Radiative Capture versus Coulomb Dissociation Experiments

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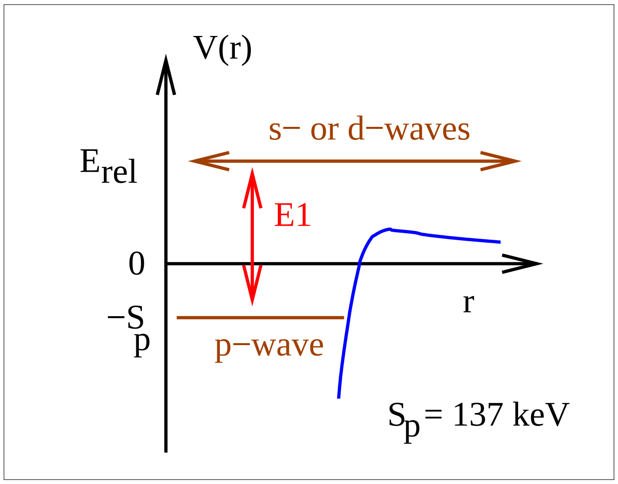
Measurements of the ^{8}B→^{7}Be+p breakup on a high-Z target is often analyzed in terms of

- 1st order E1 transitions in the far-field (FF) approx.
  FF approx.: NO OVERLAP of projectile and target.
  Nice separation of structure and reaction dynamics:

$$\frac{d\sigma^{(CD)}}{dE_{rel}} = \frac{dB(E1)}{dE_{rel}} \times \int_0^\infty d^2\mathbf{b} \, |S_{E1}(E_\gamma, b)|^2 \, \epsilon_{eff}(E_\gamma, b).$$

where $E_\gamma = S_p + E_{rel}$ is the excitation/photon energy.

- Detailed balance:
  Coulomb dissociation and radiative capture are determined by the same dipole matrix element.



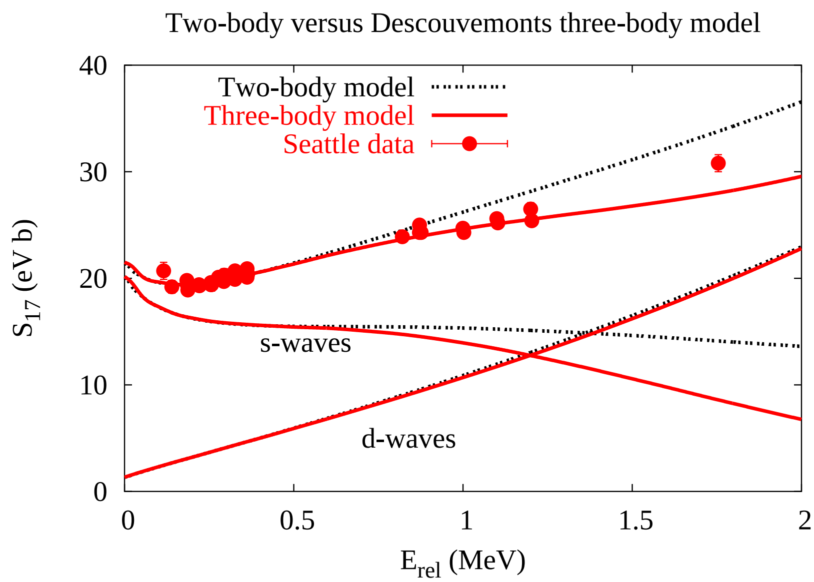
Infer : $\sigma_{E1}^{(rc)} = constant \times \frac{E_\gamma^3}{E_{rel}} \frac{dB(E1)}{dE_{rel}}$

How reliable is this method?

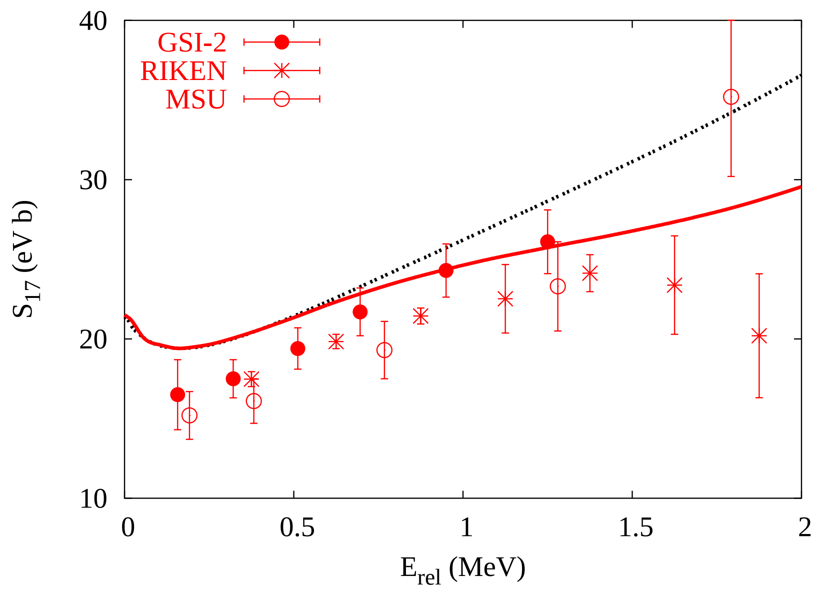
Experimental evidence: significant differences between

the S factors, $S_{17}(E_{rel}) = E_{rel}\ \sigma^{(rc)}_{E1}\ \exp(2\pi\eta)$,

obtained in direct capture measurements:

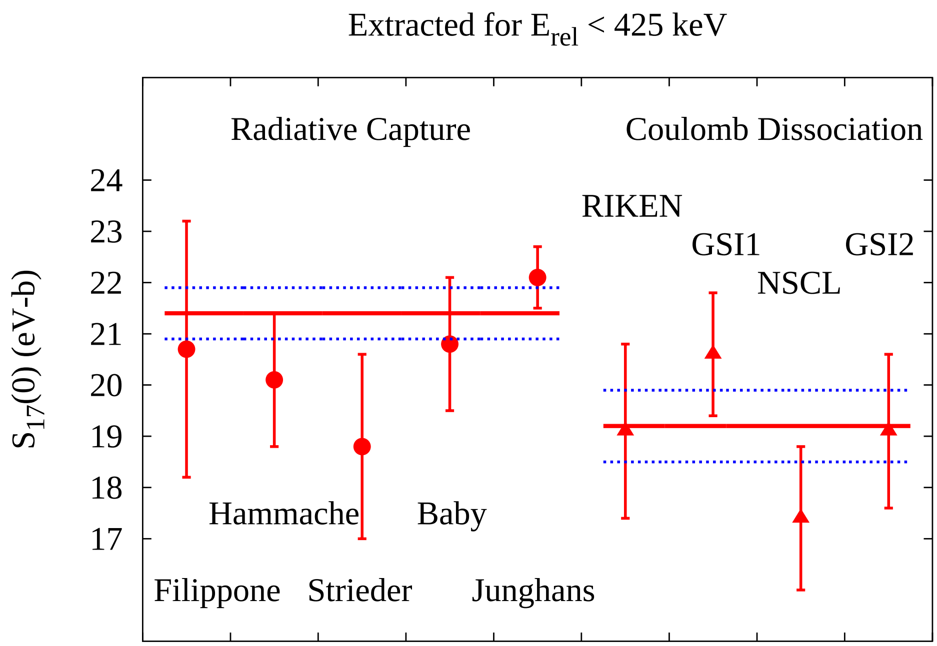


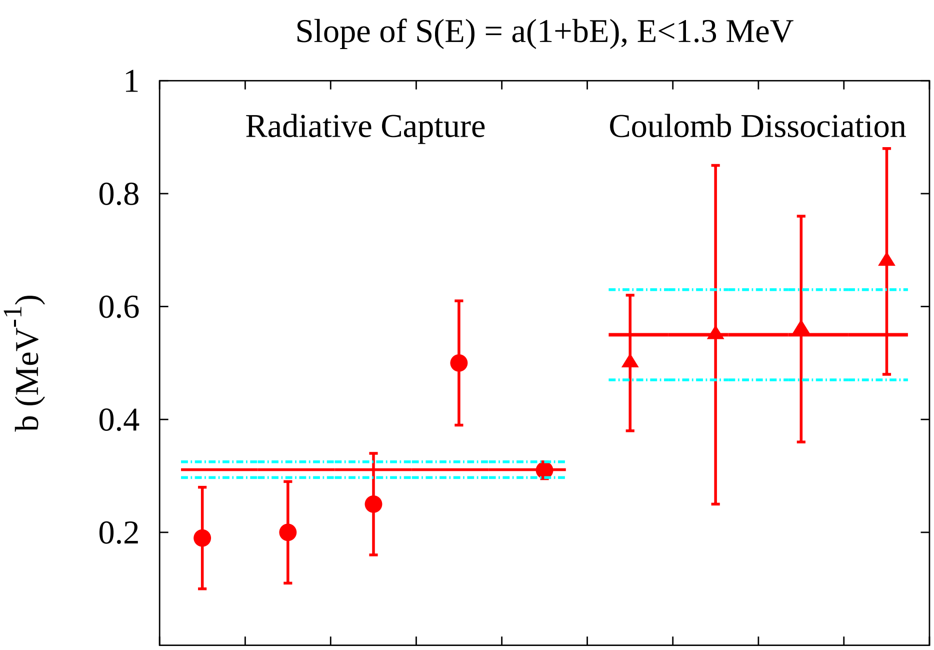
and in Coulomb dissociation experiments:



CD gives smaller $S_{17}(0)$ and steeper slope of $S_{17}(E_{rel})$.

CD gives smaller $S_{17}(0)$ and a steeper slope of $S_{17}(E)$, Junghans et al., PRC 68, 065803 (03).





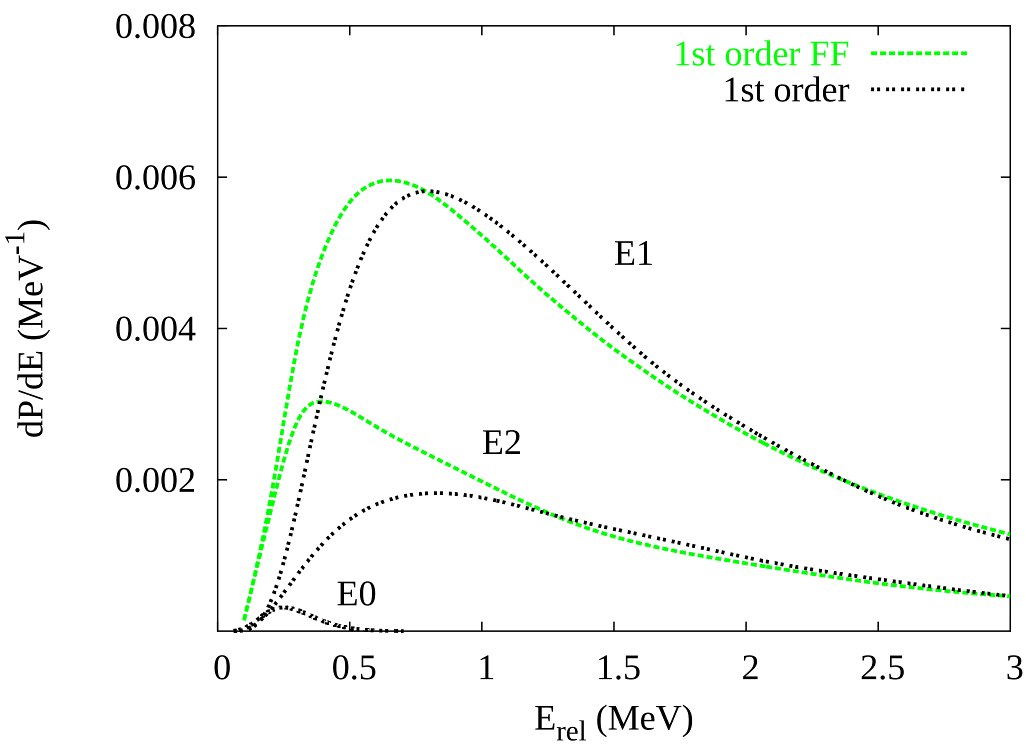
Breakdown of the far-field approximation;
the overlap of projectile and target cannot be ignored.

Use instead unrestricted multipole expansion (point charge):

$$V_{\rm Coul} = \sum_{\lambda\mu} \frac{4\pi Z_x Z e^2}{2\lambda+1} \; \frac{r_<^\lambda}{r_>^{\lambda+1}} \; Y^*_{\lambda\mu}(\hat{r}_x) Y_{\lambda\mu}(\hat{R}),$$

where $r_< = min(r_x, R)$ and $r_> = max(r_x, R)$.
R: projectile-target distance. r_x: intrinsic coordinate: r_x.
Far-field (FF) approximation: $r_x < R$.

Example: ^{8}B $\rightarrow ^7$Be+p on Pb at 52 MeV/u at b=20 fm.
First-order perturbation theory (incl. finite size effect):



Strong suppression at low excitation energies compared
to the far-field (FF) approximation, in particular E2!

Other issues: What is the significance of E2 transitions, higher-order processes, nuclear induced breakup?

Can be tested in Semiclassical Calculations of the ^{8}B$\rightarrow$^{7}Be+p breakup in the Coulomb and nuclear fields from a target nucleus.

- Use Classical Coulomb trajectories $\vec{R}(t)$.

- Quantal description of the ^{7}Be+p two-body motion. Initial state $\psi_0(\vec{r})$, $H_0\psi_0 = \epsilon_0\psi_0$, ϵ_0 = - 137 keV.

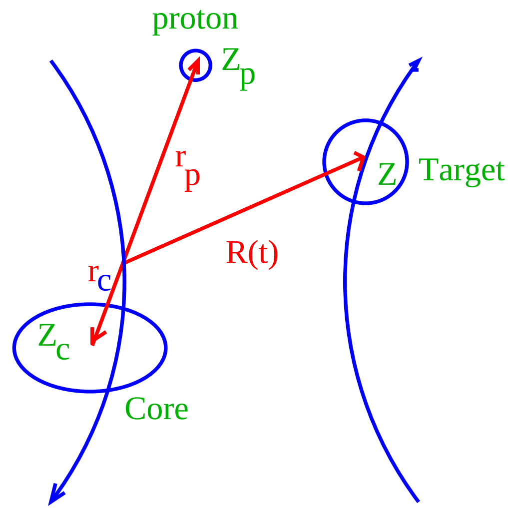
- Solve time-dependent Schrödinger equation numerically

$$i\hbar\frac{d\psi(\vec{r},t)}{dt} = \Big[H_0 + V_{pT}(\vec{R}(t) - \vec{r}_p) + V_{cT}(\vec{R}(t) - \vec{r}_c)\Big]\psi(\vec{r},t).$$

Interactions:

V_{pT}: proton-target

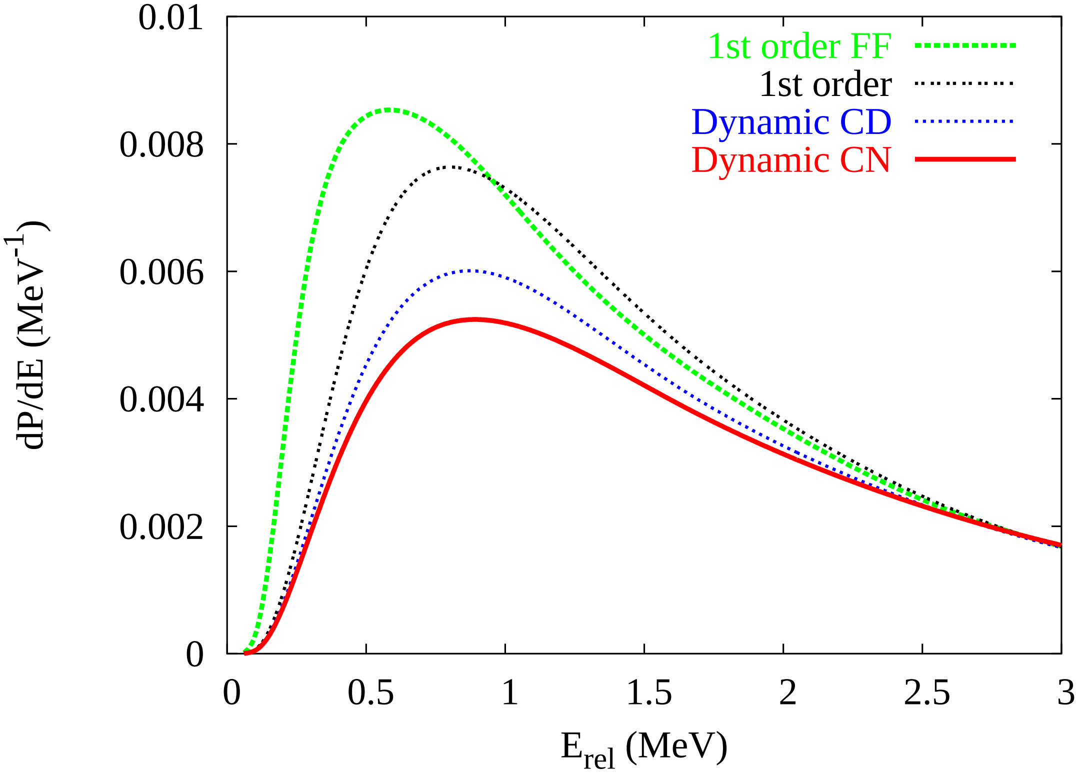
V_{cT}: core-target



See Esbensen, Bertsch & Snover, PRL 94, 042502 (2005).

^{8}B $\rightarrow$ ^{7}Be+p on Pb at 52 MeV/u, fixed b=20 fm.

Further suppression at low excitation energies
due to higher-order and nuclear processes



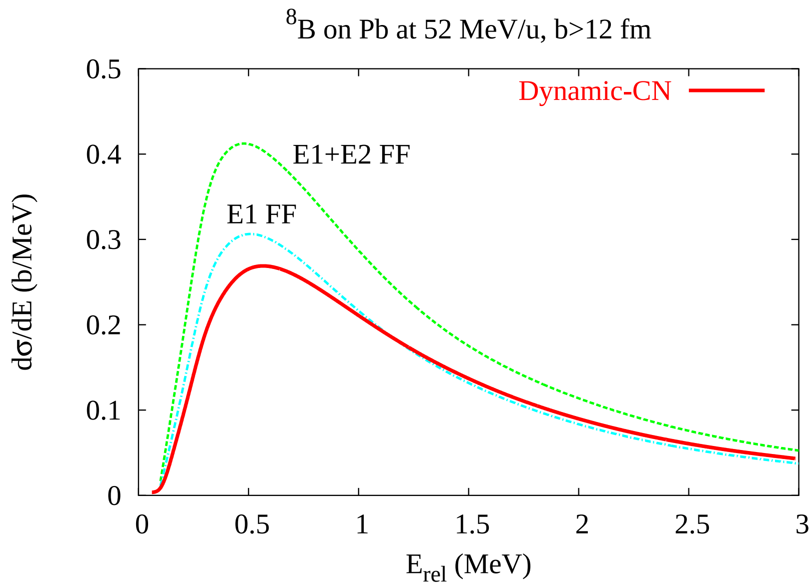
Dynamical polarization effect in CD is of order Z^3:

$$P_{\rm CD}(b) \approx P^{(1)}_{\rm P.Th.}(b) \left[1 - \frac{Ze^2}{E} \, \frac{\rm Const.}{\sqrt{b^2+a^2}}\right].$$

Caused by interference of 1st and 2nd Born amplitudes.

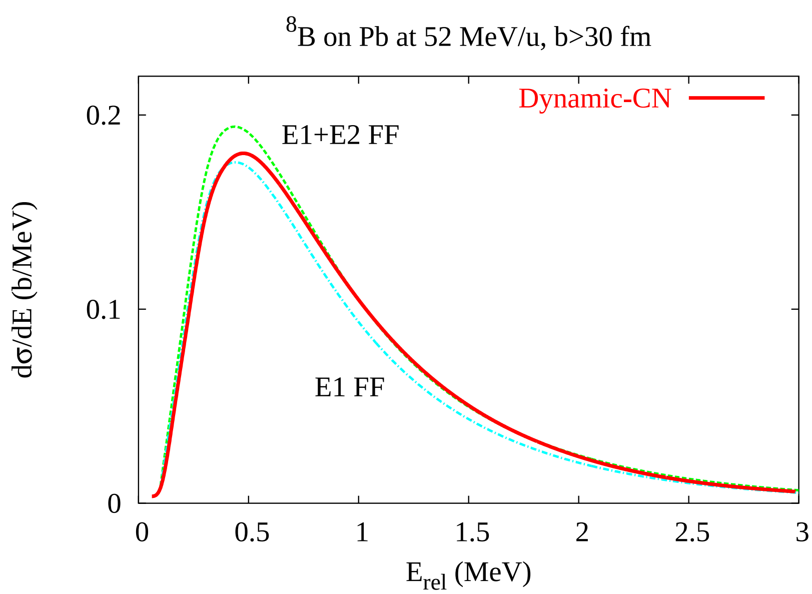
Known as the Barkas effect in atomic physics.
Explains the difference in the stopping powers
of protons and anti-protons, π^+ and π^-, etc.
See Andersen et al., PRL 62, 1731 (1989).

Decay energy spectrum for all $b > 12$ fm:



Suppression at low E_{rel}. Increases extracted $S_{17}(E_{rel})$!

Decay energy spectrum for all $b > 30$ fm:

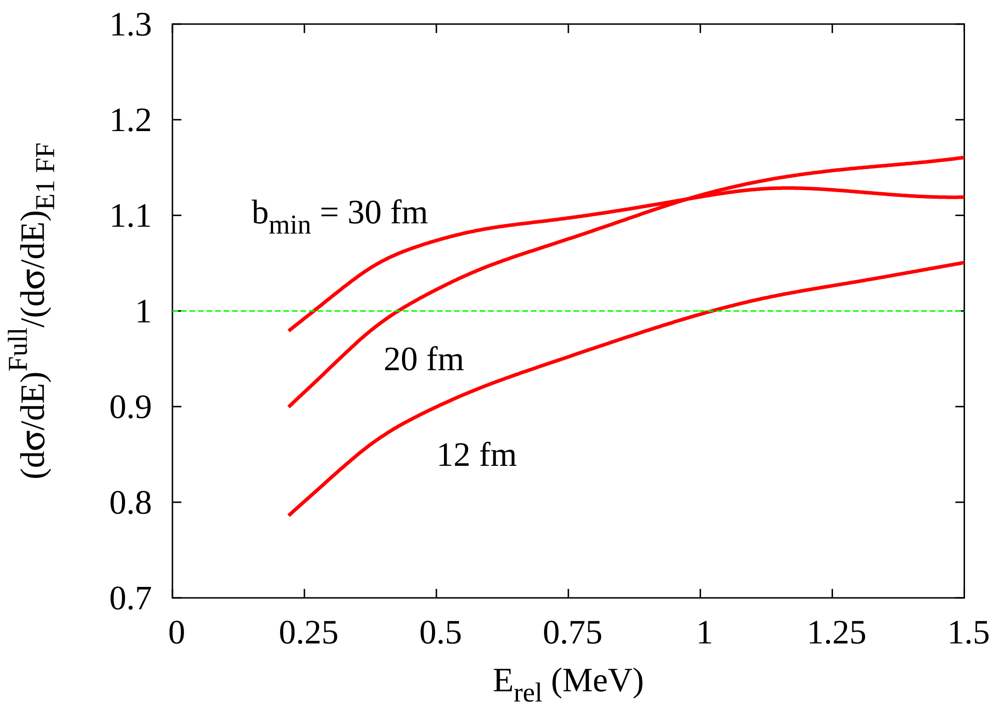


$\frac{d\sigma}{dE} \approx$ E1 FF at low E_{rel}, $\frac{d\sigma}{dE} \approx$ E1+E2 FF at high E_{rel}.

Explains why the extracted slope of $S_{17}(E_{rel})$ is large!

The full calculation (Dynamic CN) is reduced compared to the first-order E1 FF approximation by the ratio

$$\text{Ratio} = \frac{[\frac{d\sigma}{dE}]_{\text{Full}}}{[\frac{d\sigma}{dE}]_{\text{E1}}}.$$



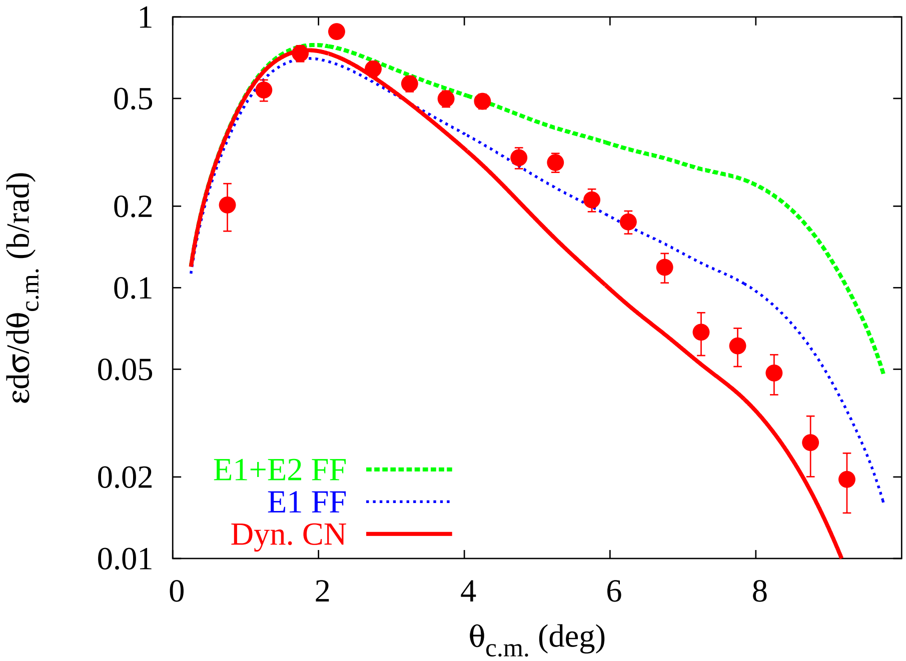
How to correct the S factor extracted in the E1 FF approx?

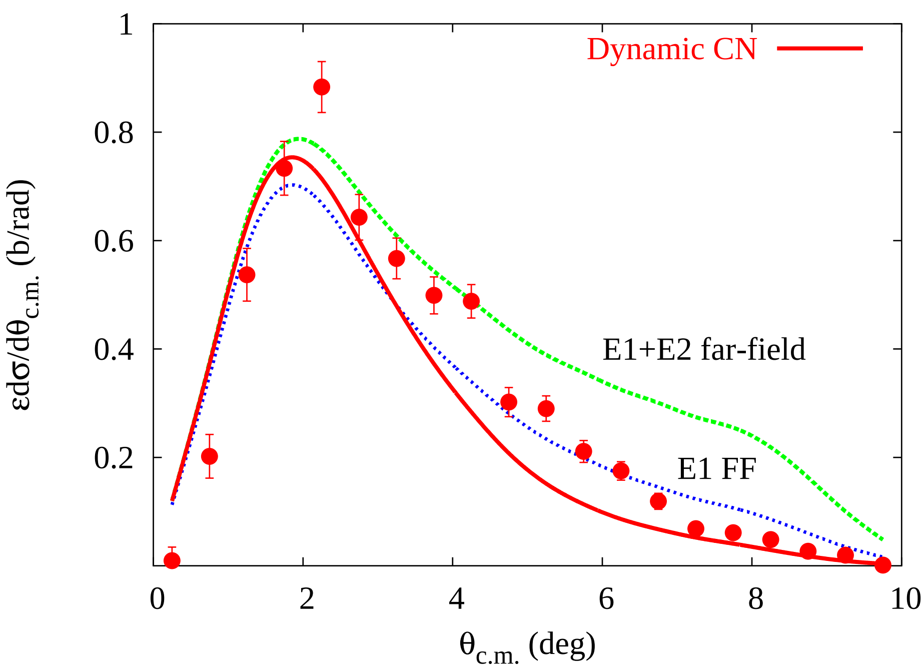
$$S^{\text{Corrected}}(E) = S^{\text{Exp}}_{\text{E1}}(E) \times \frac{[\frac{d\sigma}{dE}]_{\text{E1}}}{[\frac{d\sigma}{dE}]_{\text{Full}}} = \frac{S_{\text{E1}}(E)}{\text{Ratio}}.$$

The corrected S factor becomes larger at low E_{rel} and smaller at high relative energies.

Improves agreement with capture measurements.

RIKEN experiment at 52 MeV/A on Pb,
Kikuchi et al., PLB 391, 261 (1997).
Relative energy-cut: $0.5 < E_{rel} < 0.75$ MeV.



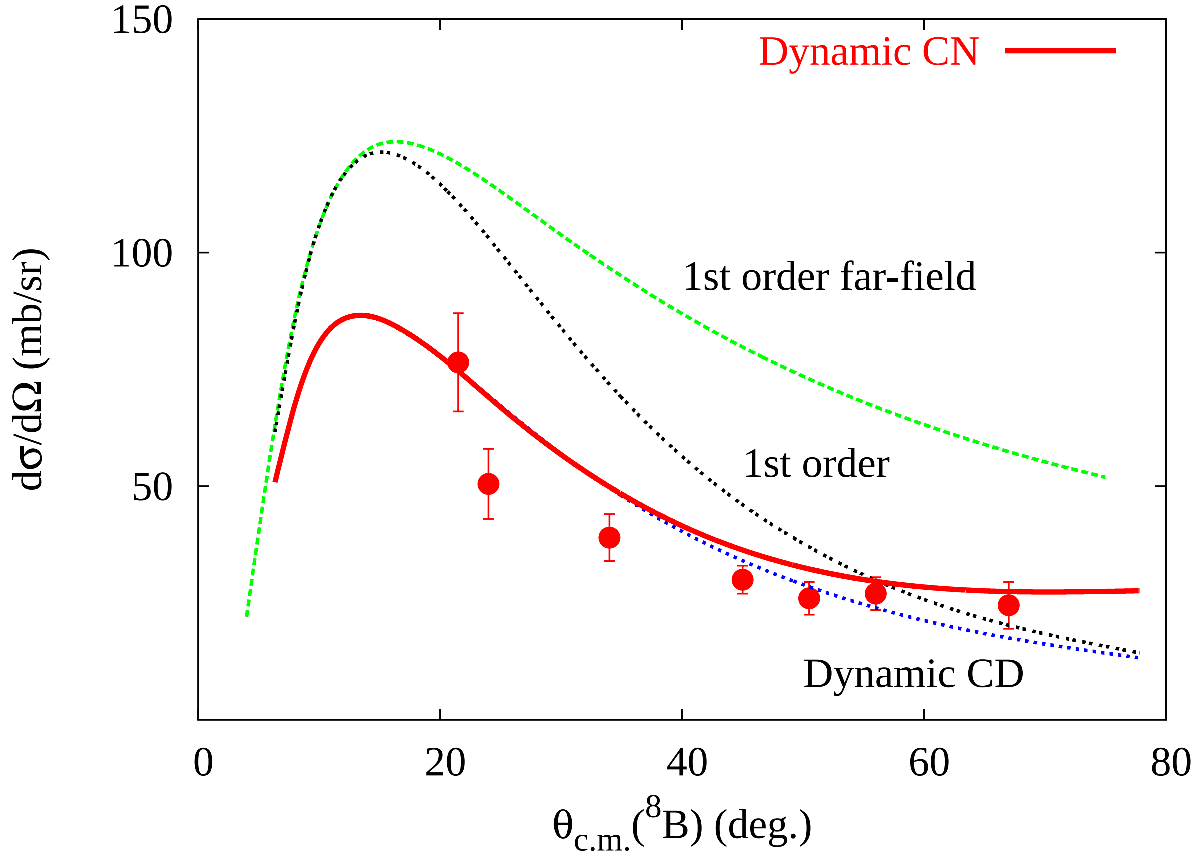


Dynamic-CN should be scaled by 1.17 [$S_{17}(0) = 22.1$ eV b].
Ogata et al. [$\theta_b < 4^\circ$, large $\delta\theta$]: $S_{17}(0) = 20.9 \pm 2$ eV b.

Experimental evidence of strong reduction compared to
1st-order E1+E2 far-field approximation.

$^{8}B \rightarrow ^{7}Be$ breakup on Ni at 26 MeV
Guimarães et al., PRL 84, 1862 (2000).

1st order: correct 1st-order E0+E1+E2 Coulomb dissoc.
Dynamic CD: Coulomb dissociation to all orders.
Dynamic CN: Coulomb + nuclear breakup to all orders (includes stripping).



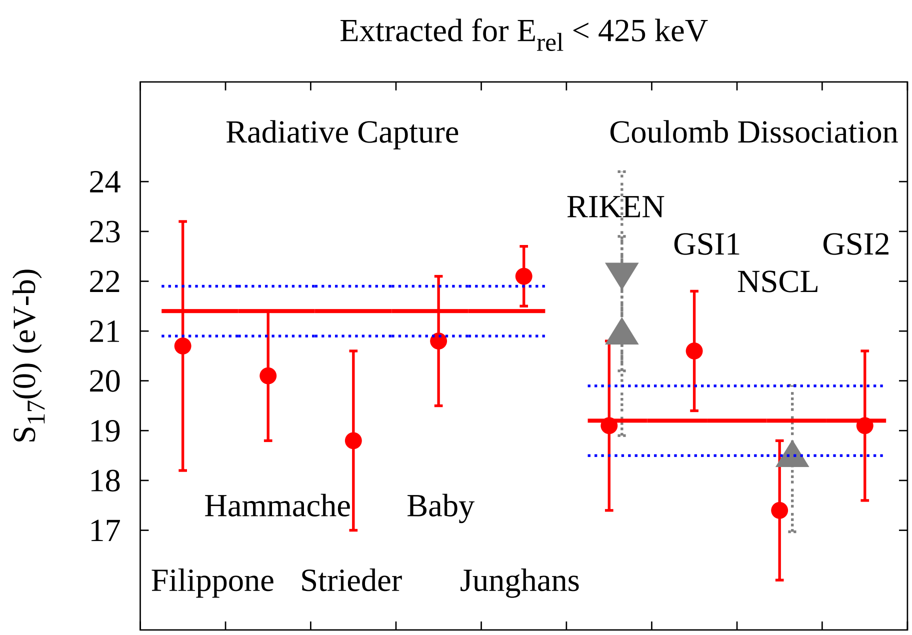
Conclusion

Low energy S factors extracted from CD experiments using the first-order E1 Far-Field approximation should (in some cases) be increased because of

- non-zero projectile-target overlap (all E, smaller b)
- dynamic polarization (at lower beam energies)
- nuclear effects (Coulomb-nuclear interference).

The S factor at high relative energies should be reduced.

These effects reduce discrepancy with capture measurements.

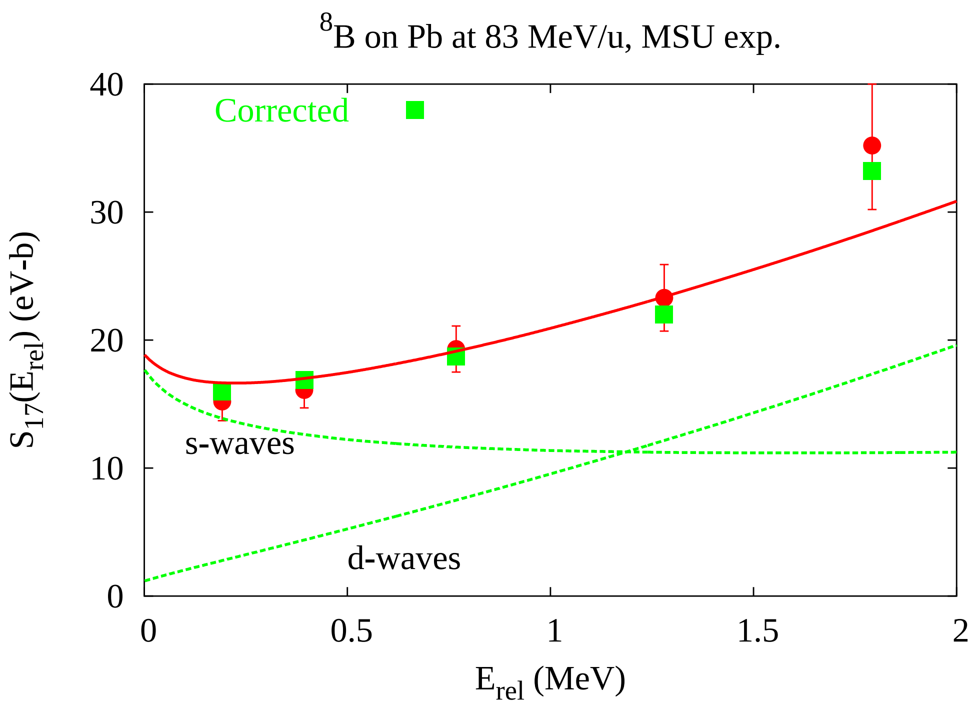


Relativistic effects should be implemented!

MSU-NSCL experiment at 83 MeV/A on Pb,
B. Davids et al., PRC 63, 065806 (2001).

Measured: $\frac{d\sigma}{dE}$ at forward angles, for $b > 30$ fm.
Analysis performed in the first-order FF approximation.
Included a quenched 5% E2 component
(Davids and Typel, PRC 68, 045802 (2003)).

Remove 5% E2 at low E_{rel}: Increase S factor by 5%.
Use 10% E2 at high E_{rel}: reduce it S factor by 5%.

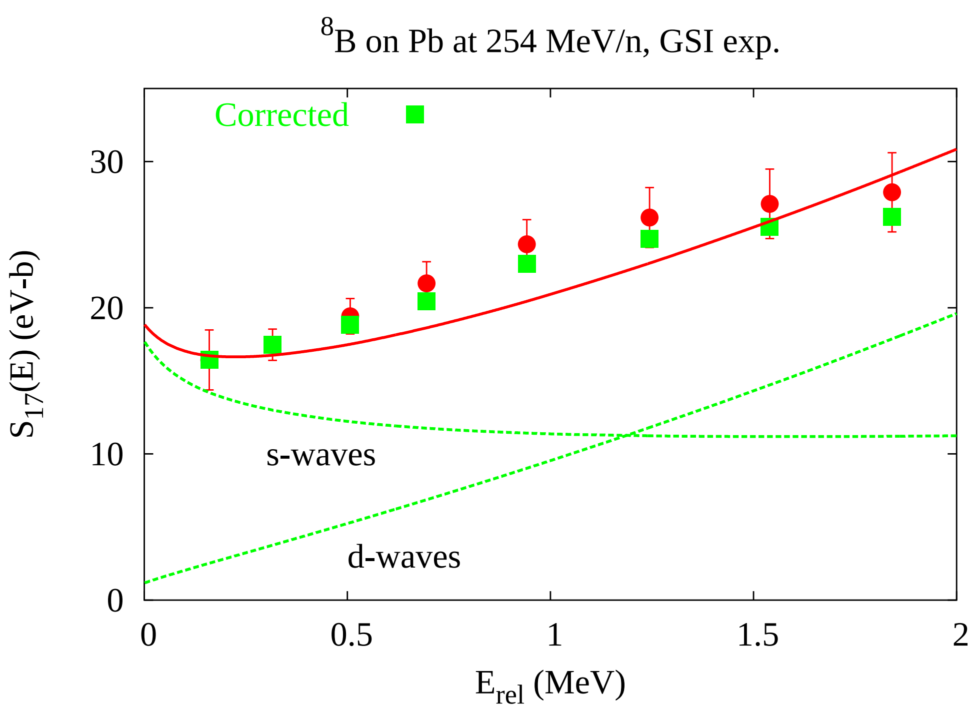


New slope in better agreement with capture measurements.
New $S_{17}(0)$ agrees with other dissociation experiments but it is lower than the mean value of capture measurements.

GSI experiment at 254 MeV/A on Pb,
Schümann et al., PRL 90, 232501 (2003).

Measured: $\frac{d\sigma}{dE}$ at forward angles, for $b > 30$ fm.
Analysis performed in the first-order FF approximation.
Included only E1 (should have included a 5% E2).

Leave $S_{17}(E_{rel})$ unchanged at low E_{rel}.
Reduce $S_{17}(E_{rel})$ by 5% at high E_{rel}.



$S_{17}(0)$ is unchanged. Reduced slope of $S_{17}(E_{rel})$.