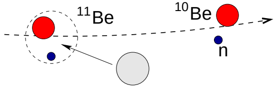
Direct Reactions with Exotic Beams, Matsue, Japan,4-8 June, 2018

Recent advances and perspectives in the theory of direct reactions with exotic beams

Antonio M. Moro

Universidad de Sevilla, Spain



^{11}Be
^{10}Be
n

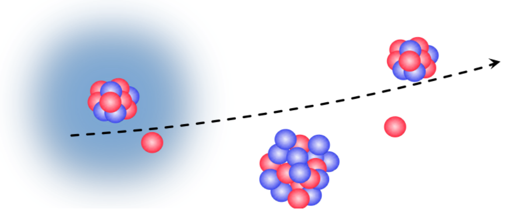
Direct Reactions ...

— Nuclei make 'glancing contact' and separate immediately
— Only few degrees of freedom modified in the process, retain recollection of initial state
— Dominance of single-particle properties over dynamical effects

... with exotic nuclei

— Weakly bound, short-lived, unstable nuclei (inverse kinematics)
— Halo structures

e.g.: collision of a halo nucleus with a target



From Sofia Quaglioni, keynote talk at DREB2016

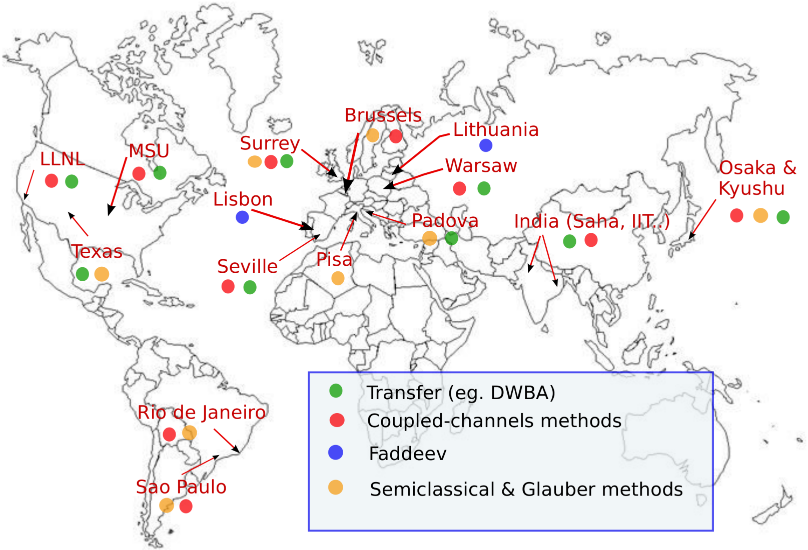
Challenges found in the study of reactions with exotic beams

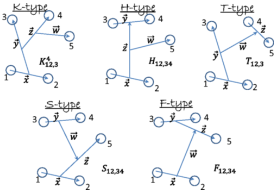
Experimentally:

- Exotic nuclei are short-lived and difficult to produce. Beam intensities are typically small.

Theoretically:

- Exotic nuclei are easily broken up in nuclear collisions $\Rightarrow$ coupling to the unbound states (continuum) plays an important role.
- Effective NN interactions, level schemes, etc are different from stable nuclei.
- Many exotic nuclei exhibit complicated cluster (few-body) structure.


Brussels
Lithuania
Surrey
Warsaw
MSU
LLNL
Osaka &
Kyushu
Lisbon
Padova
India (Saha, IIT..)
Texas
Seville
Pisa
Rio de Janeiro
Sao Paulo
Transfer (eg. DWBA)
Coupled-channels methods
Faddeev
Semiclassical & Glauber methods

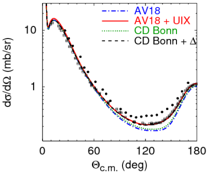


Exact solution of few-body scattering problem ➟ Faddeev (+ Yakubovsky) equations:

3-body

Deltuva, FBS58(2017)

^{2}H(p,p) @ 135 MeV

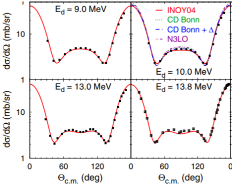


- ✔ Coulomb approximate.
- ✔ Non-local potentials, nucleon excitation...

4-body

Deltuva, PRC95, 024003 (2017)

^{3}H(d,p)^{3}H, ^{2}H(d,n)^{3}He

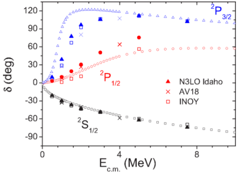


- ✔ Effective 3N and 4N forces

5-body

Lazauskas, PRC97,044002(2018)

n+^{4}He



- ✘ 3N forces still to be included.

N-body?

?

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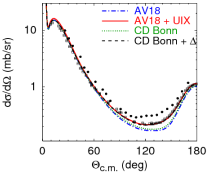

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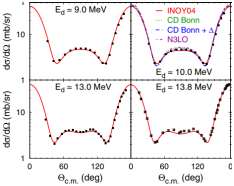

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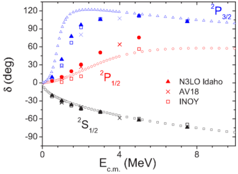


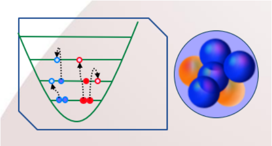
- ✘ 3N forces still to be included.

N-body?

?

✔ All open channels (elastic, transfer, BU...) included on an equal footing but ...

- ☞ Poor scaling with particle number (limited nowadays to $A = 5$.)
- ☞ Heavy systems difficult.



Goal: Seek for accurate (but approximate) solution of many-body problem starting from a realistic NN interaction

Common inputs ...

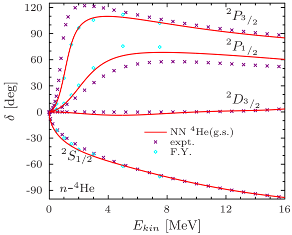
- realistic NN interactions (e.g. QCD-based chiral EFT),
- 3N forces (and beyond)

...but many "flavours":

- No-Core Shell Model (NCSM) and extensions:
  - NCSM with Continuum (NCSMC)
  - NCSM with Resonating-Group Method (NCSM/RGM)
- Green's Function Monte Carlo Method (GFMC) (A≤ 12)
- Self-Consistent Green's Function (SCGF)
- Hyperspherical Adiabatic (HA) expansion method
- Coupled-Custer Method (CCM)
- ...

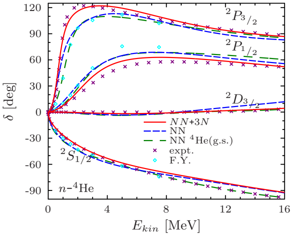
Excellent agreement with FY results ...

n+^{4}He



...and with data when 3N forces included

n+^{4}He



Courtesy of Guillaume Hupin

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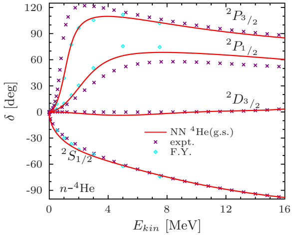

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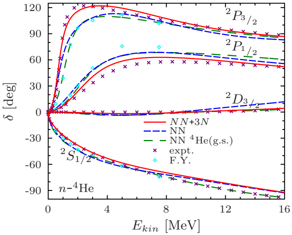

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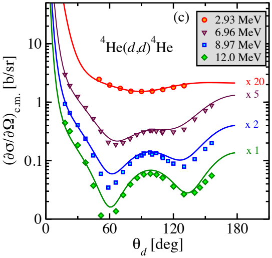
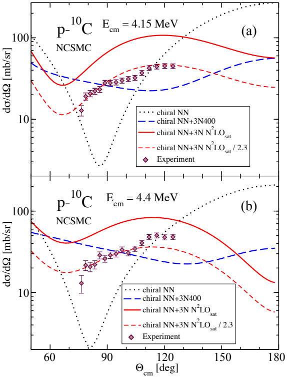


Feasible for $A > 5$ but limited so far to $A \lesssim 16$ and low energies.

☞See talks by Petr Navratil and Matteo Vorabbi

☞ Ab-initio methods applied to direct nuclear reactions have revealed excellent tools to probe different NN (and 3N) forces:



Kumar *et al*, PRL 118, 262502 (2017)

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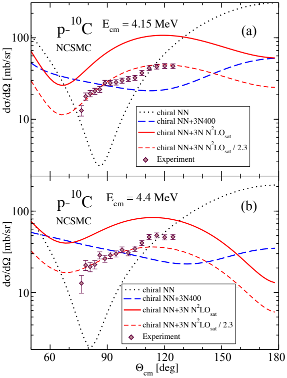


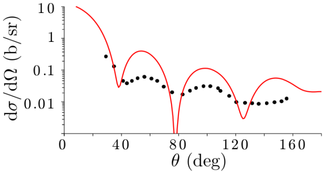
Kumar *et al*, PRL 118, 262502 (2017)

...and none of the available ones seem to be optimal:

> *"Overall, we observe that none of the available parametrizations of the chiral nuclear force are optimal in all aspects."*
>
> Kumar *et al*, PRL 118, 262502 (2017)

- SCGF → irreducible self-energy, $\Sigma(E)$: in-medium potential experienced by a nucleon.
- $\Sigma(E)$ links bound state properties (structure) with continuum (reaction):
  - For $E > 0$, $\Sigma(E)$ corresponds to *ab-initio* microscopic, non-local, dispersive optical model (DOM) potentials
  - For $E < 0$ target structure (occupation numbers, single-particle fragmentation,....)

Eg.: ^{40}Ca(n,n) at 13.6 MeV with ab-initio SCGF potential

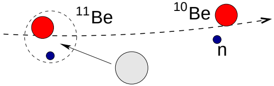


Idini *et al*, IOP Conf.Series:JoP 981, 012005 (2018)

☞ *Accuracy limited by numerical complexity*

- $\Sigma(E)$ can be also parametrized phenomenologically to yield well founded, dispersive optical model (DOM) potentials

☞See talk by Willem Dickhoff on Tuesday



^{11}Be
^{10}Be
n

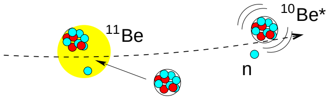
Alternative few-body models

- ➢ Faddeev and many-body *ab-initio* methods restricted so far to light systems.
- ➢ Heavier systems require simpler (more approximate) methods:
  - Continuum-Discretized Coupled Channels (CDCC): elastic, breakup
  - Distorted Wave Born Approximation (DWBA): inelastic, transfer
  - Coupled-Reaction-Channels (CRC): inelastic, transfer
  - Adiabatic Distorted Wave Approximation (ADWA): transfer
  - Semiclassical, Glauber and eikonal methods: elastic, breakup
  - ...

Some selection of relevant degrees of freedom is inherent to approximate methods

E.g.: Breakup of a one-neutron halo nucleus.

Original many-body problem



- Start from (effective) NN interaction.
- Complicated many-body scattering problem

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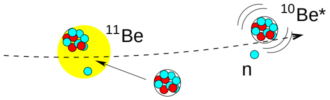

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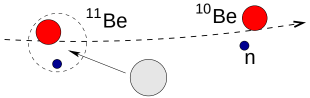
Approximate few-body problem



- Inert target approximation
- Projectile described with few-body model
- Phenomenological NA interactions

- Traditional direct reaction methods were developed well before *ab-initio* methods, so could be only validated against data.
- Nowdays, a comparison between approximate and *ab-initio* feasible, at least for "simple" systems.

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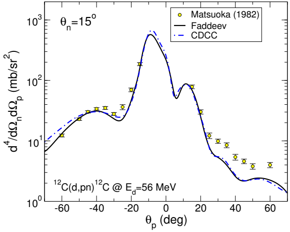
Eg.: CDCC vs Faddeev/AGS

☞ Benchmarks of CDCC with Faddeev/AGS furnished a more solid foundation to CDCC.

^{12}C(d,pn)^{12}C at $E_d = 56$ MeV



A. Deltuva *et al*, PRC76,064602('17)

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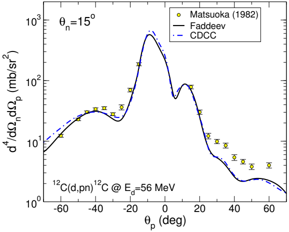
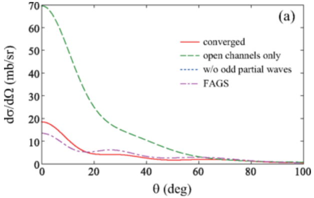


A. Deltuva *et al*, PRC76,064602('17)

...and have evidenced some limitations in previous CDCC calculations (eg. the omission of closed channels at low energies)

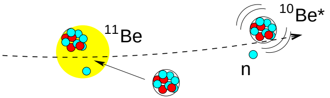
^{12}C(d,pn)^{12}C at $E_d = 12$ MeV



K. Ogata *et al*, PRC94, 051603(R)('16)

Deviations from the inert-cluster model are expected to show up when cluster d.o.f. are strongly excited during the reaction.

Microscopic models

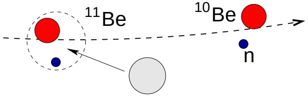


- ✔ Fragments described microscopically
- ✔ Realistic NN interactions (Pauli properly accounted for)
- ✖ Numerically demanding / not simple interpretation.

Many-body

Few-body

Inert cluster models



- ✖ Ignores cluster excitations (only few-body d.o.f).
- ✖ Phenomenological inter-cluster interactions (aprox. Pauli).
- ✔ Exactly solvable (in some cases).
- ✔ Achieved for $A \leq 5$ (eg. coupled-channels, Faddeev).

Beyond the inert-cluster model

Deviations from the inert-cluster model are expected to show up when cluster d.o.f. are strongly excited during the reaction.

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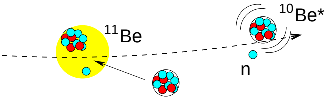

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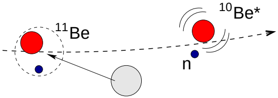
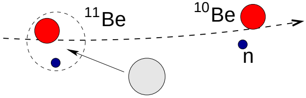
Non-inert-core few-body models



- ✔ Few-body + some relevant collective d.o.f.
- ✔ Motivated extensions of Faddeev and CDCC (XCDCC)

Inert cluster models



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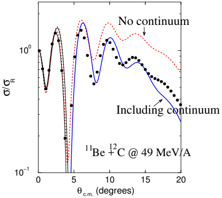
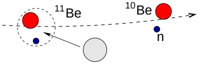
+ microscopic

CDCC with inert core

R.Johnson *et al*, PRL79,2771(1997).

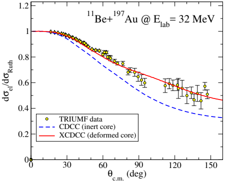


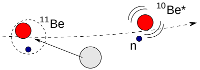


- ✔ Includes halo degree of freeom
- ✖ Clusters dynamics only through effective potentials

CDCC with deformed core

V.Pesudo *et al*, PRL118,152502(2017)

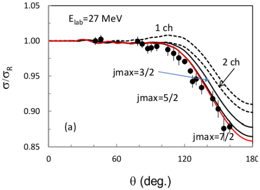


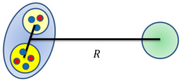


- ✔ Simple structure input (PVM, PRM, etc)
- ✘ Only collective excitations
- ✘ So far, only 2-body projetiles, coud be needed for 3-body projectiles (eg. ^{11}Li,^{14}Be)

Microscopic CDCC

P.Descouvemont, PRL111,082701(2013)

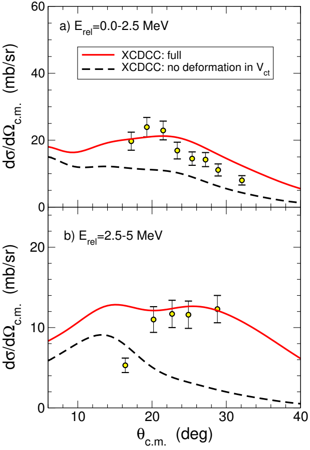




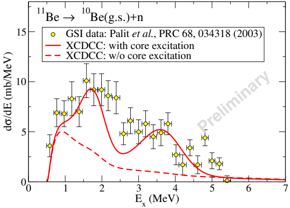
- ✔ Microscopic description of clusters.
- ✔ Core excitations "automatic"
- ✔ Collective + non-collective excitations

Core excitations may enhance dramatically the breakup cross sections in reactions of deformed halo nuclei with light targets

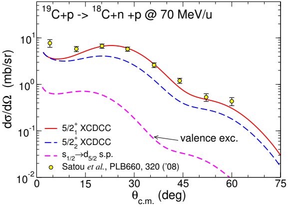
^{11}Be+ p @ 64 MeV/u



^{11}Be+ ^{12}C @ 520 MeV/u



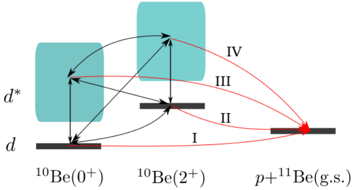
^{19}C+ p @ 69 MeV/u

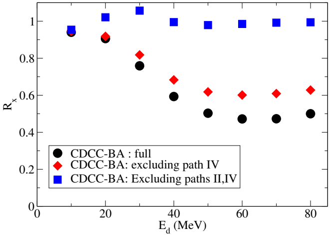


- In a one-step transfer process (eg. DWBA), $\sigma_{\text{tr}} = \mathcal{S}_F \sigma_{\text{sp}}$
- If higher order are important, this is not true and deviations can be quantified as:

$$R_x = \frac{1}{\mathcal{S}_F} \frac{\left(\frac{d\sigma}{d\Omega}\right)_{\text{def}}}{\left(\frac{d\sigma}{d\Omega}\right)_{\text{no def}}}$$

E.g.: ^{10}Be(d,p)^{11}Be including deuteron breakup and ^{10}Be excitation.





M.Gomez-Ramos,A.M.M., PRC95, 044612 (2017)

☞ Word of caution when extracting $\mathcal{S}_F$ from ADWA or DWBA calculations!

1 Direct Reactions with Exotic Beams

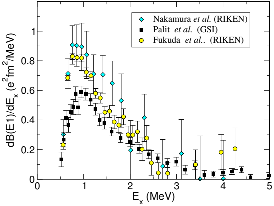
2 Exact solution of few-body problem

3 Ab-initio methods take over

4 Approximate direct reaction methods

5 Toward consistent structure information

6 A Blast from the Past



Ideally:

- Structure properties extracted from different probes and types of reactions should be consistent.
- Reactions dynamics and cross sections vary with incident energy, but extracted structure information should not!

But, is this so in practice ...?

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But, is this so in practice ...?

Two popular examples:

- Occupation numbers/spectroscopic factors
- Electric transition probabilities from Coulex.

knockout, transfer and proton knockout SFs

- Agreement theory vs experiment quantified in reduction factor:

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

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

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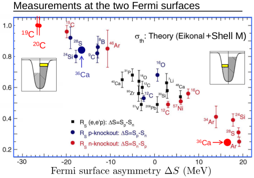
HI knockout (~100 MeV/u)

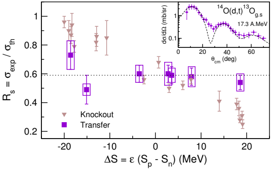
Tostevin, PRC90,057602(2014)



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

Low-energy transfer

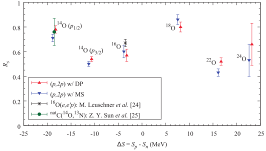
Flavigny, PRL110, 122503(2013)



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

(p, pN) @ 200-250 MeV/u

Wakase, PTEP 021D01 (2018)



- Reaction model: DWIA
- $R_s \sim$ constant.
- ☞ Similar resuts from GSI:Atar *et al*, PRL120, 052501 (2018).

☞See also talk by M. Gómez-Ramos

knockout, transfer and proton knockout SFs

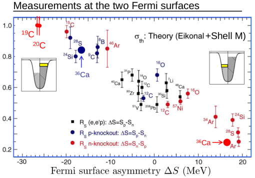
- Agreement theory vs experiment quantified in reduction factor:

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

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

HI knockout (~100 MeV/u)

Tostevin, PRC90,057602(2014)

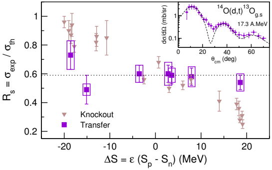


- Reaction model: eikonal + adiabatic
- R_s strongly dependent on $S_p - S_n$.

☞See also talk by M. Gómez-Ramos

Low-energy transfer

Flavigny, PRL110, 122503(2013)



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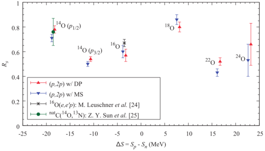

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- $R_s \sim$ constant.

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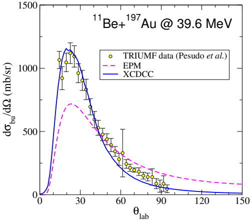
R_s from knockout disagree with those from transfer and (p, pN)
$\Rightarrow$ description of reaction mechanism?

An example: Coulomb dissociation of ^{11}Be on heavy targets

EPM vs. CDCC analyses of breakup cross sections

Coulomb-barrier

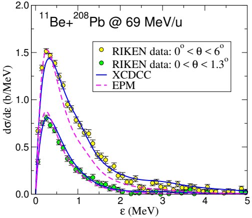
Pesudo, PRL118,152502(2017)



- ✔ Dominated by Coulomb breakup up to large θ
- ✘ Not simple 1 step (higher order couplings important)
- ✘ EPM not applicable

Intermediate (non-rel.)

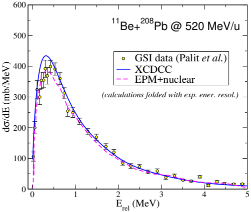
Fukuda et al, PRC70,054606(2004)



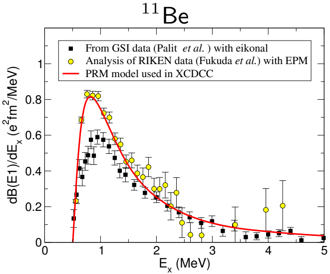
- ✔ 1 step mechanism
- ✔ EPM valid for $\theta \ll \theta_{gr}$

Relativistic

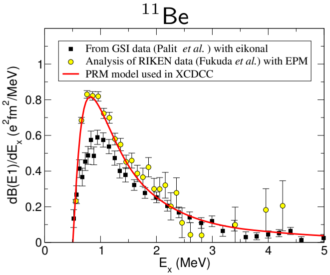
Palit, PRC8,034318('03)

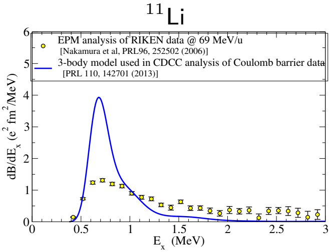


- ✔ 1 step mechanism
- ✘ Relativistic effects
- ✘ Nuclear contributions



- Inconsistencies in extracted $B(E1)$.
- Needs better understanding of connection between reaction observables (σ) and structure ($B(E1)$).
- Calls for better understanding of relation among theories.





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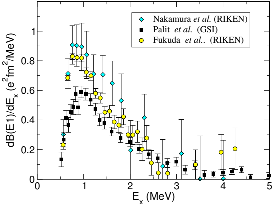
- Even larger discrepancies for ^{11}Li.

  [Core correlations/excitations?]

- More on ^{11}Li during this week:
  - J. Casal: ^{11}Li(p,pn) (theory)
  - J. Tanaka : ^{11}Li(p,p') (exp.)
  - T. Matsumoto : ^{11}Li(p,p') (theory)

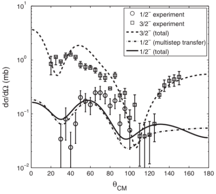

Nakamura et al. (RIKEN)
Palit et al. (GSI)
Fukuda et al.. (RIKEN)
dB(E1)/dE_x (e^2fm^2/MeV)
E_x (MeV)
0
0.2
0.4
0.6
0.8
1
1
2
3
4
5

"Old" theories are being reexamined and adapted to reactions with exotic/weakly-bound nuclei and inverse kinematics:

2N transfer

^{1}H(^{11}Li,^{9}Li)^{3}H at 3 MeV/u

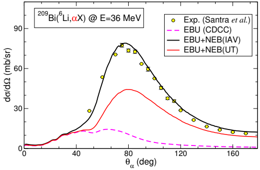
Potel *et al*, PRL105,172502(2010)



Inclusive breakup:

^{209}Bi(^{6}Li,α)X

J.Lei, A.M., PRC92,044616(2015).

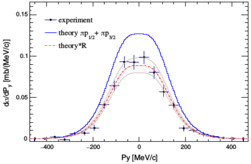


Ichimura, Austern, Vincent model

(p,2p)

^{16}O(p,2p)^{15}N inv. kin.

Atar *et al*, PRL120, 052501 (2018).



Eikonal version of DWIA

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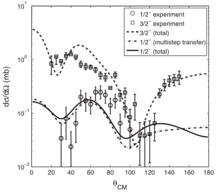

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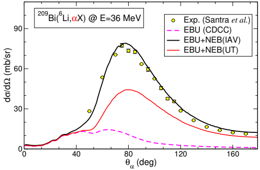

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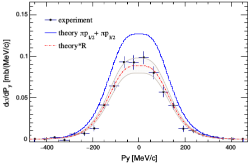

Eikonal version of DWIA

The '70s Are Back in Fashion!

N. Austern, Ichimura, Yahiro, M. Hussein (breakup theories), R.C. Jonhson (adiabatic models), Jacob & Maris (DWIA), Baymann (2N transfer), G. Baur (Trojan Horse, inclusive breakup), and many others who deserve our gratitude and recognition.

Exact solution of reaction problem (Faddeev and FY)

- Feasible for light targets (Deltuva, Lazauskas *et al.*) ☺
- Ongoing initiatives to develop Faddeev codes (eg. TORUS at USA) ☺
- Limited so far to light targets (Coulomb) ☹

Ab-initio methods

- Increasing activity on many variants (NCSM, SCGF, CCM ...)
- Accuracy comparable to Faddeev... ☺
- ...but limited to light systems (so far!) ☹

Approximate methods

- Recent benchmarks show good performance against more exact methods. ☺
- Intense activity toward the incorporation of more realistic structure models and dynamics (eg. core excitations).
- "Old" theories reexamined and updated (2N transfer, (p,pN), inclusive breakup...)

And many more exciting developments and applications which I could not cover:

- Charge–exchange and double charge exchange and its connection with the neutrino double-beta decay matrix elements
  Talk by J.A. Lay on Monday
- Revival of (p,pn) and $(p,2p)$ theories, and possible extensions to more complicated processes: (p,pd), $(p,p\alpha)$, (p,ppn),...
  Talk by Mengjiao Lyu on Wednesday
- Fully quantum-mechanical theory for CF and ICF reactions.
  Talk by Kaitlin Cook and Ed Simpson on Wednesday
- Progress towards understanding of many-body correlations and 3-body cluster dynamics (eg. ^{6}He).
- Proper error quantification in theory (Nunes *et al*).