Core-valence absorption in breakup and stripping reactions and its isospin dependence

M. Gómez-Ramos[1], J. Gómez-Camacho[1,2],A.M. Moro[1]

[1] Departamento de FAMN, Facultad de Física, Universidad de Sevilla,Av. Reina Mercedes s/n, Sevilla
[2] Centro Nacional de Aceleradores, C/ Tomás Alva Edison, 7, 41092 Sevilla

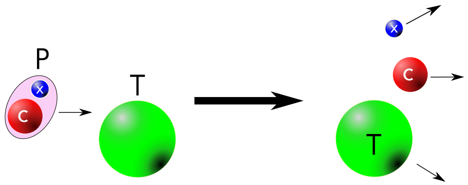
October 20, 2022

Contents

Contents

Nuclear breakup reactions

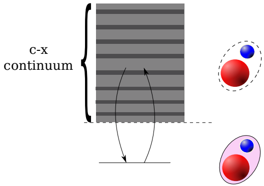
- $P(c+x)+T \rightarrow c+x+T$
- All particles are detected



- Extensively used to analyze single-particle properties of nuclei, specially exotic nuclei

Continuum-discretized coupled-channels

- State-of-the-art description of low- and mid-energy breakup reactions
- 3-body approximation of the full wavefunction, expanded in discretized $C-x$ continuum



$$\Psi \simeq \Psi^{3b}(\vec{R_{PT}}, \vec{r_{xC}}) \simeq \sum_{nJ\pi} \chi_{nJ\pi}(\vec{R_{PT}})\phi_{nJ\pi}(\vec{r_{xC}})$$

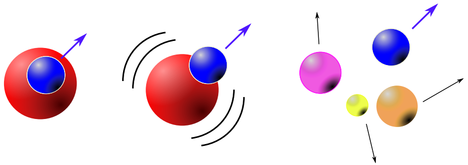
$$\phi_{nJ\pi}(k_n, \vec{r_{xC}}) = \sqrt{\frac{2}{\pi N}} \int_{k_{n-1}}^{k_n} \phi_{nJ\pi}(k, \vec{r_{xC}})\mathrm{d}k$$

- Orthogonality of states used to solve equations: V_{xC} must be real

$$\sum_{nJ\pi}[(E - T - \epsilon_m) \underbrace{\langle \phi_{nJ\pi'} | \phi_{mJ\pi} \rangle}_{\delta_{nm}\delta_{J\pi J\pi'}} - \langle \phi_{nJ\pi'} | U_{xT} + U_{CT} | \phi_{mJ\pi} \rangle]\chi_{mJ\pi} = 0$$

Absorption effects

- Imaginary parts of U_{xT} and U_{CT} describe absorption between $x-T$ and $C-T$
- In the continuum, the interaction between x and C can excite C or x, which can then break up, removing flux



- U_{xC} should be complex at positive energies, but then its eigenstates φ are no longer orthogonal!!!
- Binormal basis $\tilde{\varphi}$ is orthogonal to a set of non-orthogonal states φ

$$\sum_{nJ\pi}[(E-T-\epsilon_m)\underbrace{\langle\tilde{\varphi}_{nJ\pi'}|\varphi_{mJ\pi}\rangle}_{\delta_{nm}\delta_{J\pi J\pi'}} - \langle\tilde{\varphi}_{nJ\pi'}|U_{xT}+U_{CT}|\varphi_{mJ\pi}\rangle]\chi_{mJ\pi} = 0$$

$$\tilde{\varphi}_n^{(-)} \sim \varphi_n^{(+)*} \qquad \tilde{\varphi}_i^{(-)} = \sum_j \mathcal{A}_{ij}^{-1}\varphi_j^{(+)*} \qquad \mathcal{A}_{ji} = \left\langle \varphi_j^{(+)*}|\varphi_i^{(-)}\right\rangle$$

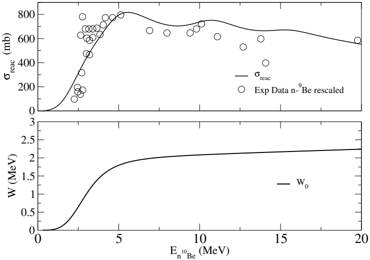
Contents

Contents

Interaction potential

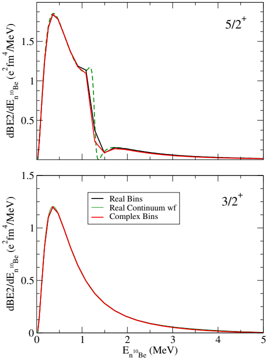
- Real part: Potential from Capel *et al* (PRC **70**, 064605 (2004)), reproduces bound states and low-energy resonance
- Imag part: Adjusted to reproduce reaction cross sections for $n-{}^{9}$Be (compilation by *A. Bonaccorso and R.J. Charity* PRC **89**,024619 (2014)), rescaled through $A^{2/3}$

$$W(E,r) = \frac{W_0(E)}{1+\exp{(r-R)/a_0}} \quad W_0(E) = \frac{(a(E-E_b)+b)E^4}{E^4+E_b^4},$$

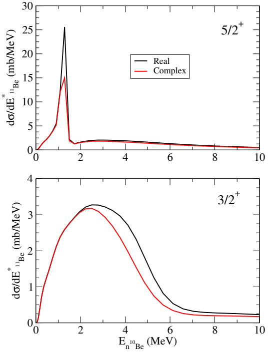


$5/2^+$ and $3/2^+$ states

$$\frac{dB(E2)}{dE}$$

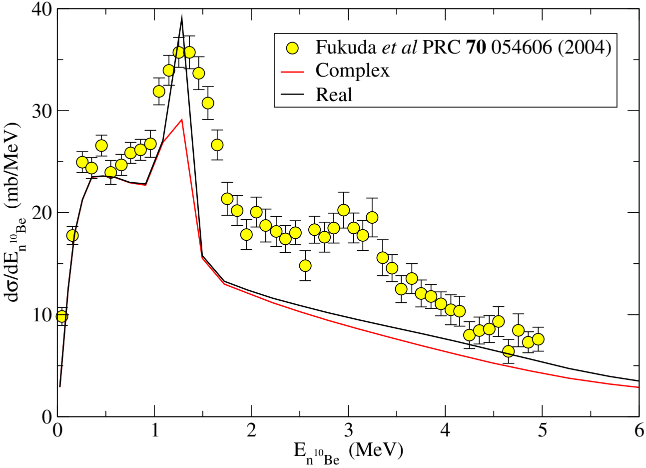


$$\frac{d\sigma}{dE}\ ^{12}\mathrm{C}(^{11}\mathrm{Be},n^{10}\mathrm{Be})^{12}\mathrm{C}$$



- Coulomb breakup barely affected by absorption (larger $x-C$ distance)
- Resonances severely affected

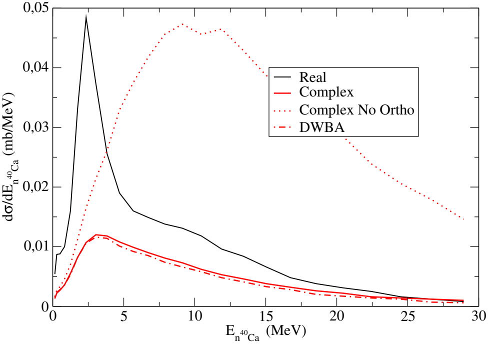
Full cross section



- Small effect of absorption: ∼10%
- Resonance too severely affected (absorption threshold possibly too low)
- Core-excitation effects have been predicted for these data (*A.M. M. and J.A. Lay* PRL **109** 232502 (2012)) but are not included here

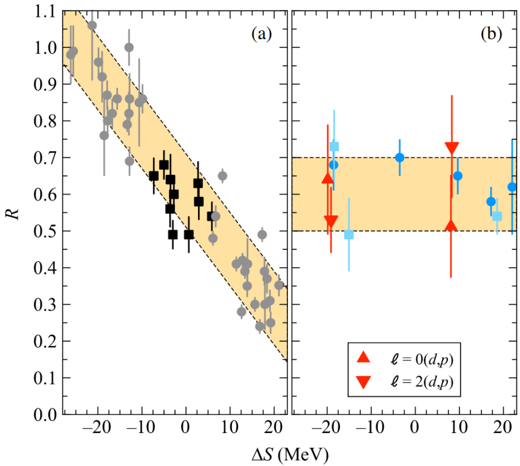
Contents

$^{12}C(^{41}Ca, n^{40}Ca)^{12}C$ at 70 MeV/A



- Much stronger effect: ∼50% reduction
- Breakup of more tightly bound nucleon explores higher energies with larger absorption, and there are more open channels
- Large effect of non-orthogonality with the ground state, use of $\varphi^{(+)*}$ is not enough

Implications?



B.P. Kay et al PRL **129** 152501 (2022)
J. A. Tostevin and A. Gade PRC **103** 054610 (2021)

- Answer to open question?

Contents

Absorption in stripping

- In usual eikonal treatment uses closure to obtain a density of the bound nucleon

$$\rho(\mathbf{r_1},\mathbf{r_2}) = \phi_b^*(\mathbf{r_1})\phi_b(\mathbf{r_2})\int \mathrm{d}\mathbf{k}\phi_{xC}^{(+)}(\mathbf{k},\mathbf{r_1})\phi_{xC}^{*(+)}(\mathbf{k},\mathbf{r_2}) = \delta(\mathbf{r_1}-\mathbf{r_2})\phi_b^*(\mathbf{r_1})\phi_b(\mathbf{r_2}) = |\phi_b(\mathbf{r_1})|^2$$

- This is only true for real, energy-independent V_{xC}.
- For absorptive potentials we can define an effective density for an average position

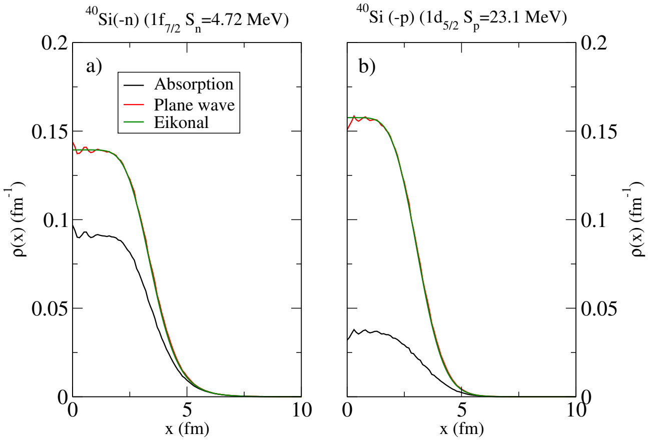
$$\rho^{\mathrm{eff}}(x,y) = \int \mathrm{d}\mathbf{r_1}\mathrm{d}\mathbf{r_2}\delta(x-\frac{x_1+x_2}{2})\delta(y-\sqrt{\frac{y_1^2+y_2^2}{2}})\phi_b^*(\mathbf{r_1})\phi_b(\mathbf{r_2})\int \mathrm{d}\mathbf{k}\phi_{xC}^{(+)}(\mathbf{k},\mathbf{r_1})\phi_{xC}^{*(+)}(\mathbf{k},\mathbf{r_2})$$

- This ρ^{eff} can be used in standard eikonal calculations

$$\sigma_{\mathrm{str}} = \int \mathrm{d}\mathbf{b}\int \mathrm{d}\mathbf{b_{VC}}\rho^{\mathrm{eff}}(x,y)|S_{CT}|^2(1-|S_{VT}|^2)$$

Effective density

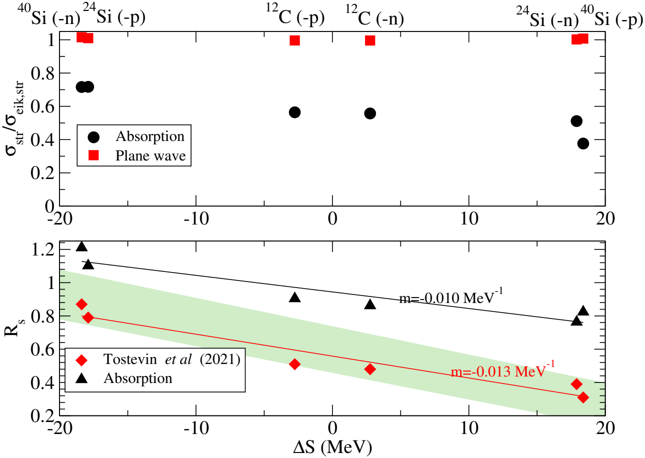
- U_{VC}: Imaginary part of Morillon potential (since we study absorption)



- Significant reduction, larger for deeply-bound nucleon

Effect on cross sections

- Only computed for stripping, effect in diffraction assumed to be the same



- Small reduction in slope
- $R_s < 1$ for weakly-bound nucleons... problematic

Elastic compound scattering

- Optical potential gives finite reaction cross section at low energies for weakly-bound nucleons (But there are no open channels!!!)
- This corresponds to compound nucleus which decays to elastic channel (This is not absorption)$\rightarrow$ Must be removed from potential
- Use compound-nucleus calculation (PACE4) to estimate and remove flux to elastic

$n+{}^{39}\mathrm{Si}$

1. Yields of residual nuclei

Z	N	A		events	percent	x-section(mb)
14	25	**39**	**Si**	1000	100%	1.7e+03
TOTAL				1000	100	1700.25

$p+{}^{39}\mathrm{Al}$

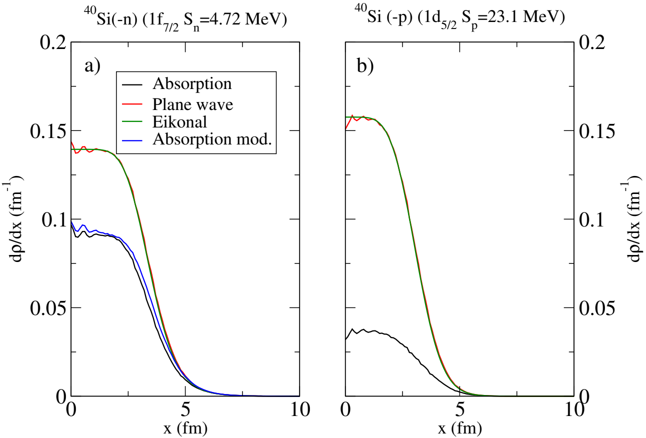
1. Yields of residual nuclei

Z	N	A		events	percent	x-section(mb)
14	25	**39**	**Si**	13	1.3%	11.8
14	24	**38**	**Si**	117	11.7%	106
14	23	**37**	**Si**	865	86.5%	786
14	22	**36**	**Si**	5	0.5%	4.54
TOTAL				1000	100	908.47

- Absorption unchanged for deeply-bound nucleons but severely reduced for weakly-bound at low energies

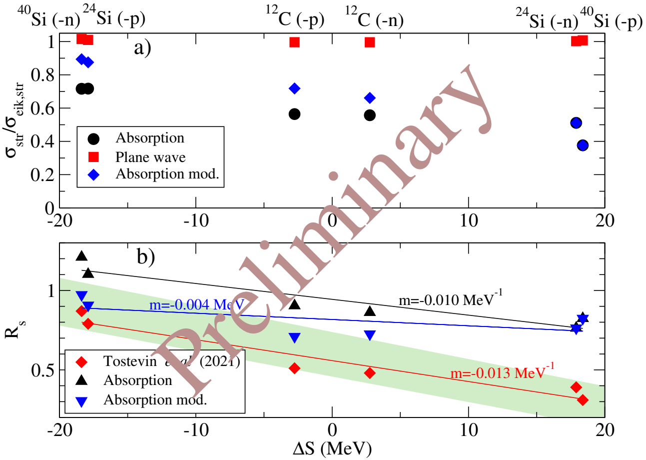
Effective density

- U_{VC}: Imaginary part of Morillon potential (since we study absorption)



- Modification in tail (relevant for stripping)

Effect on cross sections



- Significant flattening, consistent with transfer

Contents

Conclusions and outlook

- An extension of CDCC to include core-valence absorption in elastic breakup reactions has been developed
- Application to $^{12}\mathrm{C}(^{11}\mathrm{Be}, n^{10}\mathrm{Be})^{12}\mathrm{C}$ and $^{12}\mathrm{C}(^{41}\mathrm{Ca}, n^{40}\mathrm{Ca})^{12}\mathrm{C}$ at 70 MeV/A shows larger effect when removing more deeply-bound species
- Modification of eikonal formalism for stripping to include absorption
- When correcting for proper loss of flux significant reduction in isospin dependence (consistent with transfer)
- Lots of work to do!
    - Uncertainty in VC optical potentials, more reliable (ab initio, dispersive, measurements?) are required
    - Extension to diffractive dispersion
    - Inclusion of real part of VC interaction (bound states?)
    - Go beyond eikonal (Ichimura-Austern-Vincent?)
    - Complete Gade plot
    - Momentum distributions

Acknowledgements

- External funding

,,

  - Ministerio de Ciencia e Investigación: Projects No. PID2020-114687GB-I00 and and RTI2018-098117-B-C21
  - Programa Juan de la Cierva Incorporacion, IJC2020-043878-I
  - Junta de Andalucía PAIDI 2020, Ref. P20_01247