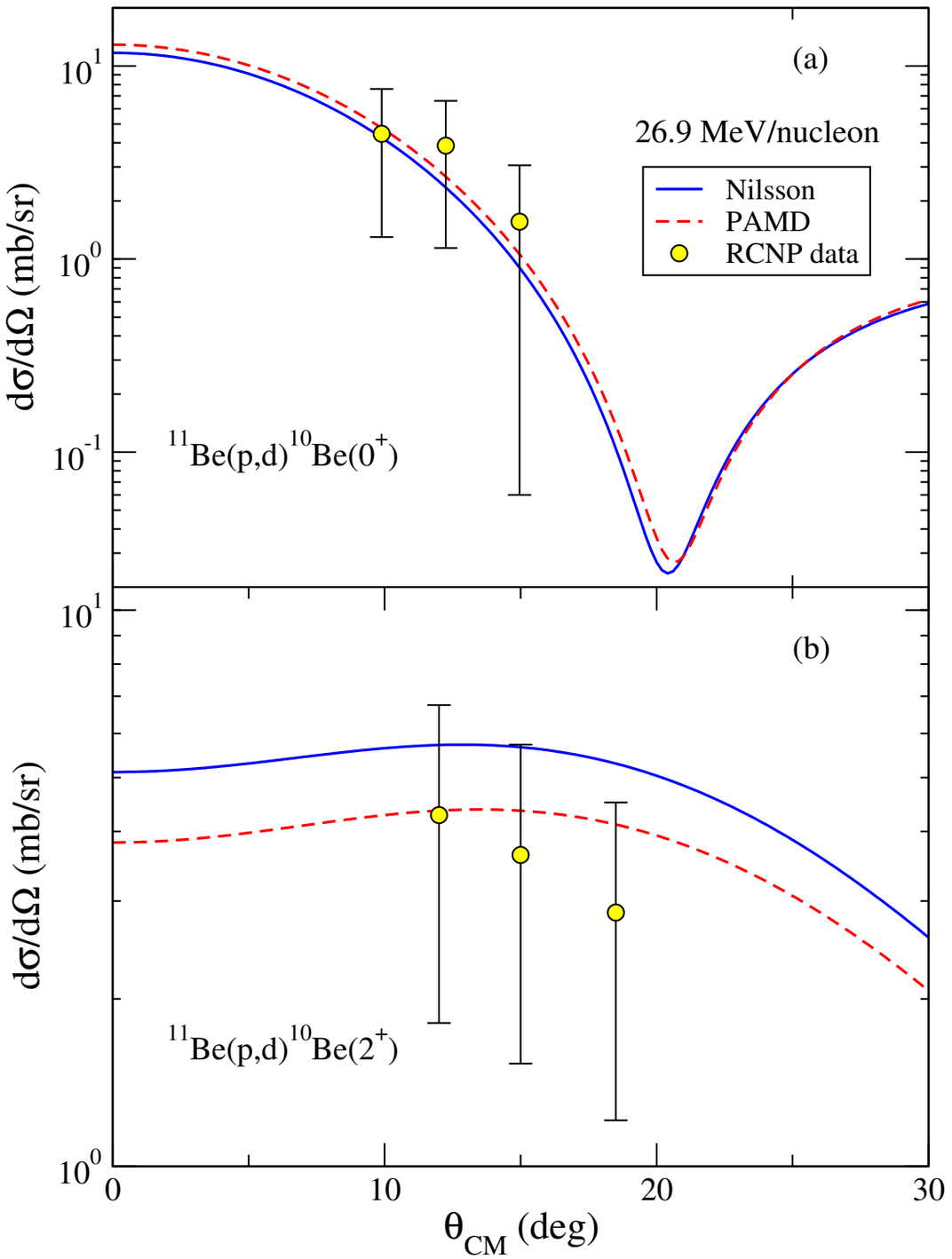
^{11}Be



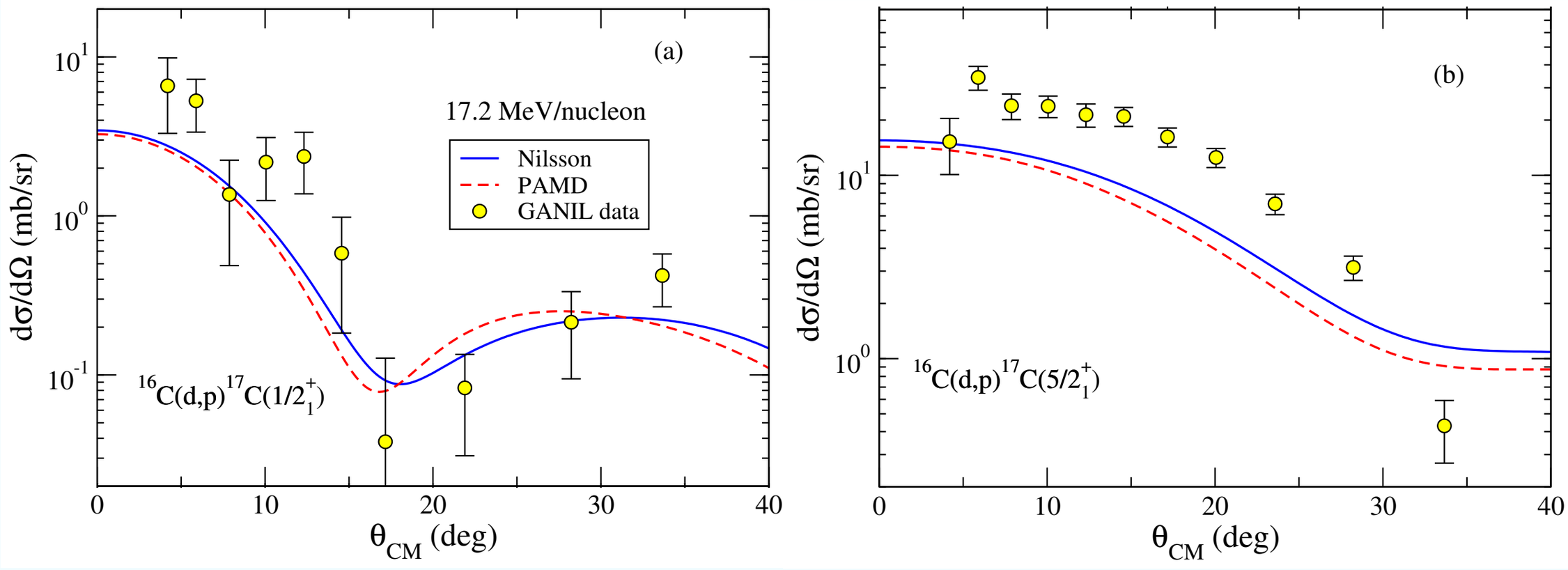
P. Punta, *et* al. PRC**108** (2023) 024613

Application to ^{11}Be(p,d)^{10}Be





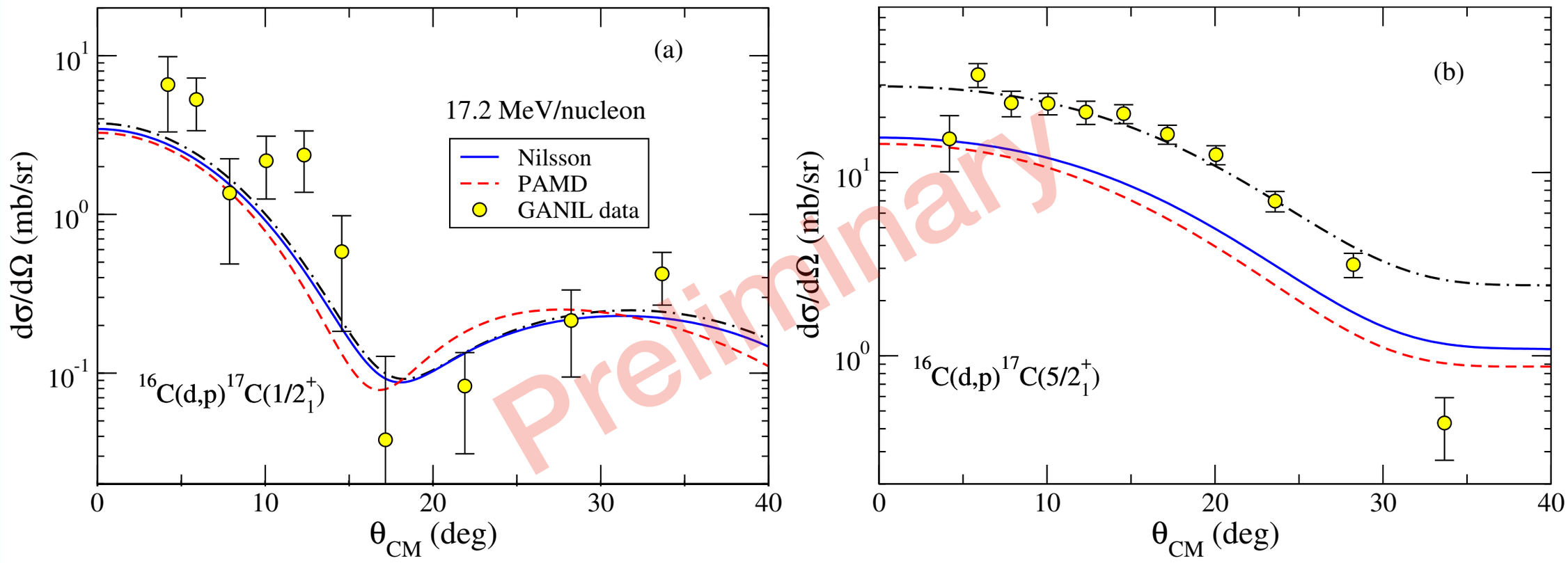
Application to $^{16}C(d,p)^{17}C$



Comparison with data suggest that:

- $\langle {}^{17}C(1/2^+_1)|{}^{16}C(0^+)\rangle$ *overlaps are realistic in our models.*
- $\langle {}^{17}C(5/2^+_1)|{}^{16}C(0^+)\rangle$ *too small, suggesting a larger spectroscopic factor.*

Application to $^{16}C(d,p)^{17}C$



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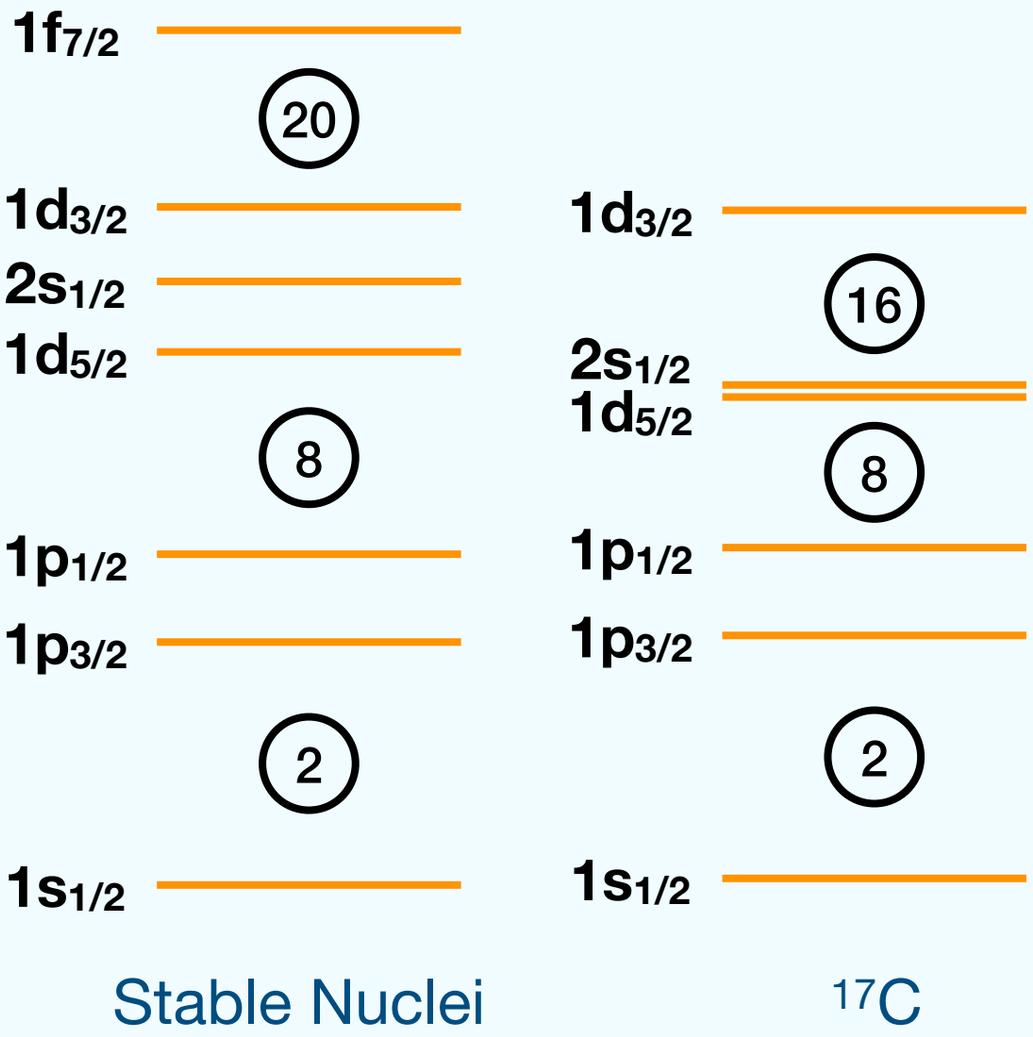
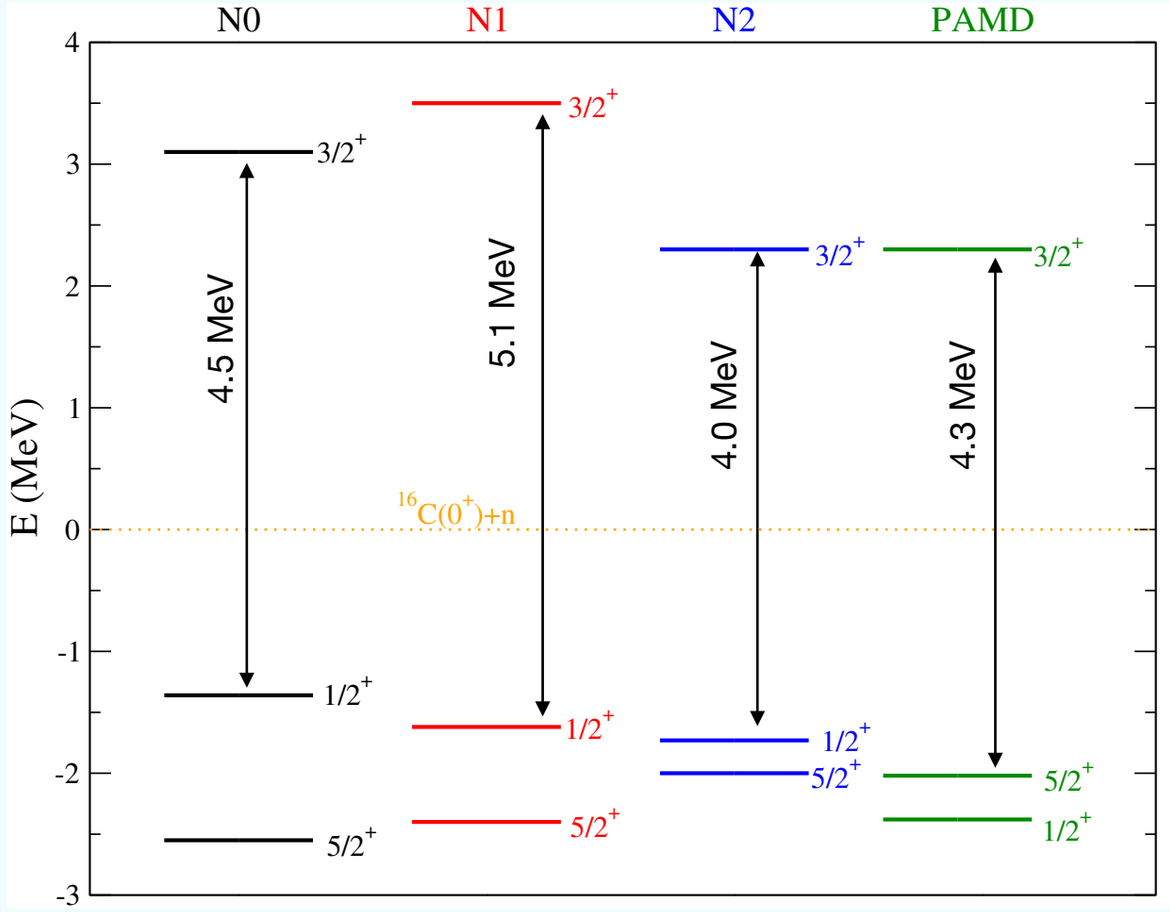
↓

Pauli blocking

N=16 Shell-Gap

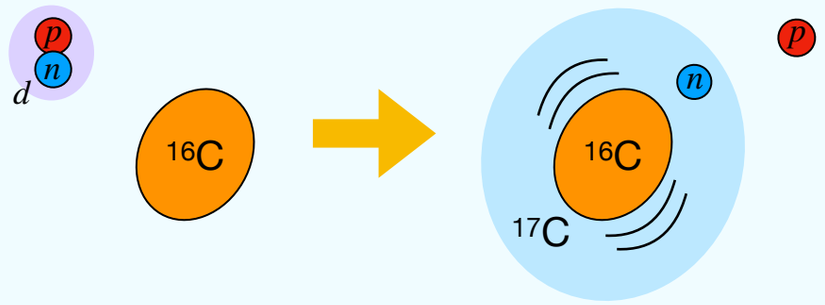


Single Particle Leves



Pseudo-states discretization method

^{16}C(d,p)^{17}C



$$\mathscr{F}(k,\theta) = \sqrt{\frac{\mu_i \mu_f k_f}{(2\pi\hbar^2)^2 k_i}} \langle \chi_f^{(-)} \varphi_p \Psi_{^{17}C} \,|\, U \,|\, \chi_i^{(+)} \psi_d \phi_{^{16}C} \rangle$$

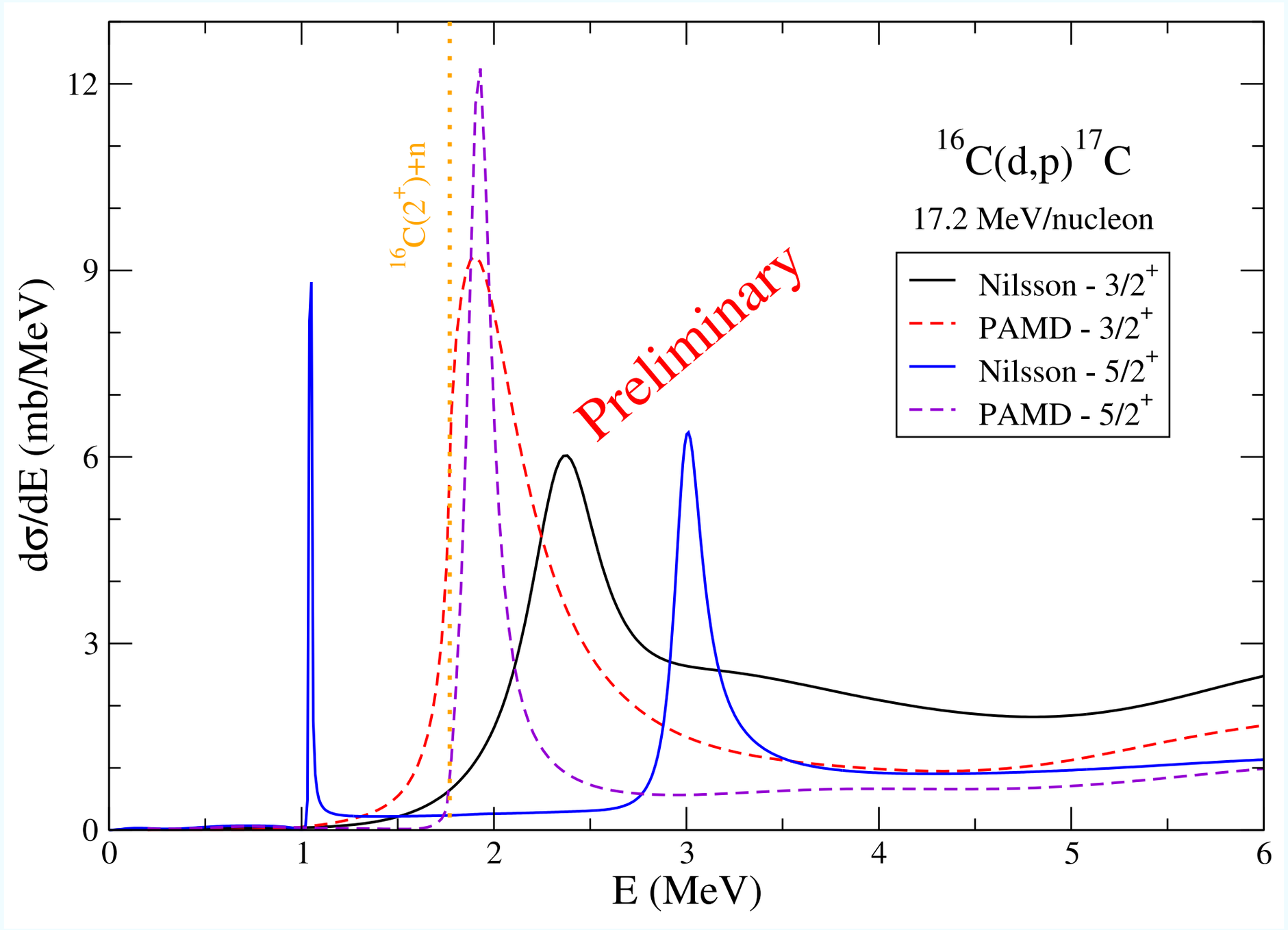
- Scattering amplitudes for a discrete number of pseudo-states

$$\mathscr{F}_n^{THO}(\theta) = \sqrt{\frac{\mu_i \mu_f k_f}{(2\pi\hbar^2)^2 k_i}} \langle \chi_f^{(-)} \varphi_p \Psi_n^{THO} \,|\, U \,|\, \chi_i^{(+)} \psi_d \phi_{^{16}C} \rangle$$

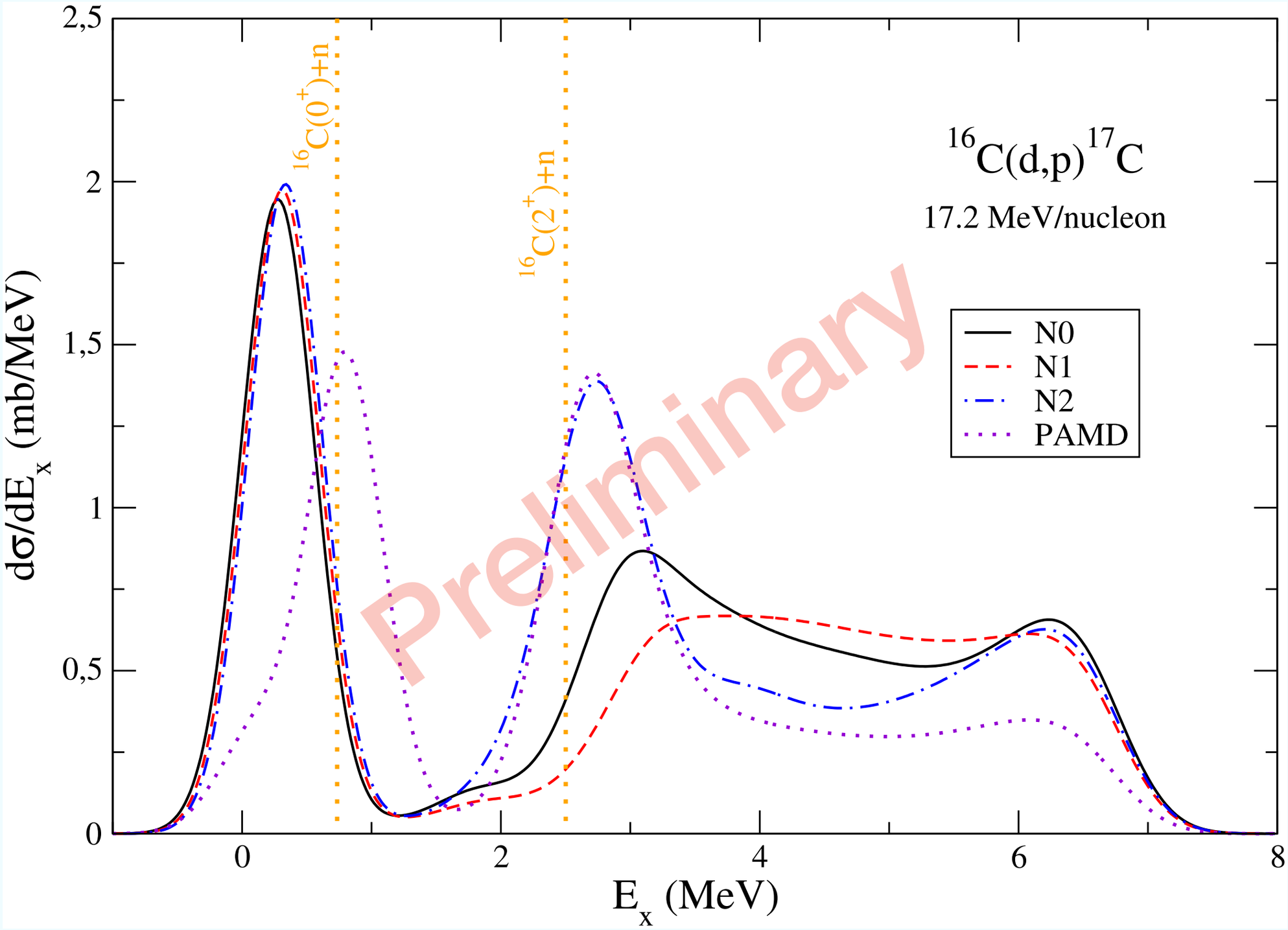
- Convolution with the *exact n*+core scattering states

$$\mathscr{F}(k,\theta) \approx \sum_n \langle \Psi_{^{17}C}(k,r) \,|\, \Psi_n^{THO}(r) \rangle \mathscr{F}_n^{THO}(\theta)$$

Transfer to the continuum: $^{16}C(d,p)^{17}C$



Transfer to the continuum: $^{16}C(d,p)^{17}C$



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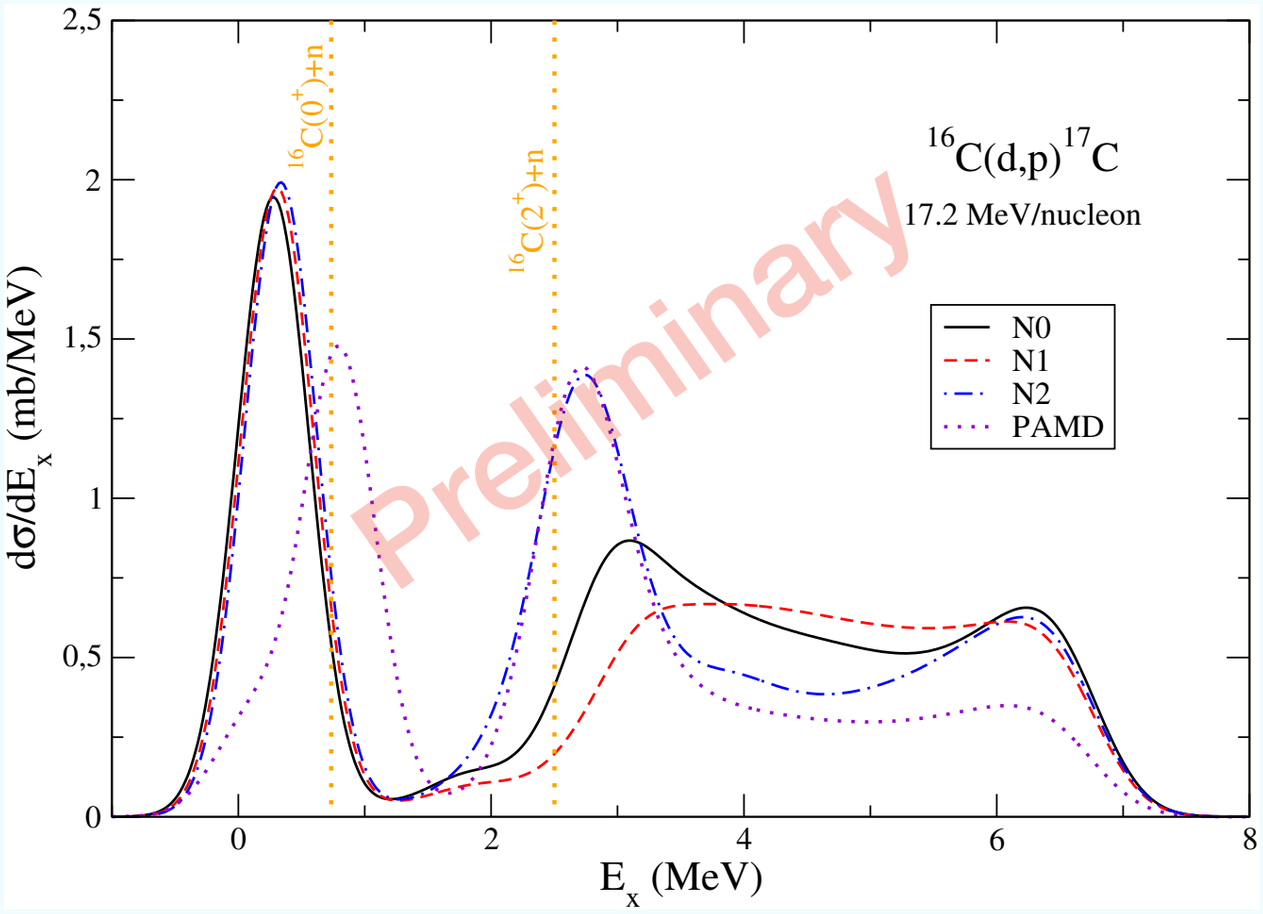
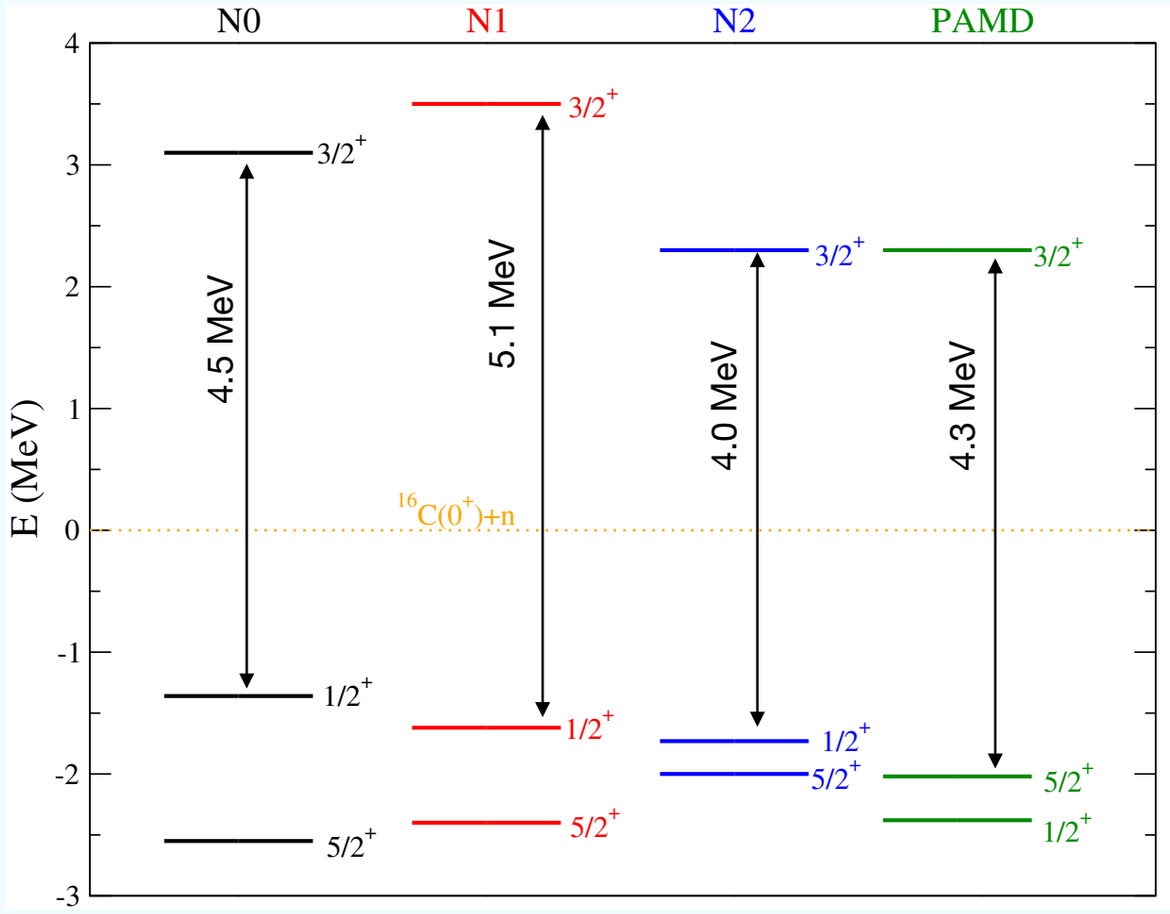
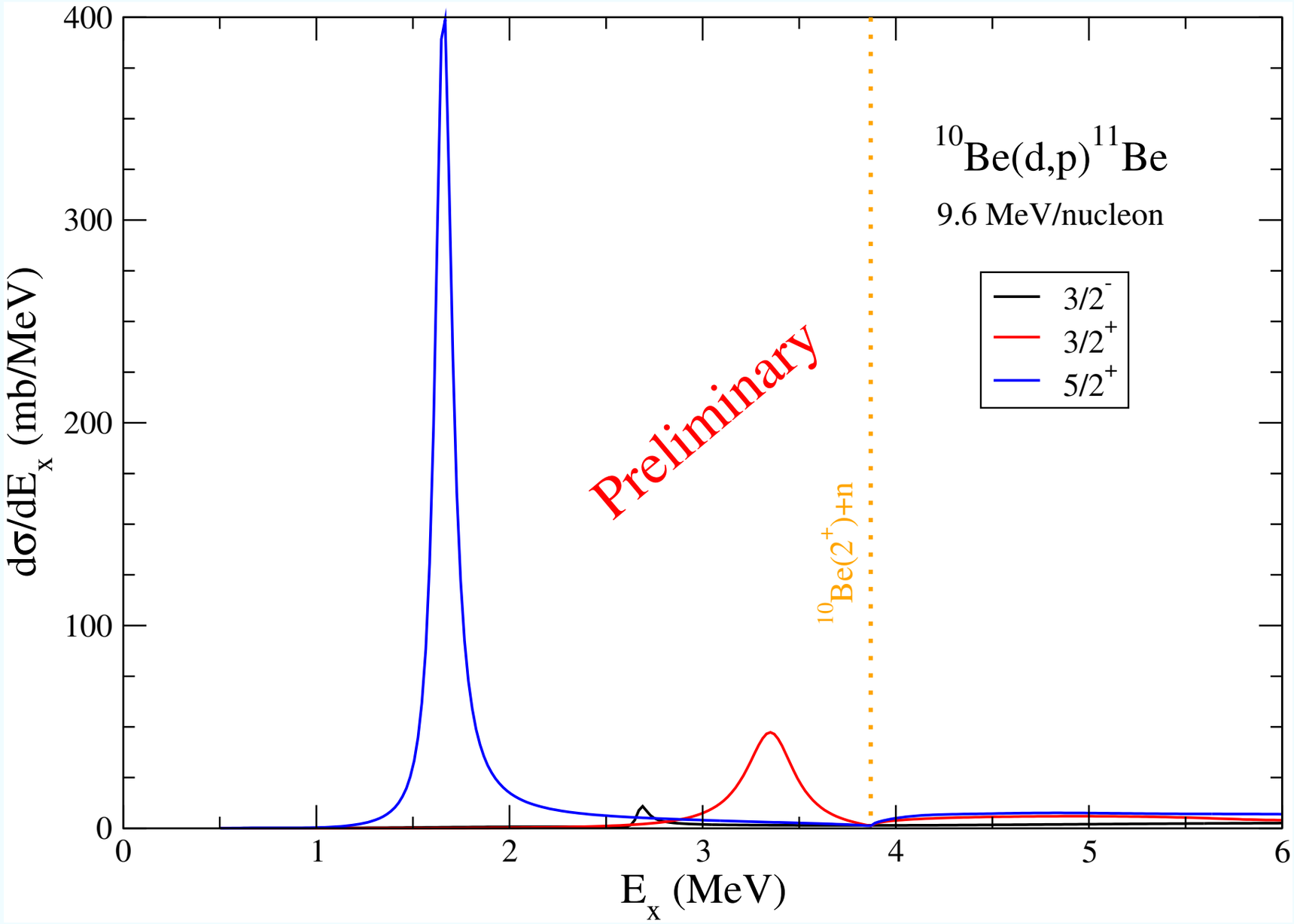




Transfer to the Continuum: ^{10}Be(d,p)^{11}Be



Conclusions

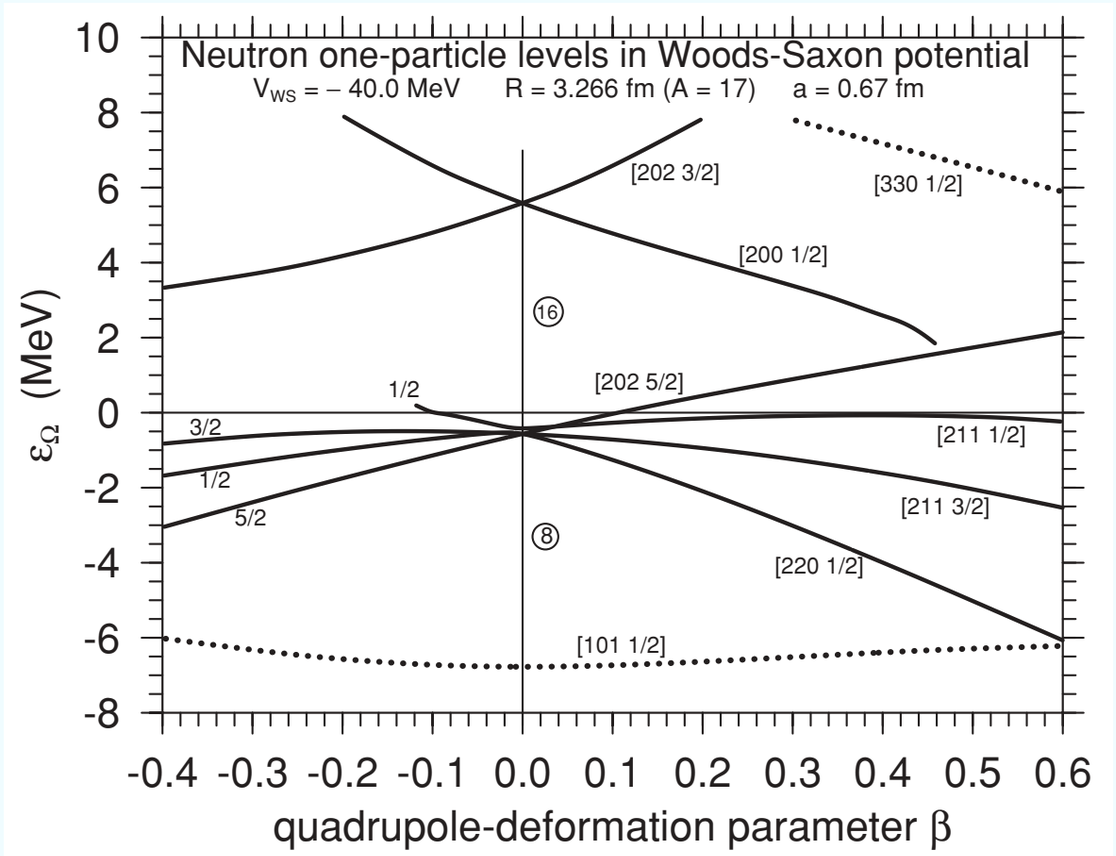
- We have checked the suitability the PAMD and Nilsson models to describe ^{11}Be and ^{17}C systems.
  - ^{11}Be: better with PAMD model (weak-coupling limit)
  - ^{17}C: better with Nilsson model (strong-couplig limit)
- These models have been applied to transfer reactions to bound states and to the continuum using pseudo-states.
- A good reproduction of the structure and transfer reactions have been found.
- The reaction ^{16}C(d,p)^{17}C to the continuum have been studied in order to confirm the existence of the N=16 shell-gap.
- Extensions to breakup reactions and other weakly bound nuclei are in progress.

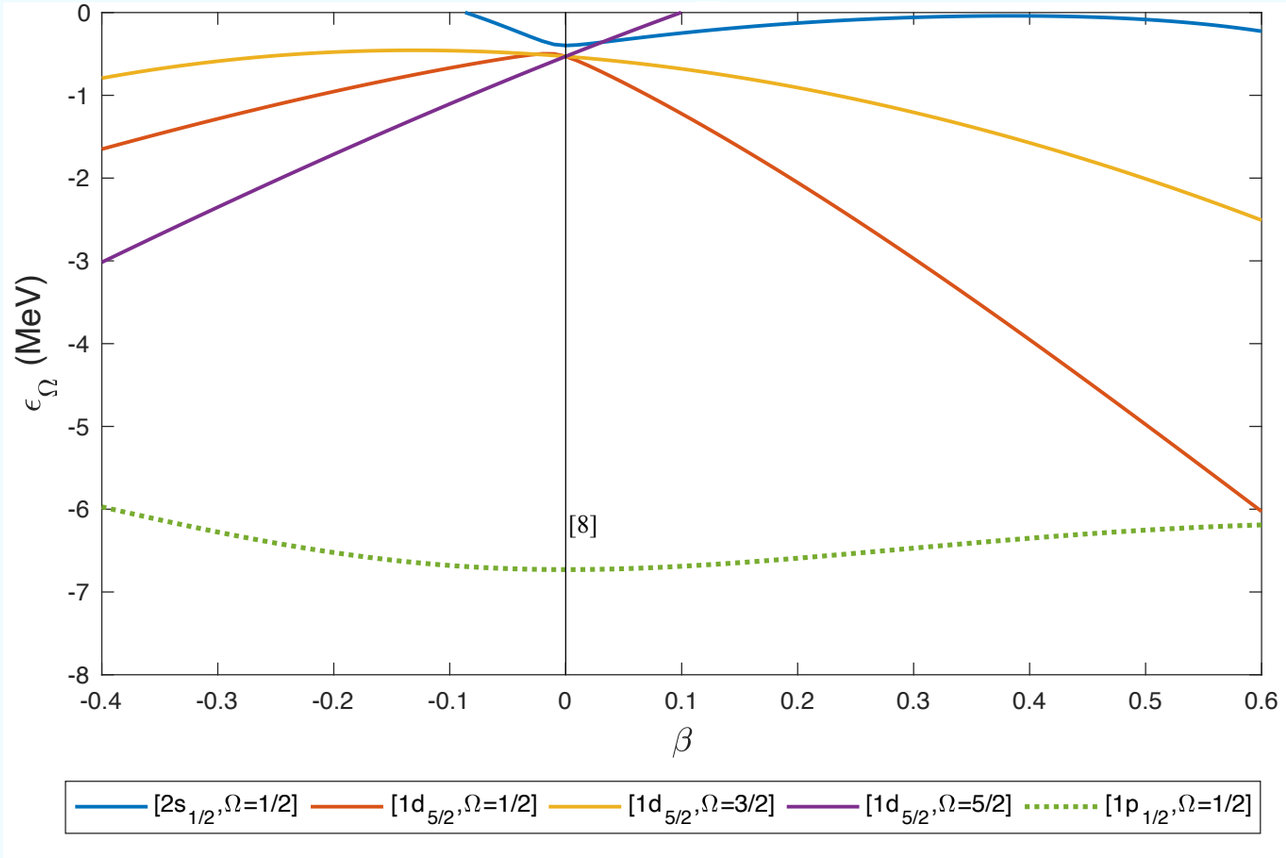
Thanks for your attention

Backup

Nilsson Diagram for ^{17}C

$$H_{sp} = -\frac{\hbar^2}{2\mu}\nabla^2 + V_c(r) + V_{ls}(r)(\vec{l}\cdot\vec{s}) - r\beta\frac{dV_c(r)}{dr}Y_{20}(\theta')$$

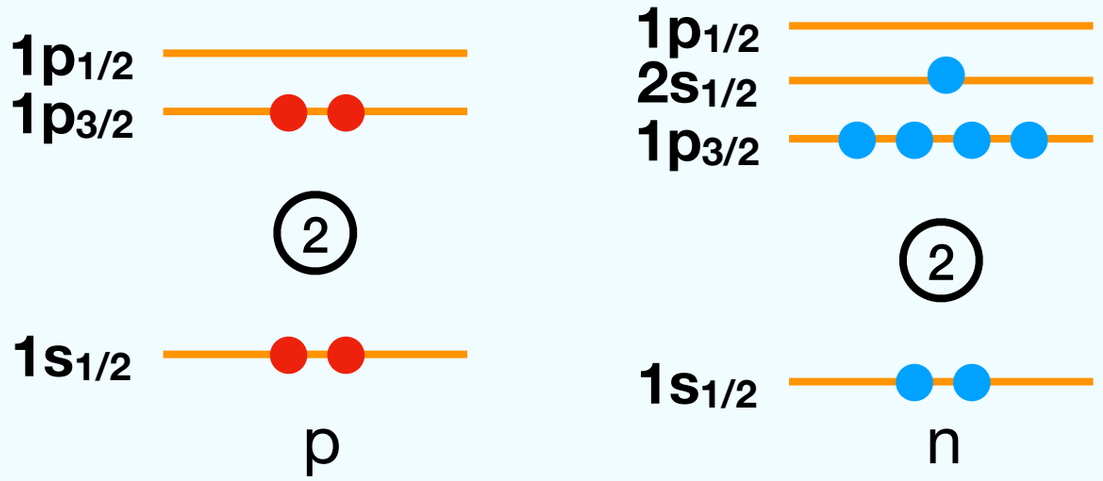




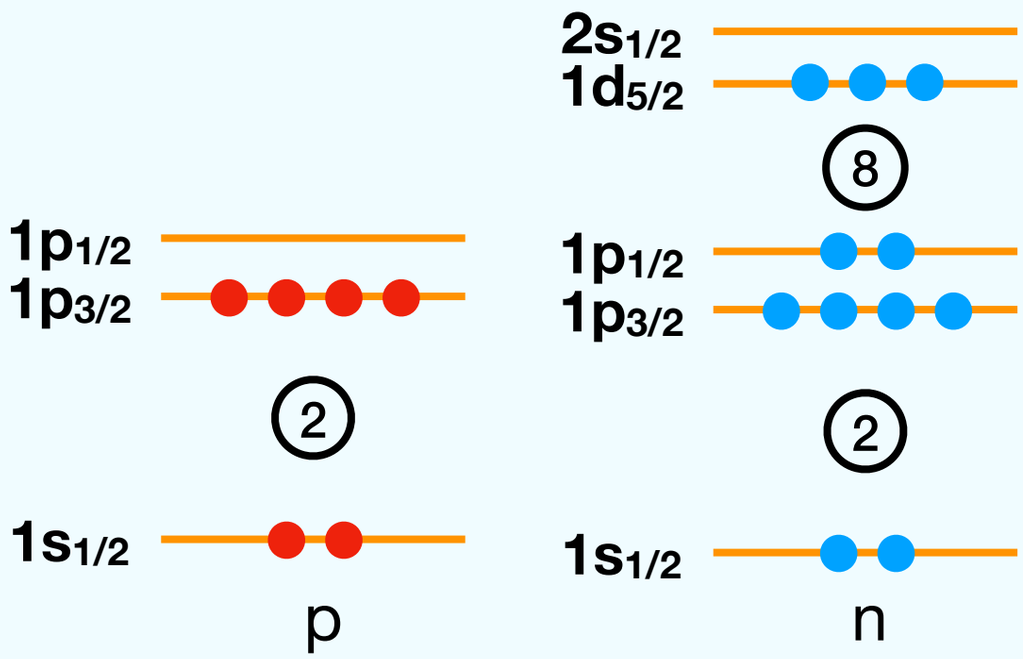
I. Hamamoto, PRC76 (2007) 054319

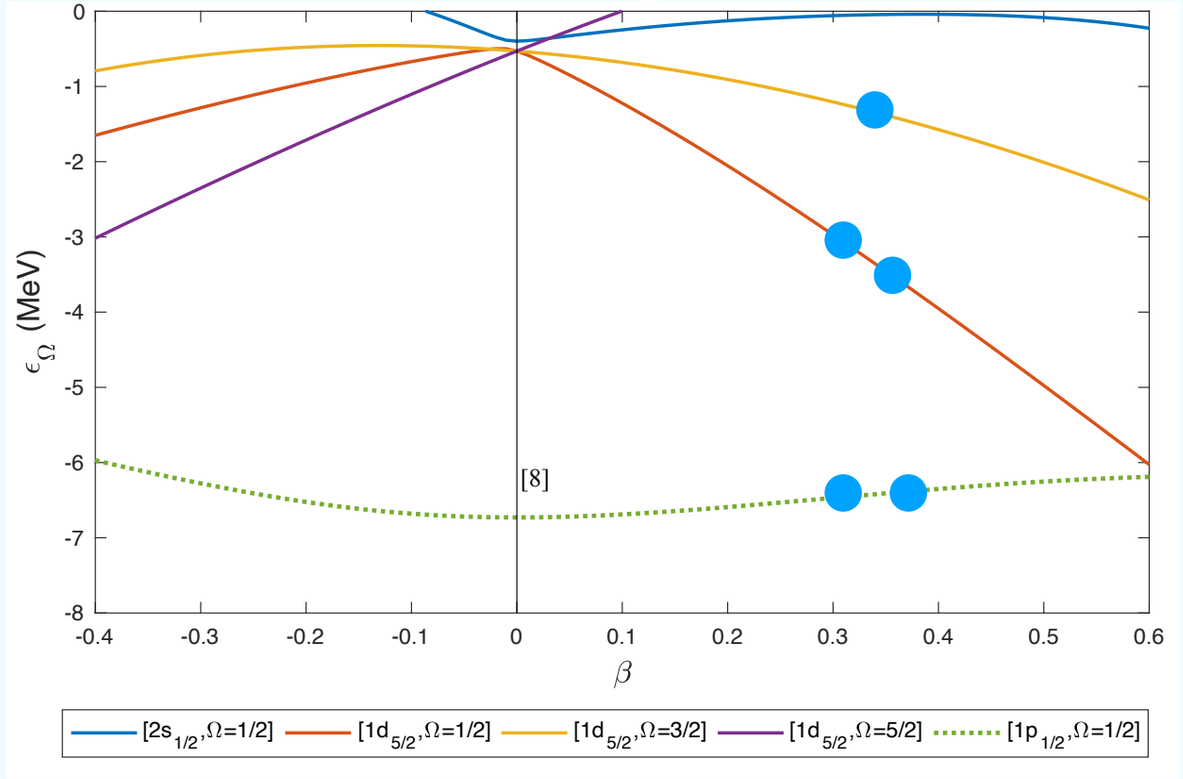
Occupation of single-particular levels

^{11}Be



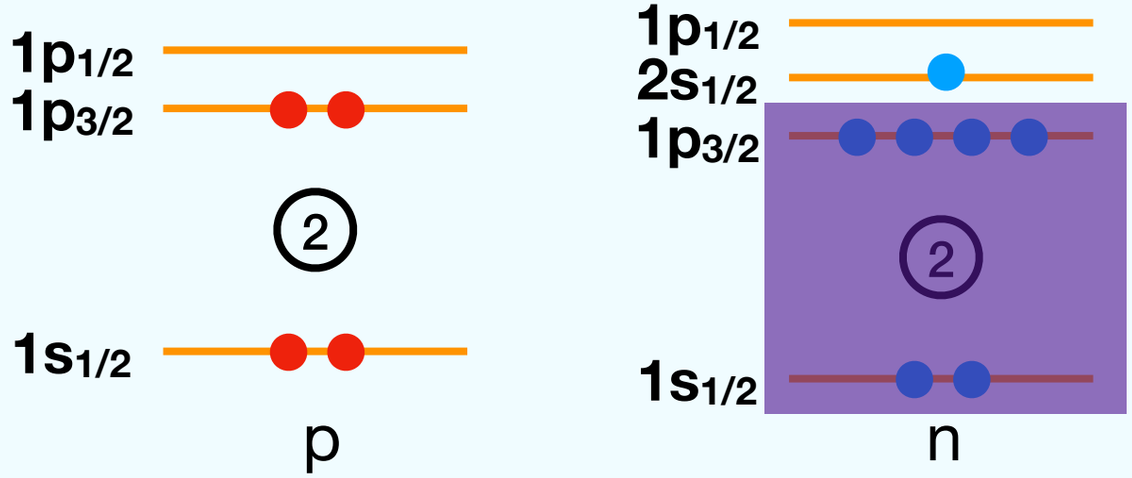
^{17}C



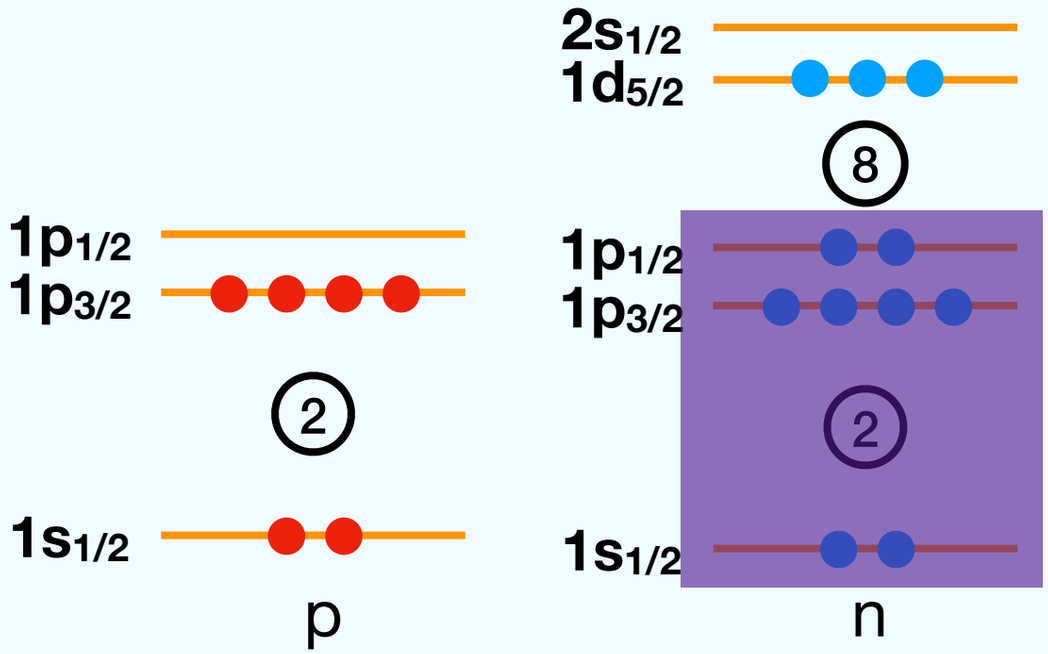


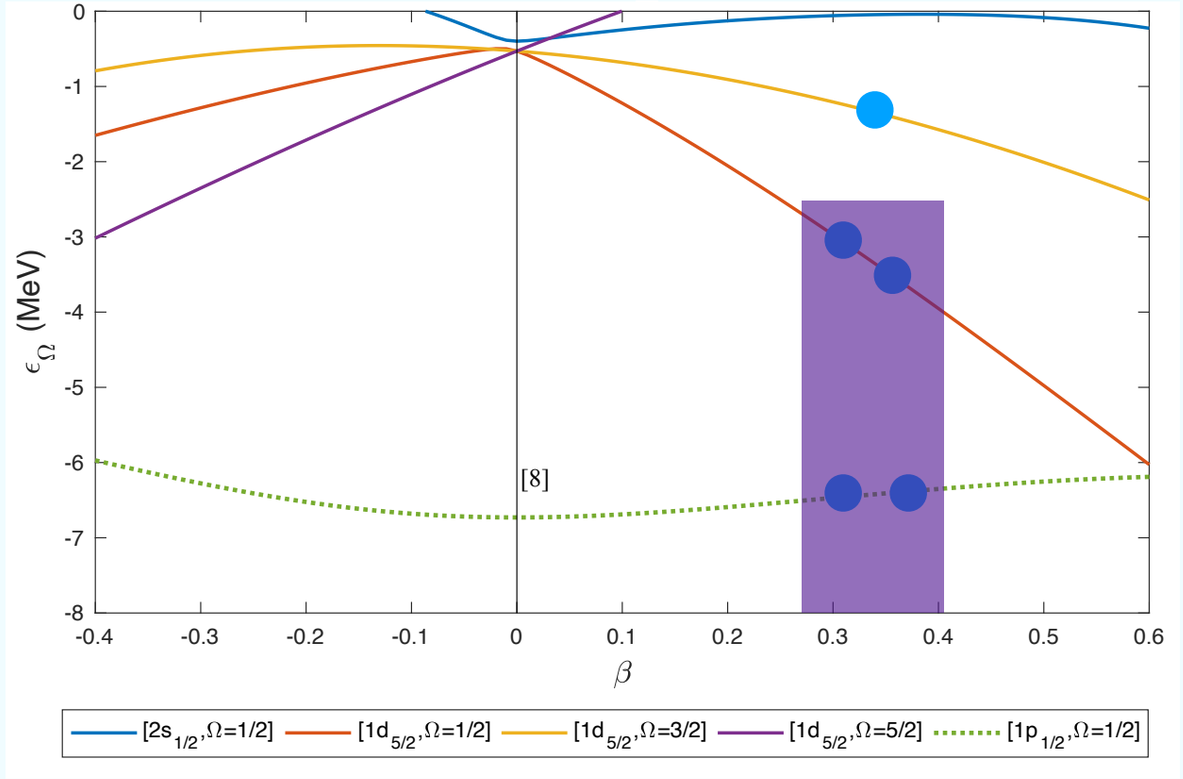
Pauli Blocking

^{11}Be



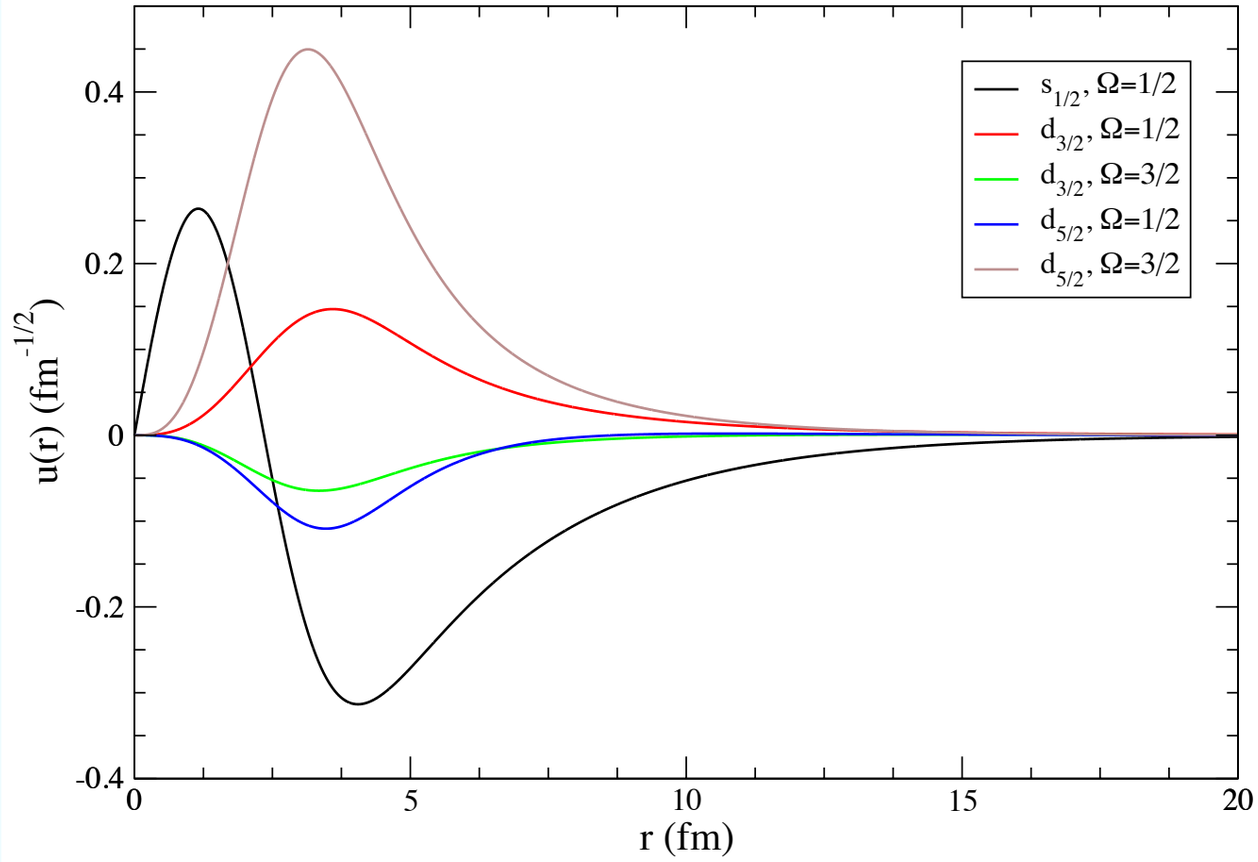
^{17}C

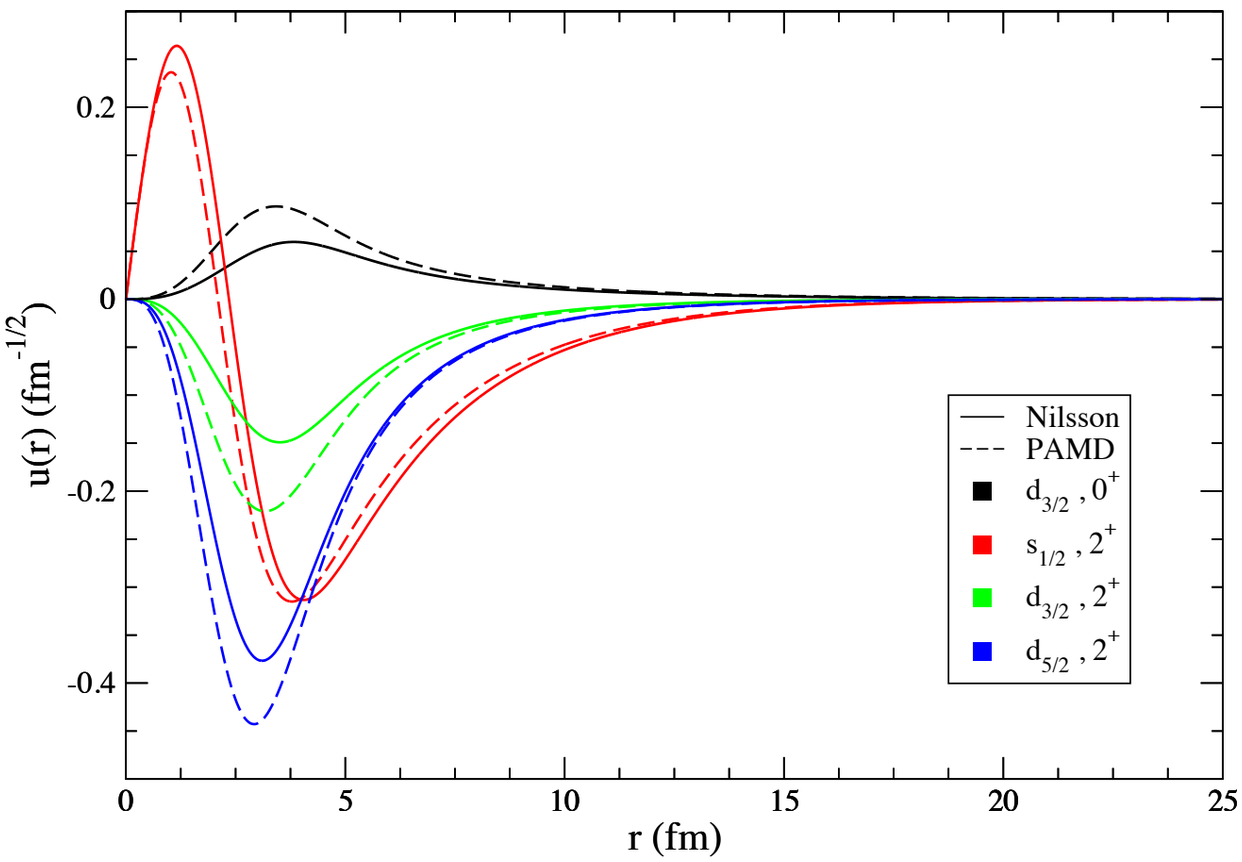




Wave Functions

^{17}C ground state 3/2+



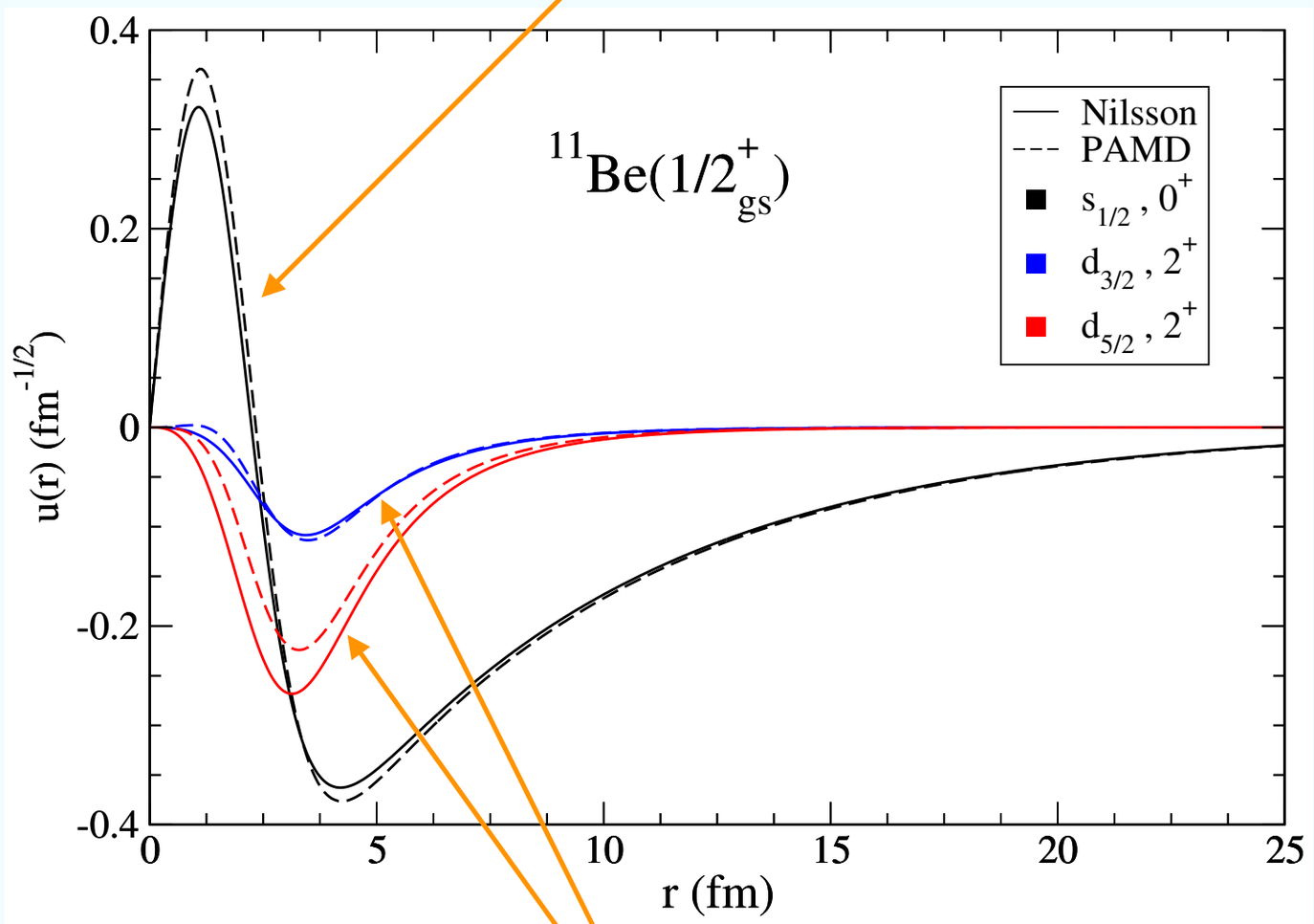


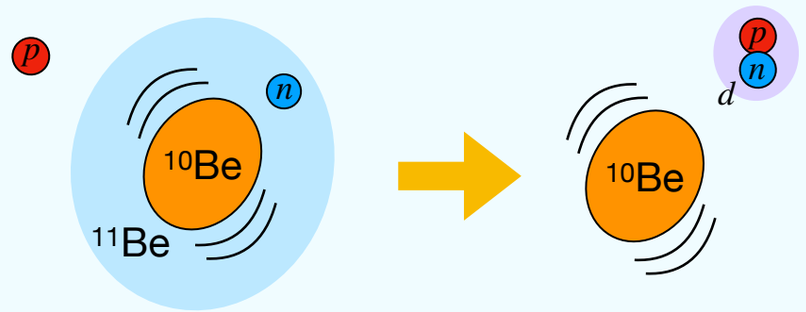
Ω - axial projections ⟶ I - core states

$$u_{jI}^{\lambda J^\pi}(r) = \sqrt{2} \sum_{\Omega} (-1)^{J+\Omega} \langle I0 \,|\, j - \Omega J \Omega \rangle u_{j\Omega}^{\lambda J^\pi}(r)$$

^{11}Be(p,d)^{10}Be

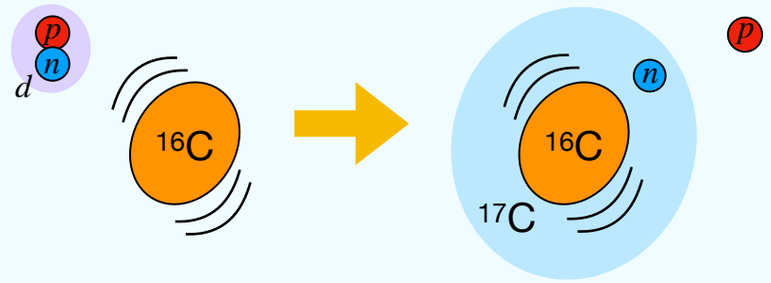
$$\langle {}^{10}\mathrm{Be}(0^+) | {}^{11}\mathrm{Be}(1/2^+_{gs}) \rangle \quad \rightarrow \quad \left(\frac{d\sigma}{d\Omega} \right)_{{}^{10}\mathrm{Be}(0^+)}$$

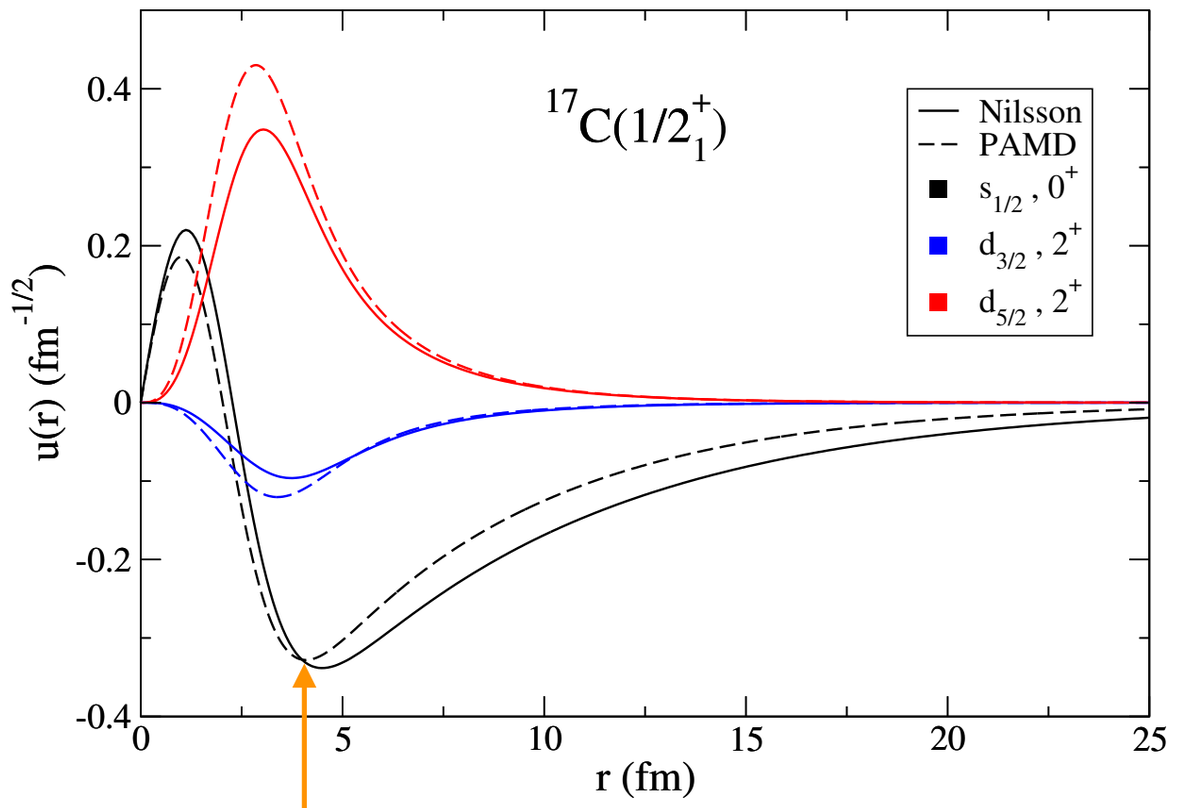


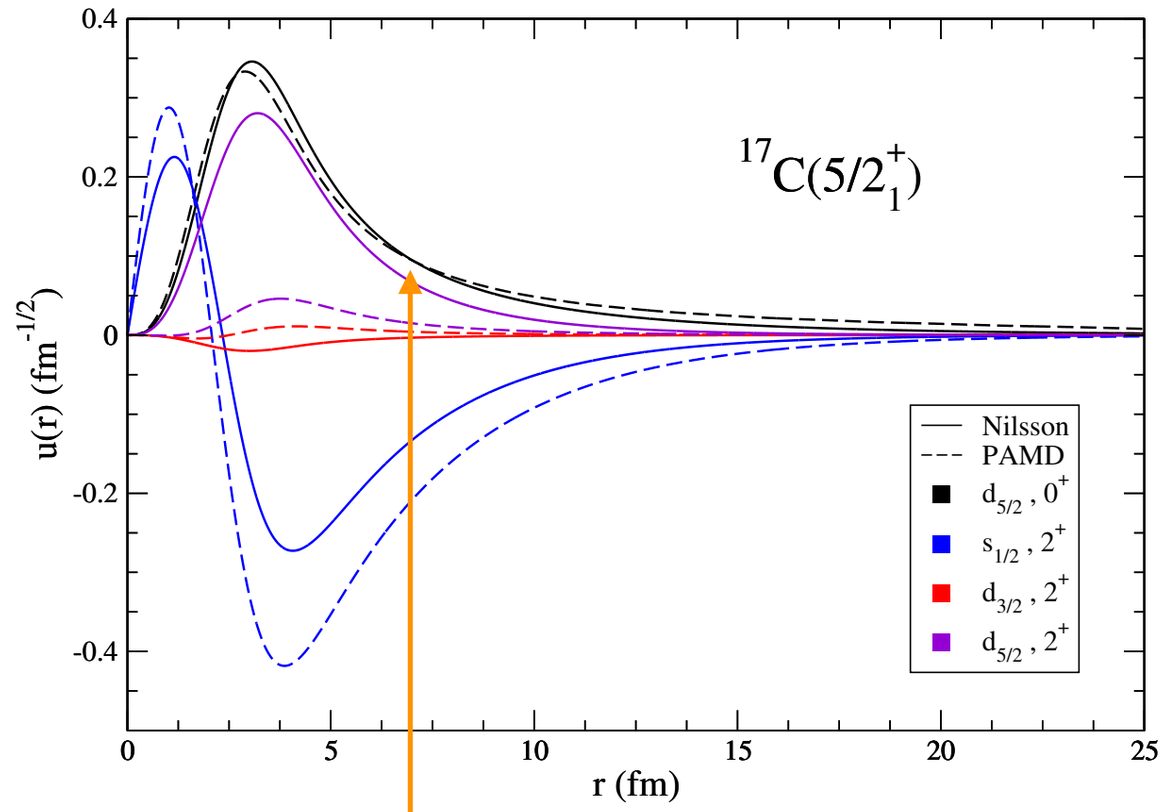


$$\langle {}^{10}\mathrm{Be}(2^+) | {}^{11}\mathrm{Be}(1/2^+_{gs}) \rangle \quad \rightarrow \quad \left(\frac{d\sigma}{d\Omega} \right)_{{}^{10}\mathrm{Be}(2^+)}$$

^{16}C(d,p)^{17}C





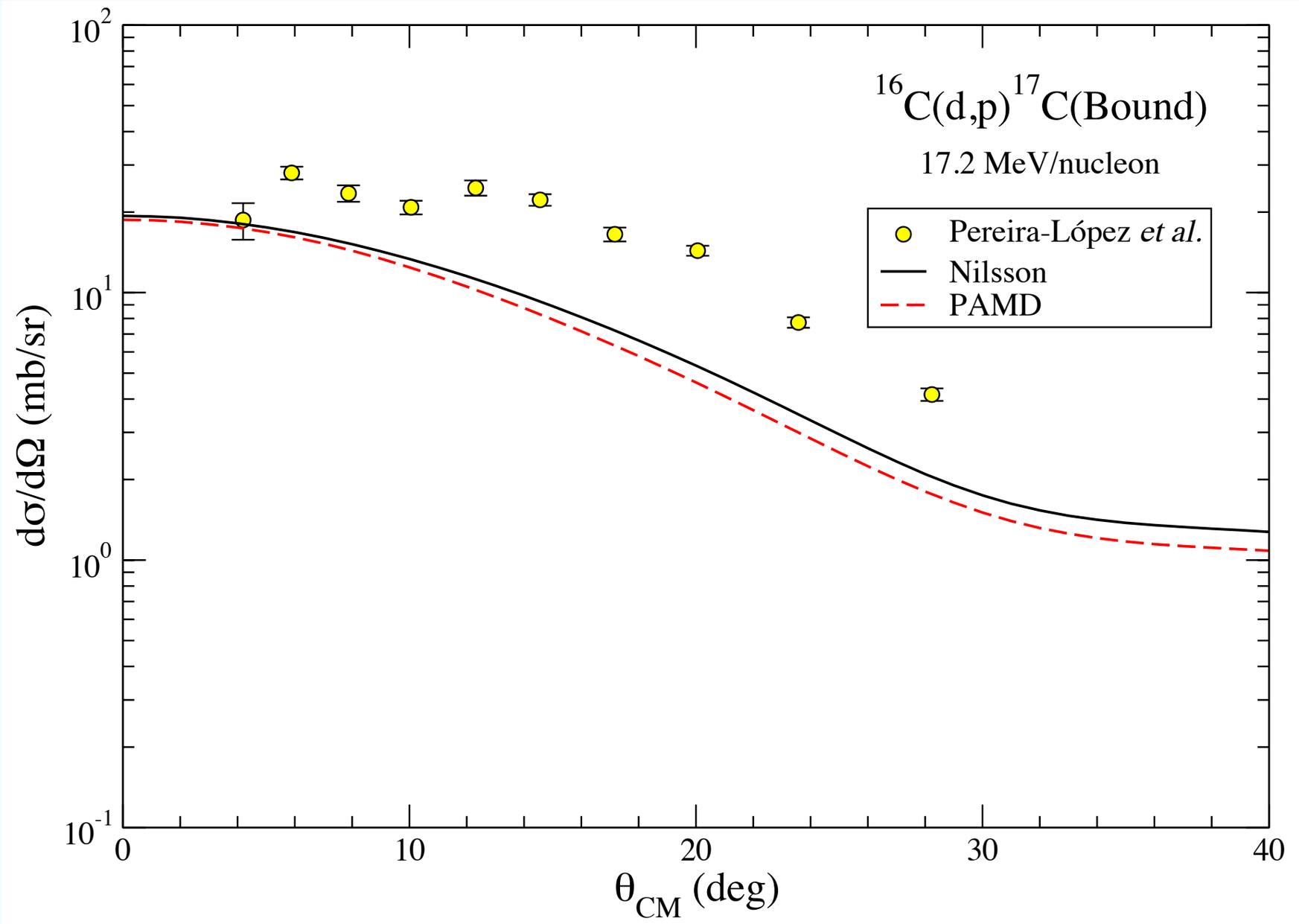


$$\langle {}^{17}\mathrm{C}(1/2^+_1)|{}^{16}\mathrm{C}(0^+)\rangle \rightarrow \left(\frac{d\sigma}{d\Omega}\right)_{{}^{17}\mathrm{C}(1/2^+_1)}$$

$$\langle {}^{17}\mathrm{C}(5/2^+_1)|{}^{16}\mathrm{C}(0^+)\rangle \rightarrow \left(\frac{d\sigma}{d\Omega}\right)_{{}^{17}\mathrm{C}(5/2^+_1)}$$

Transfer to bound states

Sum for the three bound states



Transfer to the continuum

- The *prior* form of the ADWA approximation is used

  X $\langle {}^{17}\mathrm{C} \,|\, {}^{16}\mathrm{C} \rangle$ → Too much spatial extension

  ✓ $\langle {}^{17}\mathrm{C} \,|\, V_{n-{}^{16}C} \,|\, {}^{16}\mathrm{C} \rangle$ → Little spatial extension

- The continuum is discretized with the pseudo-states method

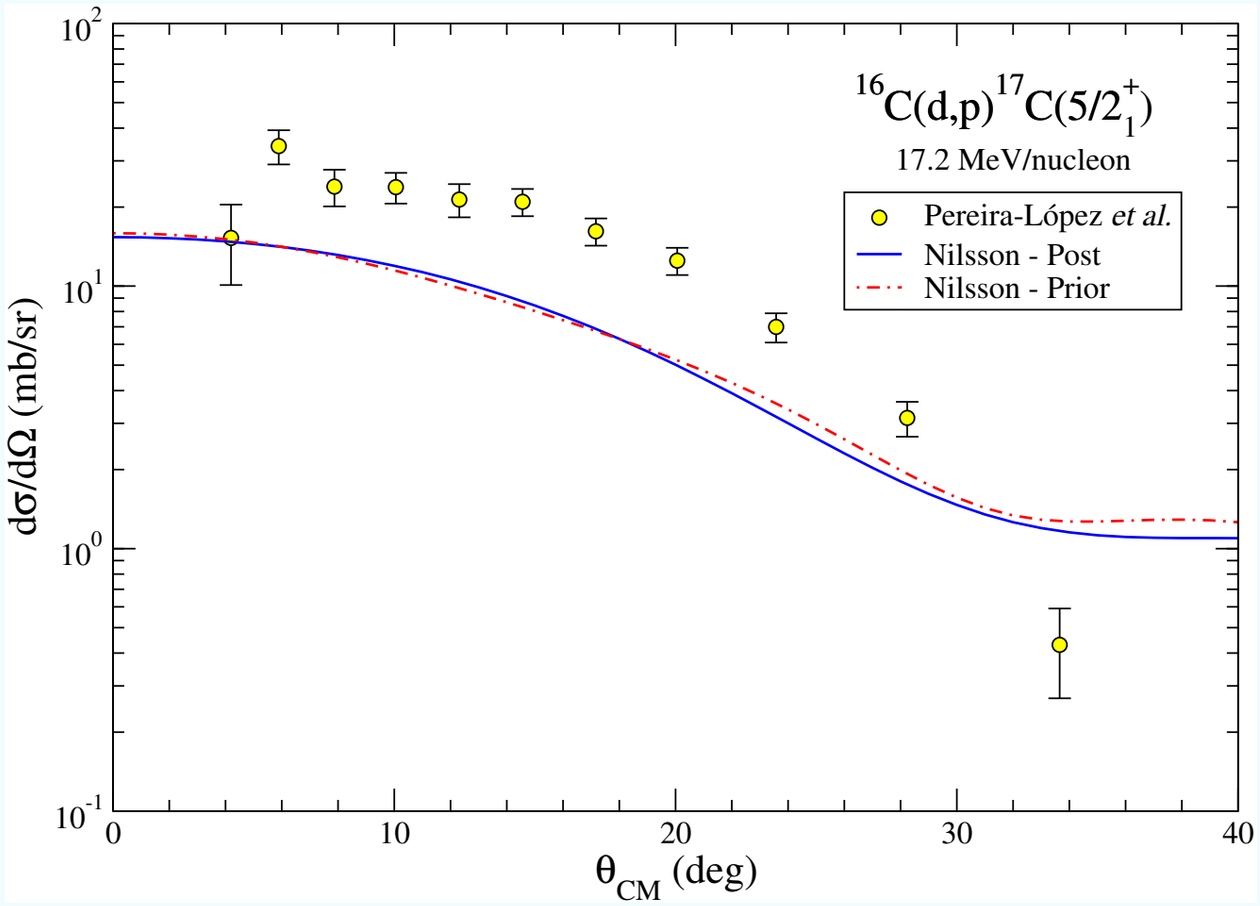
  - Scattering amplitudes for a discrete number of pseudo-states

  - Convolution with the *exact n*+core scattering states

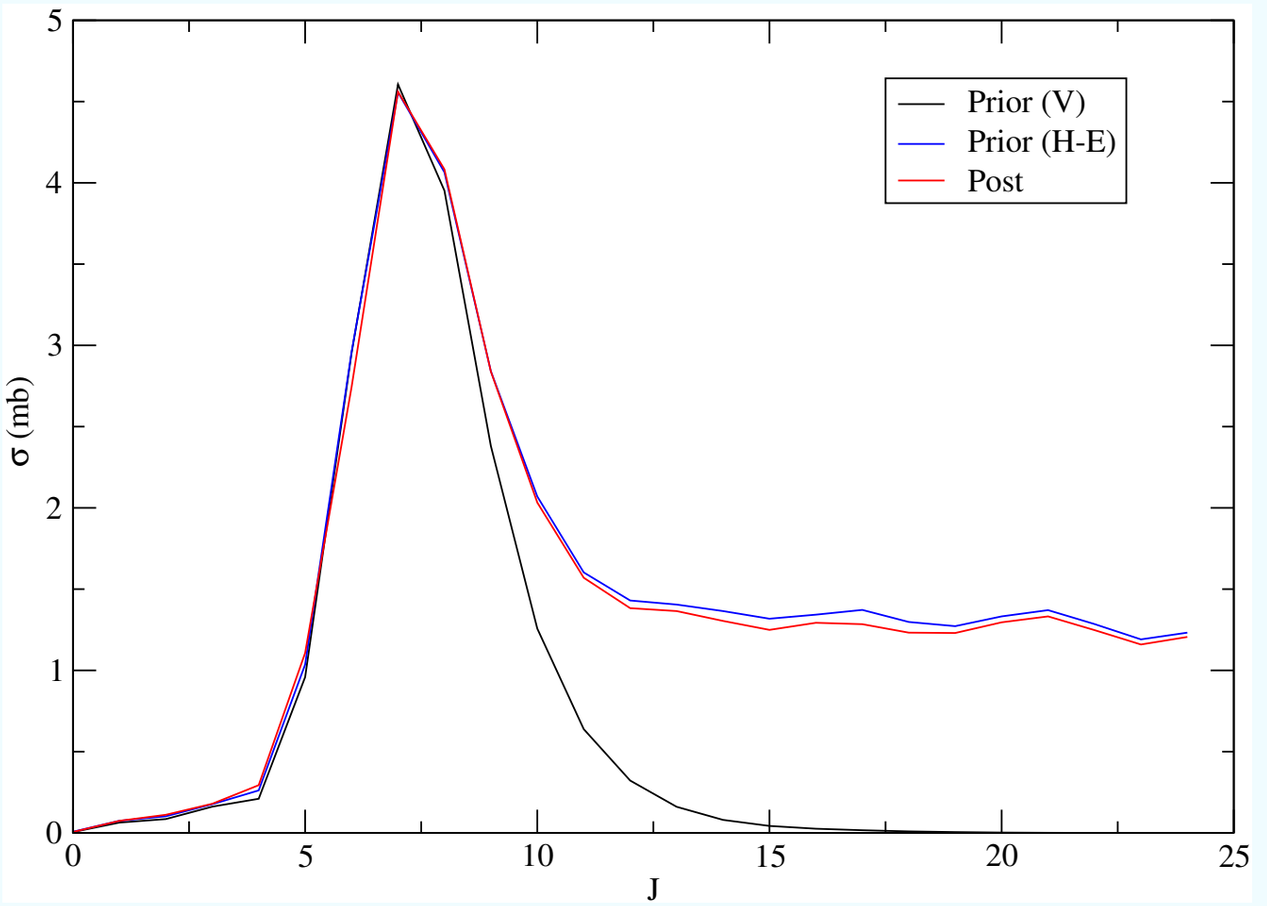
$$\mathscr{F}(k,\theta) \approx \sum_n \langle \Psi(k,r) \,|\, \Psi_n^{THO}(r) \rangle \mathscr{F}_n^{THO}(\theta)$$

$^{16}C(d,p)^{17}C$: Prior-Post

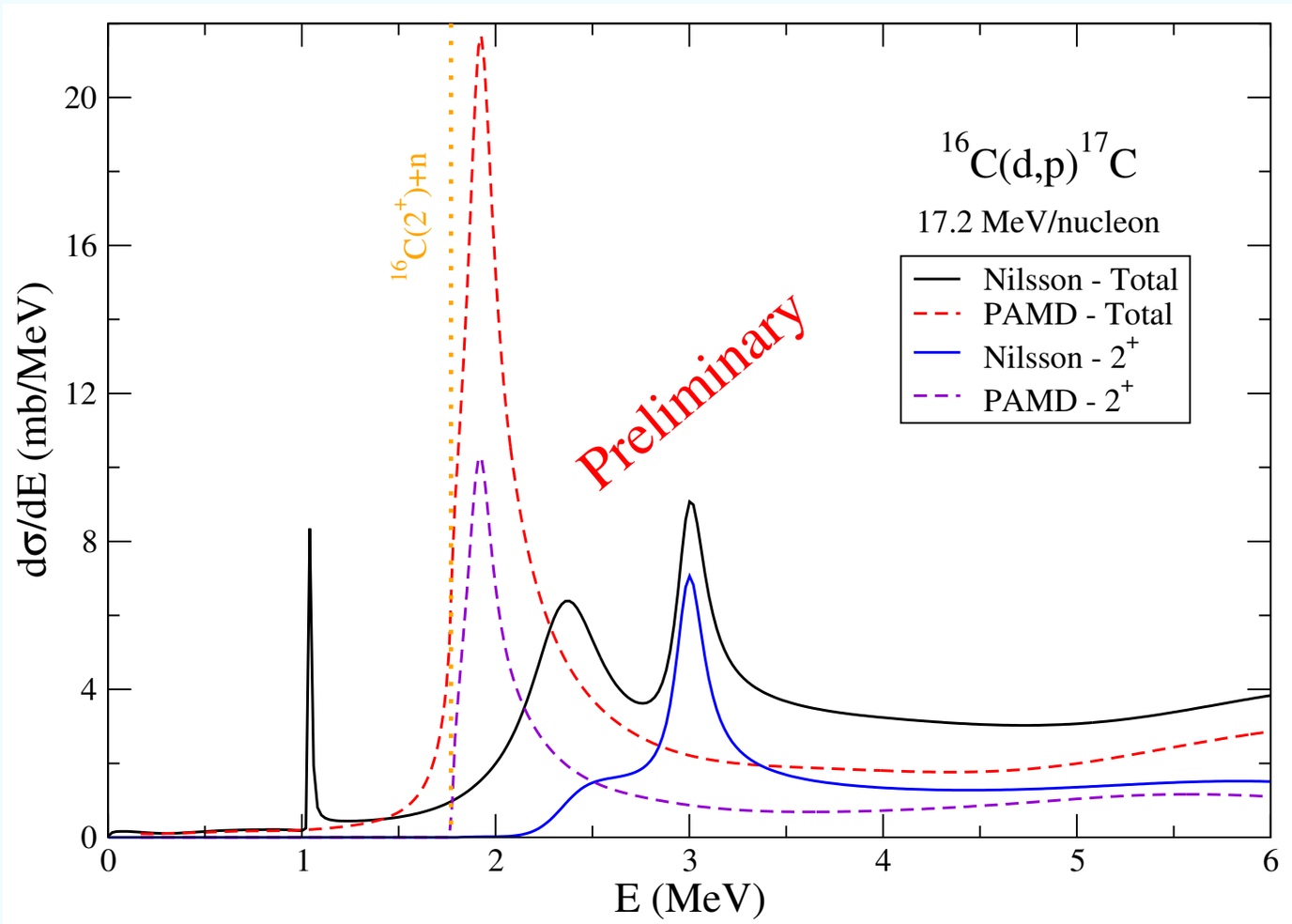
Bound states



Transfer to the continuum



Transfer to the continuum: Decay mode



^{17}C → ^{16}C+n