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The effect of core-valence absorption in the evaluation of single-nucleon removal cross sections

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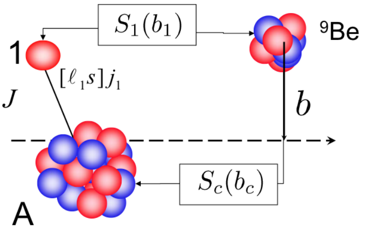
AGENCIA ESTATAL DE INVESTIGACIÓN

- Fast-moving projectile on a (typically) light target.
- One nucleon suddenly removed (absorbed) due to its interaction with the target.
- The remaining residue remains unchanged and is detected.
- The momentum of the core is related to that of the removed nucleon because in the projectile rest frame $\vec{P} = 0$.



(by J. Tostevin)

$$\boxed{\vec{P} = \vec{p}_c + \vec{p}_1 = 0}$$

Extraction of SFs from knockout reactions

- Inclusive cross sections are computed as:

$$\boxed{\sigma_{\text{theor}} = \sum_{n\ell j} S^{a}_{bx}(I;n\ell j)\sigma_{\rm sp}(I;n\ell j)}$$

- The s.p. cross section is conveniently separated into elastic breakup ("diffration") and nonelastic breakup ("stripping") contributions:

$$\boxed{\sigma_{\rm sp}(I;n\ell j) = \sigma^{\rm EBU}_{\rm sp} + \sigma^{\rm NEB}_{\rm sp}}$$

- Agreement theory vs experiment quantified with the reduction factor:

$$\boxed{R_s = \frac{\sigma_{\text{exp}}}{\sigma_{\text{theor}}}}$$

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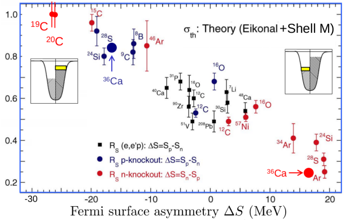
Measurements at the two Fermi surfaces



☞ $R_s < 1 \Rightarrow$ possible correlations (long-range, short-range, tensor,...) not included in σ_{theor}?

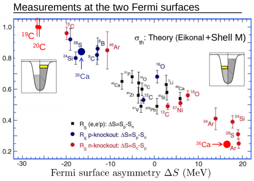
☞ R_s strongly dependent on $\Delta S = S_p - S_n$.

Gade et al, PRC 77, 044306 (2008), Tostevin, PRC90,057602(2014)

Comparison with transfer and (p, pN) reactions

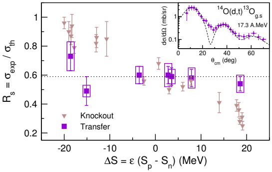
...however, this behaviour has not been corroborated by other probes, such as transfer or proton-induced knockout reactions (p, pN)

HI knockout
(∼100 MeV/u)
Tostevin, PRC90,057602(2014)



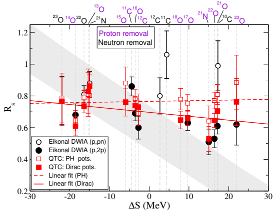
- Reaction model: eikonal + adiabatic
- R_s strongly dependent on $S_p - S_n$.

Low-energy transfer
Flavigny, PRL110, 122503(2013)



- Reaction model: ADWA, DWBA, CRC
- $R_s \sim$ constant.

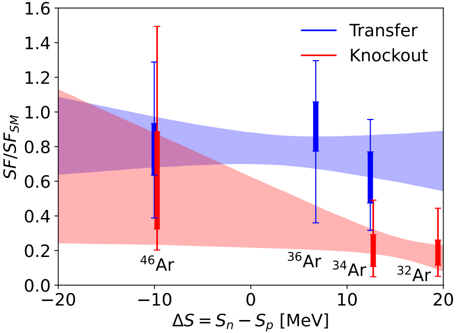
(p, pN) @ 200-400 MeV/u
Aumann, PPNP118,103847(2021)



- Reaction models: DWIA, TC
- $R_s \sim$ constant.
- ☞ Similar results from RIKEN Wakase, PTEP 021D01 (2018)

Proposed explanations for the R_s puzzle

- From the structure side:
  - Enhancement of short-range correlations for well-bound nuclei not included in standard SM calculations
  - Coupling to near-threshold single-particle configurations in the continuum
  - 3N force effects (missing in standard SM)
- From the reaction side:
  - Unadequacy of the eikonal approximation at the typical knockout experiment energies ($<$100 MeV/u)
  - Theoretical uncertainties in simplified transfer reaction analyses.
    Nunes, Deltuva, and June Hong, Phys. Rev. C 83, 034610 (2011)

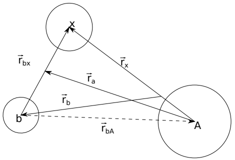


Hebborn, Nunes, Lovell, arXiv:2302.14343

Testing the eikonal approximation: comparison with the IAV model

See also Lei, AMM, PRC92, 044616 (2015)

- Inclusive reaction $\underbrace{(b+x)}_{a}+A \to b+(x+A)^*$
- b singles cross section: $\sigma_b^{inc} = \sigma_b^{\rm EBU} + \sigma_b^{\rm NBU}$



- EBU: $a+A \to b+x+A_{\rm g.s.}$ can be computed with CDCC, DWBA, etc
- $\sigma_b^{\rm NEB}$ can be interpreted as the absorption occurring in the $x+A$ channel:

$$\boxed{\frac{d\sigma^{\rm NEB}}{d\Omega_b dE_b} = -\frac{2}{\hbar v_a}\rho_b(E_b)\langle\varphi_x^{(\mathbf{k}_b)}|W_{xA}|\varphi_x^{(\mathbf{k}_b)}\rangle} \qquad W_{xA} = \mathrm{Im}[U_{xA}]$$

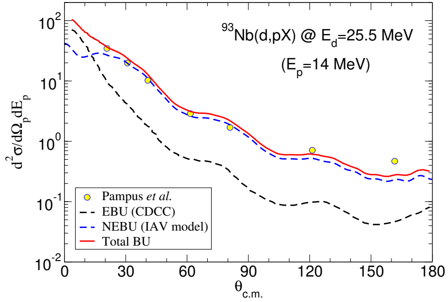
where $\varphi_x^{(\mathbf{k}_b)}(\mathbf{r}_x)$ describes x-A relative motion when b scatters with $\mathbf{k}_b$:

$$\boxed{[E_x - K_x - U_{xA}]\varphi_x^{(\mathbf{k}_b)}(\mathbf{r}_x) = (\chi_b^{(-)}|V_{bx}|\chi_a^{(+)}\phi_a(\mathbf{r}_{bx})\rangle} \qquad V_{\rm post} = V_{bx}+U_{bA}-U_{bB}$$

with :

- $\phi_a(\mathbf{r}_{bx})$ projectile ground state wf.
- $\chi_a^{(+)}(\mathbf{k}_b,\mathbf{r}_b)$ =distorted wave for entrance channel $(a+A)$.
- $\chi_b^{(-)}(\mathbf{k}_b,\mathbf{r}_b)$ =distorted wave for "spectator" particle (b).

- EBU calculated with CDCC.
- NBU calculated with IAV model



Calculations:

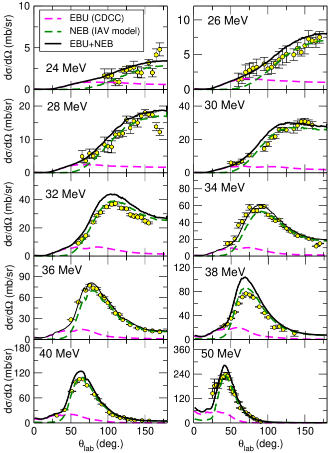
J. Lei, A.M.M., PRC 92, 044616 (2015)

Data:

Pampus et al, NPA311 (1978)141

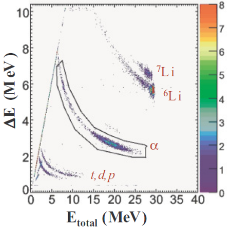
Application to ^{209}Bi (^{6}Li,α)X

Assume: $\sigma_\alpha \simeq \underbrace{\sigma^{\rm EBU}}_{\rm CDCC} + \underbrace{\sigma^{\rm NEB}}_{\rm IAV}$



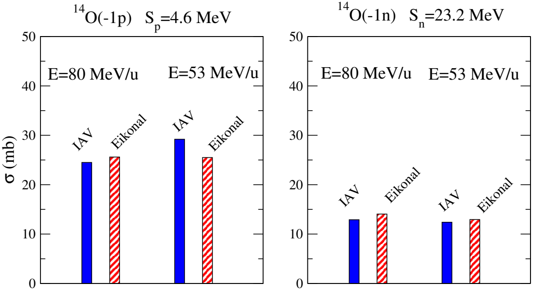
J. Lei and AMM, PRC92, 044616 (2015)

- Inclusive data well accounted for by EBU+NEB
- Inclusive α's dominated by NEB
- EBU (^{6}Li $\to \alpha + d$) only relevant for small scattering angles.



Santra et al, PRC85, 014612 (2012)

Test case: ^{14}O(-1n) and ^{14}O(-1p) on ^{9}Be target with the same (energy-independent) potentials and structure model



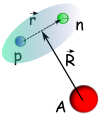
M. Gomez-Ramos et al, EPJA (2021) 57:57

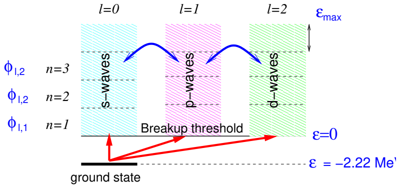
- The Eikonal model compares very well with the IAV result, even at relatively low incident energies (∼50 MeV/u)
- Other effects relevant for the comparison with data (e.g. energy dependence of OMPs) not considered here (see Flavigny, PRL 108, 252501 (2012), J. Lei and Bonaccorso, PLB813 (2021) 136032)

The effect of “core-valence” absorption in elastic and nonelastic breakup

Reminder of the Continuum-Discretized Coupled-Channels method (CDCC)

- Effective solution for two-body or three-body projectiles on an inert target.
- Breakup treated as inelastic excitations to two-body continuum.
- Continuum states are represented by a finite set of square-integrable functions





- Three-body wavefunction (after discretization):

$$\Psi^{\mathrm{CDCC}}(\mathbf{r},\mathbf{R}) = \phi_0(k_0,\mathbf{r})\chi_0(\mathbf{K}_0,\mathbf{R}) + \sum_{n',j,\pi} \phi_{n'}^{j\pi}(k_{n'},\mathbf{r}')\chi_{n',j,\pi}(\mathbf{K}_{n'},\mathbf{R}')$$

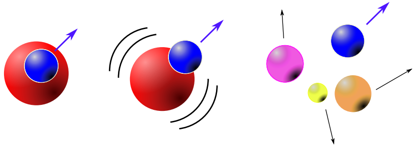
- $[H-E]\Psi^{\mathrm{CDCC}} = 0$: Orthogonality of states used to solve the equations: V_{xC} must be real:

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

- Provides only elastic cross section and elastic breakup (diffraction) observables.

Absorption effects in $a(x+C)+T \to x+C+T$

- 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_i are no longer orthogonal!!!
- Orthogonality can be recovered using a binormal basis, $\tilde{\varphi}$, defined to be orthogonal to the set of non-orthogonal states φ: $\langle\bar{\varphi}_i|\varphi_j\rangle = \delta_{ij}$
- When the energy dependence of the potential is small: $\tilde{\varphi}_n^{(-)} \simeq \varphi_n^{(+)*}$
- In a more general case:

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

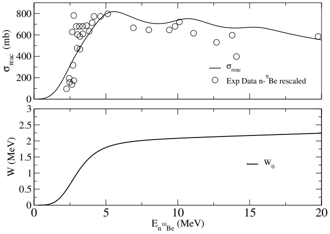
- Coupled equations in the binormal basis:

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

Choice of complex n+^{10}Be interaction:

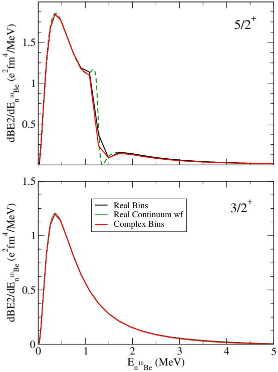
- **Real part:** Potential from Capel *et al* (PRC **70**, 064605 (2004)), reproduces bound states and low-energy resonances.
- **Imag part:** Adjusted to reproduce reaction cross sections for $n-^{9}$Be (*A. Bonaccorso and R.J. Charity* PRC **89**,024619 (2014)), rescaled through $A^{2/3}$.

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

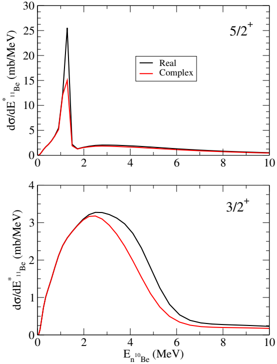


Application to ^{12}C(^{11}Be,n^{10}Be)^{12}C (cont.)

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

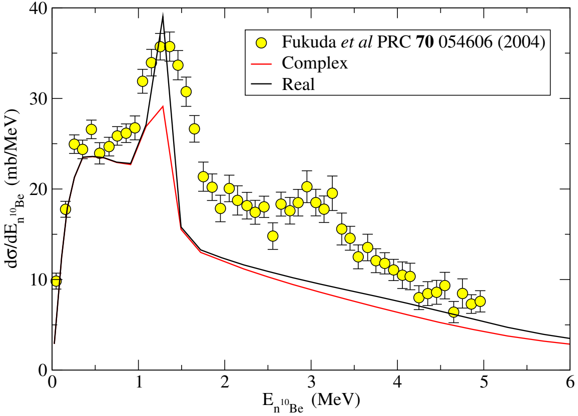


$$\frac{d\sigma}{dE}\ {}^{12}\mathrm{C}({}^{11}\mathrm{Be}, n^{10}\mathrm{Be})^{12}\mathrm{C}$$



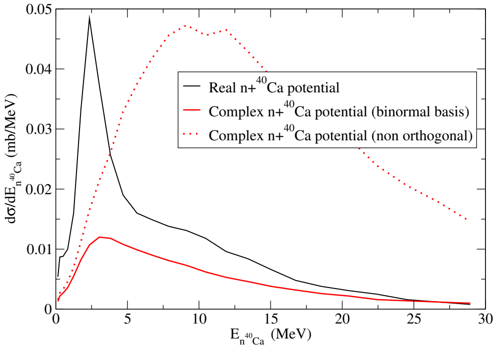
- Coulomb breakup barely affected by absorption (larger $x-C$ distance)
- Resonances severely affected

Full cross section

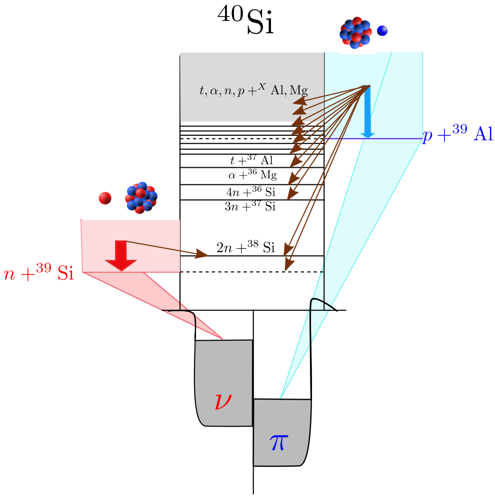


- Small effect of absorption: $\sim$10%
- Resonance too severely affected (absorption threshold possibly too low)
- Core-excitation effects have been predicted for these data (*A.M. M. and J.A. Lay* PRL **109** 232502 (2012)) but are not included here

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



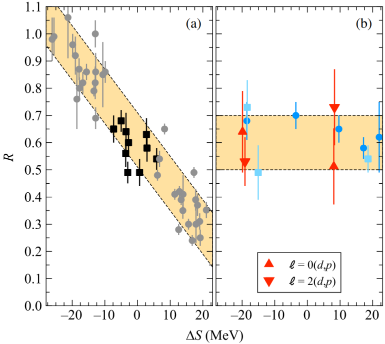
- Smaller breakup cross section, due to larger separation energy ($S_n = 8.4$ MeV)
- Additional suppression due to core-valence absorption (∼50% reduction).
- Large effect of non-orthogonality with the ground state. Replacement $\tilde{\varphi}^{(-)} \to \varphi^{(+)*}$ not accurate.



➩ Breakup of more tightly bound nucleon explores higher energies with larger absorption, and there are more open channels.

Implications?

⇨ Inclusion of valence-core absorption might explain the R_s asymmetry observed in knockout reactions.



B.P. Kay et al, PRL **129** 152501 (2022)

J. A. Tostevin and A. Gade PRC **103** 054610 (2021)

Including the effect of "core-valence" absorption in non-elastic breakup

Revisiting the standard eikonal formula

- Stripping cross section:

$$P_{\rm str}(\vec{b}) = \int d^3\ \vec{k} \sum_{j\neq 0} |A_j(\vec{b},\vec{k})|^2$$

$$A_j(\vec{b},\vec{k}) = \int d^3\vec{r}\phi_g(\vec{r})^*\, S^0_{CT}(b_{CT}) S^j_{VT}(b_{VT}) \varphi^{(-)}_{VC}(\vec{k},\vec{r})$$

- Involves the nonlocal density matrix:

$$\langle \vec{r_2}|\rho_f|\vec{r_1}\rangle = \int \mathrm{d}\vec{k}\, \varphi^{(-)}_{VC}(\vec{k},\vec{r}_1)\varphi^{*(-)}_{VC}(\vec{k},\vec{r}_2)$$

- For real core-nucleon interaction, closure can be used:

$$\langle \vec{r_2}|\rho_f|\vec{r_1}\rangle = \delta(\vec{r_1}-\vec{r_2}) \quad \Rightarrow \quad \sum_{j\neq 0} |S^j_{VT}(b_{VT})|^2 = 1 - |S^0_{VT}(b_{VT})|^2$$

- Leads to standard eikonal expression:

$$\boxed{P^{\rm Eik}_{\rm str}(\vec{b}) = \int d^3\vec{r}\, |\phi_g(\vec{r})|^2 |S^0_{CT}(b_{CT})|^2 \left(1 - |S^0_{VT}(b_{VT})|^2\right),}$$

Eikonal calculations with complex valence-core interaction

- For complex V_{VC}, closure cannot be used, but we can define an effective density for an average position:

$$\rho^{\text{eff}}(x,y) = \int \mathrm{d}\vec{r}_1 \mathrm{d}\vec{r}_2 \, \delta\left(x - \frac{x_1 + x_2}{2}\right) \delta\left(y - \sqrt{\frac{y_1^2 + y_2^2}{2}}\right) \phi_b^*(\vec{r}_1)\phi_b(\vec{r}_2) \int \mathrm{d}\vec{k}\, \varphi_{VC}^{(-)}(\vec{k},\vec{r}_1)\varphi_{VC}^{*(-)}(\vec{k},\vec{r}_2)$$

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

$$\boxed{\sigma_{\text{str}} = \int \mathrm{d}^3\vec{b} \int \mathrm{d}^3\vec{b}_{VC}\; \rho^{\text{eff}}(x,y)|S_{CT}(b_{CT})|^2(1 - |S_{VT}(b_{VT})|^2)}$$

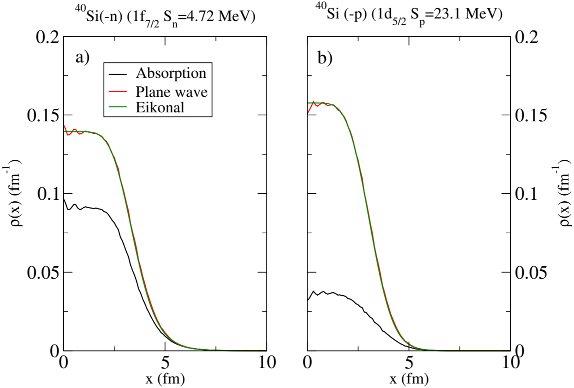
$$b_{VT} = \sqrt{(b + \alpha x)^2 + (\alpha y)^2}$$

$$\alpha = \frac{A-1}{A}; \quad x = \frac{x_1 + x_2}{2}; \quad y = \sqrt{\frac{y_1^2 + y_2^2}{2}}.$$

Details in: M. Gomez-Ramos, J. Gomez-Camacho, A.M.M., arXiv:2303.00426

Effective density for weakly-bound and tightly-bound nuclei

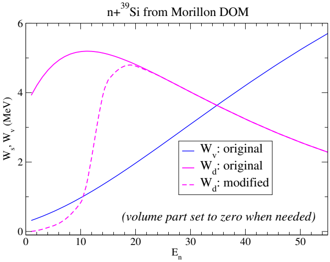
- U_{VC}: Imaginary part of Morillon potential (since we study absorption)



- Significant reduction, larger for deeply-bound nucleon

Elastic compound scattering

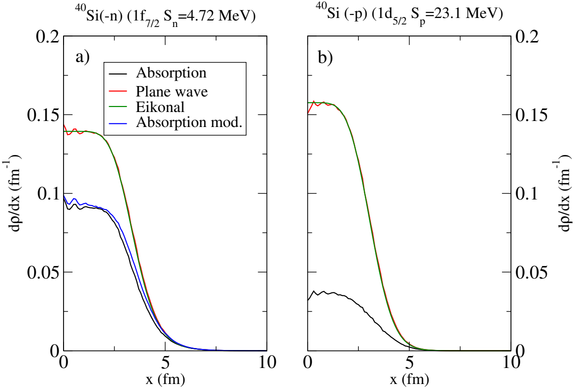
- Optical potential gives finite reaction cross section at low energies for weakly-bound nucleons (But there are no open channels!!!)
- This corresponds to compound nucleus which decays to elastic channel (This is not absorption)→ Must be removed from potential
- Use compound-nucleus calculation (PACE4)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



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

Effective density

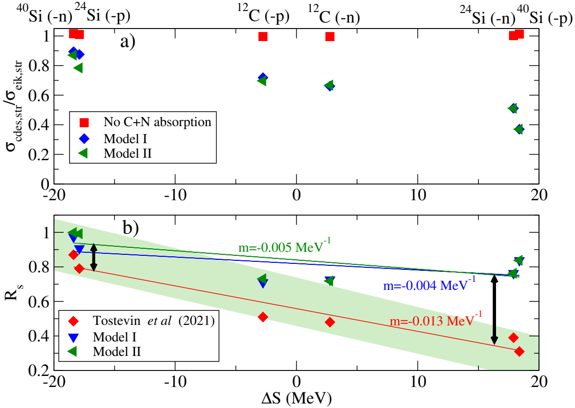
- U_{VC}: Imaginary part of Morillon potential (since we study absorption)



- Modification in tail (relevant for stripping)

Effect on cross sections

- Core-valence absorption described with Morillon DOM potential, corrected with PACE (Model I) or GEMINI (Model II) predictions for compound elastic.



- Significant flattening, consistent with transfer

Conclusions and outlook

- We have explored the effect of inter-cluster absorption in two-body breakup reactions.
- CDCC and eikonal models extended to accommodate core-valence absorption in elastic (diffraction) and non-elastic (stripping) breakup.
  - Application to ^{12}C(^{11}Be, n^{10}Be)^{12}C and ^{12}C(^{41}Ca, n^{40}Ca)^{12}C at 70 MeV/A shows a large suppression of elastic breakup when removing more deeply-bound species.
  - Preliminary knockout calculations indicate that this core-valence absorption is a promising candidate to explain the Gade plot puzzle.

Possible extensions

- Uncertainty in U_{xC} optical potentials, more reliable (ab initio, dispersive, measurements?) are required
- Extension of modified eikonal formalism to diffraction
- Go beyond eikonal (Ichimura-Austern-Vincent?)
- Complete Gade plot
- Momentum distributions

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  - 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
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