Role of $^{6}\mathrm{Li}$ clustering strength in direct transfer reactions

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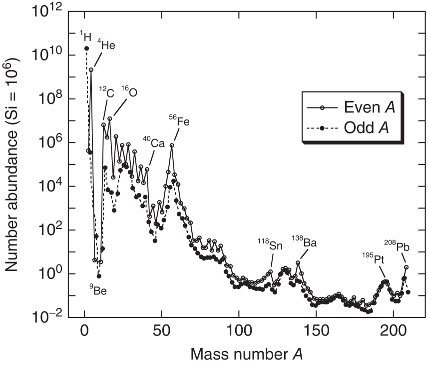
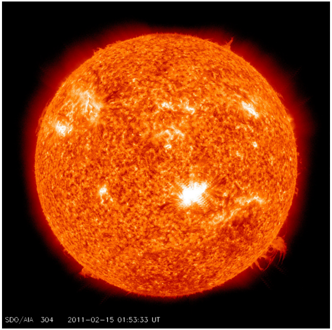
- **Introduction**
  - Context
  - Electron screening
- **The $^{6}\mathrm{Li}(\mathrm{p},{}^{3}\mathrm{He})\alpha$ reaction**
  - One-particle (deuteron) transfer
  - Two-nucleon transfer

Theoretical investigation on nuclear reactions between light charged particles at energies below the Coulomb barrier.

Focus on systems of astrophysical interest



C. Iliadis. *Nuclear Physics of Stars*. 2015, fig. 1.2



`sdo.gsfc.nasa.gov/gallery`

Astrophysical factor $S(E)$

Process dominated by quantum tunnelling of the Coulomb barrier.

Astrophysical S-factor:

$$S(E) = E\, e^{2\pi\eta(E)}\sigma(E) \quad , \quad \eta(E) = \alpha_e Z_1 Z_2 \sqrt{\frac{\mu c^2}{2E}}$$

(σ angle-integrated cross-section, E center-of-mass collision energy,
Z_i reactants charge number, α_e fine-structure constant,
μ reactants reduced mass, c speed of light).

- Small variations of the effective E_{cm} are important for σ due to $\exp$ behaviour.

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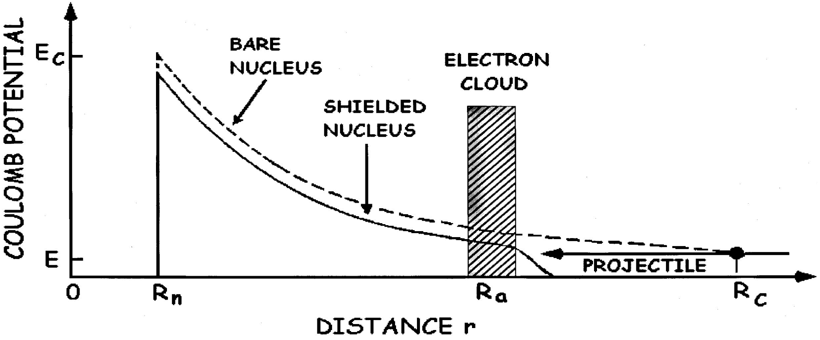
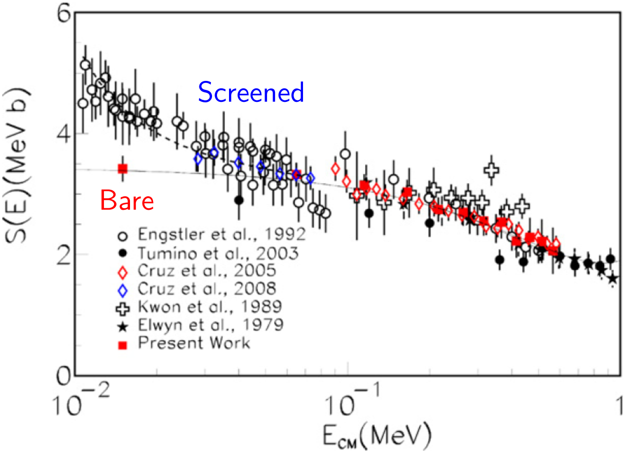
Atomic electrons lower the Coulomb barrier: (fig. from H. J. Assenbaum et al. *Zeitschrift für Physik A: Atomic Nuclei* 327.4 (1987))



Cross-section enhancement for $E \to 0$.

See e.g. L. Bracci et al. *Nuclear Physics A* 513.2 (1990).



L. Lamia et al. *The Astrophysical Journal* 768.1 (2013), $^{6}\mathrm{Li}(\mathrm{p},{}^{3}\mathrm{He})\alpha$

Discussion of anomalies in C. Spitaleri et al. *Physics Letters B* 755 (2016)

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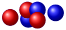
Goal

Quantify the influence of ground-state ("static") structure in a fully quantum framework.

- Explicit evaluation of the cross-section in terms of the properties and interactions of reactants.
- No adjusting on reaction experimental data.

Study of ${}^{6}\mathrm{Li} + \mathrm{p} \to \alpha + {}^{3}\mathrm{He}$ transfer, focus on ${}^{6}\mathrm{Li}$ structure.

- Two-cluster models: $|{}^{6}\mathrm{Li}$  $\rangle = |\alpha\, \mathrm{d}$  $\rangle$
- Three-cluster models: $|{}^{6}\mathrm{Li}$  $\rangle = |\alpha\, \mathrm{p}\, \mathrm{n}$  $\rangle$
- Quadrupole deformation, strength of clustering, ...

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$\langle \alpha\, \mathrm{d} \,|\, {}^6\mathrm{Li} \rangle$ overlap function

${}^6\mathrm{Li}$ g.s. $J^\pi = 1^+$ in inert two-cluster model $= \alpha + \mathrm{d}$.

$$\left|\mathrm{Li}_{1^+,\mu}\right\rangle = \sum_{l=0,2} \sum_m c_l \, \langle (l,m),(1,\mu-m) \,|\, 1,\mu \rangle \cdot$$

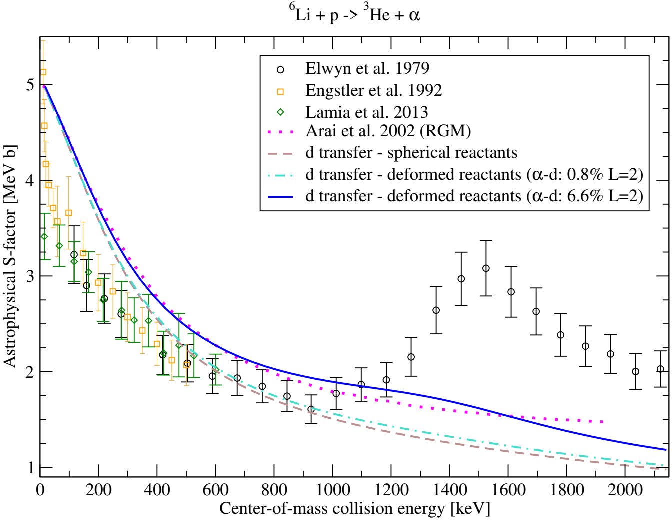
$$\cdot \left|\alpha_{0^+,0}\right\rangle \left|\mathrm{d}_{1^+,\mu-m}\right\rangle |Y_{lm}\, \chi_l\rangle$$

$\sum_l |c_l|^2$ (i.e. spectroscopic factor) $= 0.82$
reproducing experimental ANC.

Phenomenological $2s$ and $1d$ radial WFs
similar to H. Nishioka et al. *Nuclear Physics A* 415.2 (1984).

$\alpha + \mathrm{d}$	Experimental	$l = 0$ only	$l = 2$: $0.8\,\%$
g.s. rms radius	2.59 fm	2.66 fm	2.66 fm
g.s. quadrupole moment	−0.806 mb	2.86 mb	−0.806 mb
g.s. dipole moment	$0.8220\,\mu_\mathrm{N}$	$0.8574\,\mu_\mathrm{N}$	$0.8530\,\mu_\mathrm{N}$

$^6\mathrm{Li} + \mathrm{p} \rightarrow {}^3\mathrm{He} + \alpha$: deuteron transfer



Brown dashed line: point-like d transfer, $\alpha{-}\mathrm{d}$ motion in $L = 0$

Blue solid line: point-like d transfer, $6.6\,\%$ of $L = 2$ in $\alpha{-}\mathrm{d}$ motion

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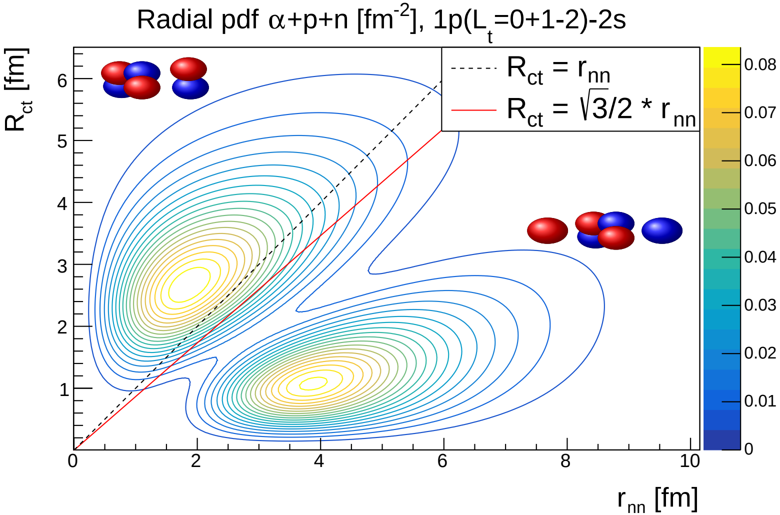
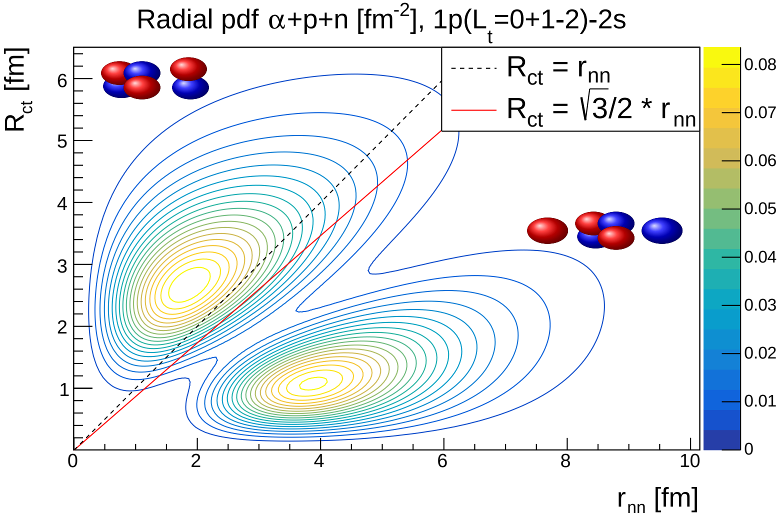
α+n+p reduced probability density function

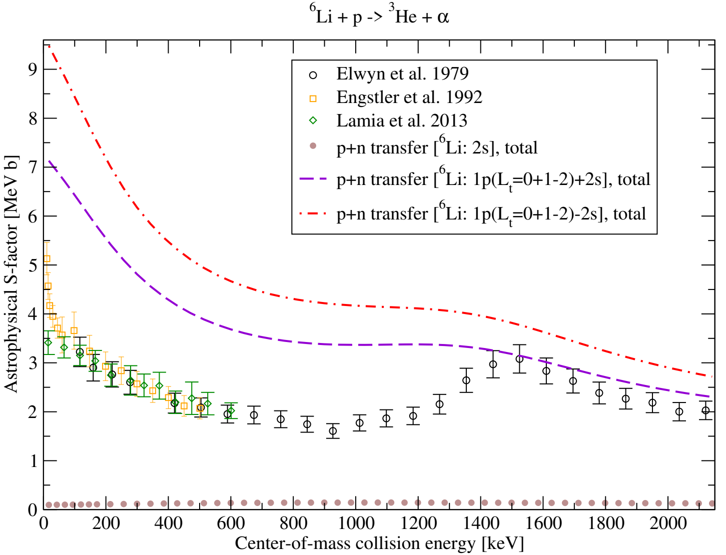


α+n+p reduced probability density function



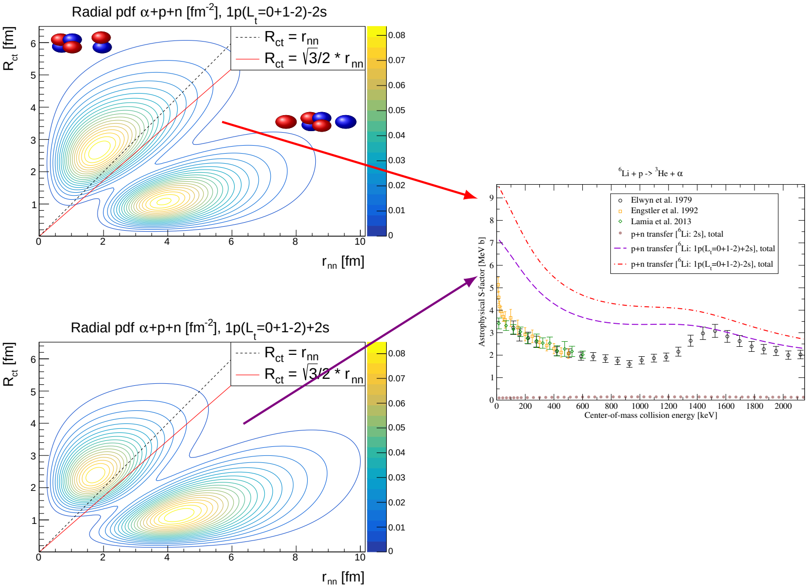
Currently: fictitious bound $^5\mathrm{Li}$ $\rightarrow$ altered binding potentials

^{6}Li + p → ^{3}He + α: role of ^{6}Li $(2s)^2$ contribution

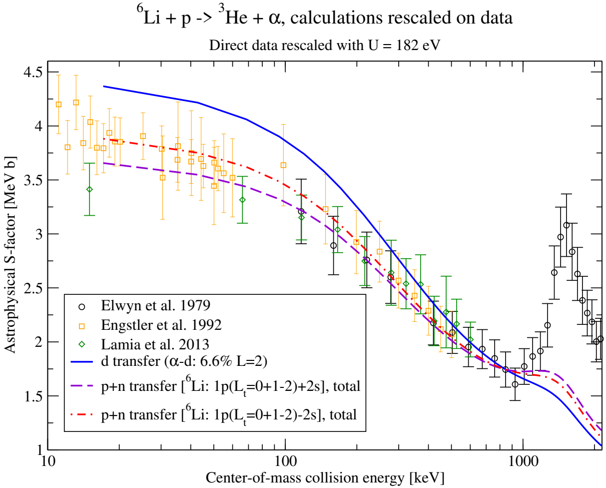


Red and violet: total p+n, opposite sign for ^{6}Li $(2s)^2$ amplitude.

α+p+n reduced probability density functions



$^6\mathrm{Li} + \mathrm{p} \to {}^3\mathrm{He} + \alpha$: calculations rescaled to transfer data



Direct data rescaled by adiabatic-limit ($U = 182\,\mathrm{eV}$) screening.
Calculations rescaled by arbitrary constant factor (Blue: d-transfer.
Red: $\mathrm{p{+}n}$ transfer. Violet: $\mathrm{p{+}n}$ for less-clustered $^6\mathrm{Li}$).

Summary

What: $^{6}\mathrm{Li} + \mathrm{p} \to {}^{3}\mathrm{He} + \alpha$ around and below the Coulomb barrier

How:
- DWBA 1- or 2-particle transfer
- Emphasis on the role of cluster structure.

So far:
- Ground-state ("static") deformation alone:
  - Only affects details at astrophysical energies.
  - Is relevant to describe resonant behaviour.
- "Clustering strength" important at all energies (absolute value and energy trend).

To do:
- Microscopic construction for three-particle WFs.
- Better treatment of unbound $^{5}\mathrm{Li}$ in sequential transfer.
- Coupled reaction channel approaches (virtual excitations).