Dynamical limits of nucleon knockout at intermediate energy.

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DREB conference, 25-29\textsuperscript{th} March 2012, Pisa
**Shell occupancies in stable nuclei**

**(e,e’p) reactions**
- electromagnetic probe
- 30-40% reduction
- Beyond mean-field correlations


**No binding energy dependance**
- Deeply bound orbitals, \(0.78 \pm 0.02 \pm 0.08\).


**Agreement between (d, \(^3\)He) and (e,e’p)**

**Reminder** : Shell occupancies are not observables / SF are model dependent (R. J. Furnstahl, H. W. Hammer, PLB 531 203 (2002)).
Deeply-bound nucleon knockout from exotic nuclei

Intermediate energy knockout

Disagreement between theory and experiment:

Possible sources:

⇒ The calculated shell occupancies $C^2 S$.
⇒ The single particle cross section $\sigma_{sp}$.

$$\sigma_{th} \propto C^2 S_{th} \cdot \sigma_{sp}^{th}$$
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Low energy transfer (d,p)
⇒ Constant reduction $\simeq 30\%$
⇒ Limited $\Delta S$ range up to $\simeq 12$ MeV
Outline

Question

What are the limits of standard eikonal + sudden approaches?
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Experimental investigation

- One-nucleon knockout from $^{16}\text{C}$ and $^{14}\text{O}$, NSCL

- One-nucleon transfer from $^{14}\text{O}$ at SPIRAL, GANIL
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Interpretation

- Beyond the ”sudden approximation” dynamics.

- Core-target excitations in deeply-bound nucleon removal
  C. Louchart, A. Obertelli, A. Boudard, and F. Flavigny, PRC 83 011601 (2011)
Primary beam: \(^{18}\text{O}\) (120 MeV/nucleon)

Secondary beams:

- \(^{16}\text{C}\) beam at 70 MeV/nucleon
- \(^{14}\text{O}\) beam at 53 MeV/nucleon

Cocktail beam from A1900

\(<I> \approx 5.10^5\) pps
Inclusive parallel momentum distributions and cross sections

Loosely-bound nucleon

\[ \frac{d\sigma}{dp_{\parallel}} \left( \text{mb} \times (20 \text{ MeV/c}) \right) \]

\[ 16\text{C} (-1n) \]

\[ 14\text{O} (-1p) \]

Deeply-bound nucleon

\[ E = 75 \text{ MeV/u} \]

\[ E = 53 \text{ MeV/u} \]
Inclusive parallel momentum distributions and cross sections

Loosely-bound nucleon

\[ \sigma(16\text{C} -1n) = 80(7)^* \text{ mb} \]
\[ \sigma(14\text{O} -1p) = 64(6) \text{ mb} \]

Deeply-bound nucleon

\[ \sigma(16\text{C} -1p) = 15(1) \text{ mb} \]
\[ \sigma(14\text{O} -1n) = 14(1) \text{ mb} \]

*\[ \sigma(16\text{C} -1n) = 77(9) \text{ mb at 62 MeV/u} \]

V. Maddalena et al., PRC 63 (2001) 024613
Inclusive parallel momentum distributions and cross sections

**Loosely-bound nucleon**

- $^{16}\text{C} (-1n)$
- $^{14}\text{O} (-1p)$

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<th>$d\sigma / dp_{\parallel}$ (mb*(20 MeV/c))</th>
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High-momentum cutoff

Parallel momentum of the residue $^{A-1}X$

$$P_{//} = \sqrt{(T_p - S_n - \epsilon_f)^2 + 2M_r(T_p - S_n - \epsilon_f)}$$

$T_p$ : initial kinetic energy of the projectile (beam)
$S_n$ : separation energy of the removed nucleon
$\epsilon_f$ : final energy of the nucleon with respect to the target

→ Momentum threshold $p_{max}$ for $\epsilon_f = 0$

A. Bonnacorso, PRC 60, 054604 (1999)
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Comparison to experimental data

$T_p = 75$ MeV/u
$S_n = 22.6$ MeV
$p_{\text{max}} = 5804$ MeV/c

$16$C ($-1$p)
$14$O ($-1$n)

$T_p = 53$ MeV/u
$S_n = 23.2$ MeV
$p_{\text{max}} = 4042$ MeV/c
High momentum cutoff: existing data

A. Gade et al. PRC 71 (2005) 051301.

E(46Ar) = 70 MeV/u

E(28S) = 81 MeV/u

E(24Si) = 85 MeV/u

E(10C) = 120 MeV/u


"Barely visible" effect in published data
High momentum cutoff: existing data

$E^{(14}\text{O}) = 53 \text{ MeV/u}$

![Graph of $^{14}\text{O} (-1n)$](image)

$E^{(46}\text{Ar}) = 70 \text{ MeV/u}$

![Graph of $^{46}\text{Ar}$](image)

$E^{(16}\text{C}) = 75 \text{ MeV/u}$

![Graph of $^{16}\text{C} (-1n)$](image)

$E^{(28}\text{S}) = 81 \text{ MeV/u}$

![Graph of $^{28}\text{S} (-1n)$](image)

$E^{(24}\text{Si}) = 85 \text{ MeV/u}$

![Graph of $^{24}\text{Si} (-1n)$](image)

$E^{(10}\text{C}) = 120 \text{ MeV/u}$

![Graph of $^{10}\text{C} (-1p)$](image)

A. Gade et al. PRC 71 (2005) 051301.


"Barely visible" effect in published data
Dynamical limit for nucleon knockout

\[ P_{/\parallel} = \sqrt{(T_p - S_n - \varepsilon_f)^2 + 2M_r(T_p - S_n - \varepsilon_f)} \]

\[ p_{\text{max}} = P_{/\parallel}(\varepsilon_f = 0) \]

\[ \delta p(E_p, S_n) = p_{\text{max}} - p_0 \]

F. Flavigny et al., in preparation (2012)
Transfer to the continuum model

Intrinsic momentum of the removed neutron + Energy dependent \((n+^9\text{Be})\) potential

**Properties**

- Transfer from initial neutron bound state to continuum neutron-target state.
- Generalization of a semi-classical method.
- Contain energy and momentum conservation

**Inputs**

- Neutron bound-state \(\text{wf} \) (HF constraint)
- Core-target \(S\)-matrix (same as model 1)
- \(n+^9\text{Be}\) pot. (fitted on cross section data)
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Limits
- Restricted to neutron removal
- No breakup of ^9 Be target
- No final state interactions

A. Bonnacorso and D Brink, PRC 43 299 (1991)
A. Bonnacorso and G. M. Bertsch, PRC 63 04604 (2001)
\( \gamma \)-ray spectroscopy of \(^{15}\)B : dissipative processes

\[ \begin{align*}
\sigma_{gs}(-1p) &= 18.3 \pm 2.2 \text{ mb} \\
\sigma_{5/2^-}(-1p) &= 1.3(2) \text{ mb} \\
\sigma_{7/2^-}(-1p) &= 0.8(1) \text{ mb} \\
\sigma(-1p) &= 20.4 \pm 2.2 \text{ mb}
\end{align*} \]
Questioning the "inert core" approximation

Intra Nuclear Cascade model (INC)

\[ \sigma_{th} = \sigma_{casc} + \sigma_{evap} \]

Structure inputs:
- HF neutron and proton densities.
- Spectroscopic factors.

C. Louchart, A. Obertelli, A. Boudard, and F. Flavigny, PRC 83 011601 (2011)

Deeply-bound nucleon removal:
- **Core excitations** deplete the one-nucleon removal channel.
- Call for **exclusive measurements**, along the line of D. Bazin *et al.*, PRL 102 232501 (2009).
Summary and Conclusion

Loosely-bound nucleon knockout

- Good agreement between th. and exp.
  - $R_s \simeq 0.8-0.9$.
  - Mom. distributions in agreement with eikonal predictions.

Deeply-bound nucleon knockout

- Strong deviations from eikonal/sudden picture
  - $R_s \simeq 0.2-0.3$.
  - High-momentum cutoff $\rightarrow$ Kinematical effect ($E,S_n$)
  - Important low-energy tail $\rightarrow$ Hypothesis: Dissipation, core-target int.
  - Indirect population of excited states.

Determination of dynamical limits for nucleon knockout

Role of indirect processes in the mechanism questioned
Outlook

Comparison with transfer results on $^{14}$O in GANIL

See A. Gillibert’s talk tomorrow!

Exclusive measurement at RCNP (2013)

- $^{12}$C($^{14}$O,$^{13}$O+X)
  - Population of unbound states in $^{13}$O (proton detection)
- $^{1}$H($^{14}$O,$^{13}$O) and $^{1}$H($^{14}$O,$^{13}$N)
  - Proton induced nucleon breakup

Spokespersons: J. Lee, A. Obertelli, Y. Ye.
Co-authors:

A. Obertelli, C. Louchart, L. Nalpas (CEA-Saclay, SPhN)
A. Bonnacorso (INFN, Pisa)

Many thanks for support in data taking and fruitful discussions to:

D. Bazin, T. Baugher, B. A. Brown, A. Gade, T. Ginter, G. F. Grinyer, A. Ratkiewicz, S. Mc Daniel, D. Wheisshar (NSCL) and J. A. Tostevin (University of Surrey)