Nuclear reactions

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theory opportunities with FRIB

DOE Nuclear Physics Mission is to understand the fundamental forces and particles of nature as manifested in nuclear matter, and provide the necessary expertise and tools from nuclear science to meet national needs

DOE Nuclear Physics Mission is accomplished by supporting scientists who answer overarching questions in major scientific thrusts of basic nuclear physics research

Science Drivers (Thrusts) from NRC RISAC

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
Overarching Questions from NSAC 2007 LRP			
What is the nature of the nuclear force that binds protons and neutrons into stable nuclei and rare isotopes? What is the origin of simple patterns in complex nuclei?	What is the nature of neutron stars and dense nuclear matter? What is the origin of the elements in the cosmos? What are the nuclear reactions that drive stars and stellar explosions?	Why is there now more matter than antimatter in the universe?	What are new applications of isotopes to meet the needs of society?

Overarching questions are answered by rare isotope research

17 Benchmarks from NSAC RIB TF measure capability to perform rare isotope research

Nuclear Structure	Nuclear Astrophysics	Tests of Fundamental Symmetries	Applications of Isotopes
1. Shell structure 2. Superheavies 3. Skins 4. Pairing 5. Symmetries 13. Limits of stability 14. Weakly bound nuclei 15. Mass surface	6. Equation of State (EOS) 7. r-Process 8. $^{15}O(\alpha,\gamma)$ 9. ^{59}Fe supernovae 15. Mass surface 16. rp-Process 17. Weak interactions	12. Atomic electric dipole moment	10. Medical 11. Stewardship

FRIB-CDR, 2010

Benchmarking few-body methods for scattering

4N bound state

TABLE I. The expectation values $\langle T \rangle$ and $\langle V \rangle$ of kinetic and potential energies, the binding energies E_b in MeV, and the radius in fm.

Method	$\langle T \rangle$	$\langle V \rangle$	E_b	$\sqrt{\langle r^2 \rangle}$
FY	102.39(5)	−128.33(10)	−25.94(5)	1.485(3)
CRCGV	102.30	−128.20	−25.90	1.482
SVM	102.35	−128.27	−25.92	1.486
HH	102.44	−128.34	−25.90(1)	1.483
GFMC	102.3(1.0)	−128.25(1.0)	−25.93(2)	1.490(5)
NCSM	103.35	−129.45	−25.80(20)	1.485
EIHH	100.8(9)	−126.7(9)	−25.944(10)	1.486

Method	S wave	P wave	D wave
FY	85.71	0.38	13.91
CRCGV	85.73	0.37	13.90
SVM	85.72	0.368	13.91
HH	85.72	0.369	13.91
NCSM	86.73	0.29	12.98
EIHH	85.73(2)	0.370(1)	13.89(1)

H. Kamada, et al, PRC 64, 044001 (2001)

TABLE III. AV18 n-^{3}H

$E_{c.m.}$	σ (b)	
0.40	1.73	AGS
	1.75	FY
	1.76	HH
0.75	1.79	AGS
	1.78	FY
	1.79	HH
1.50	2.22	AGS
	2.06	FY
	2.06	HH
2.625	2.51	AGS
	2.24	FY
	2.24	HH
3.0	2.48	AGS
	2.21	FY
	2.21	HH

Lazauskas et al., Phys. Rev. C 71, 034004 (2005)

Ab-initio reactions with 3N forces

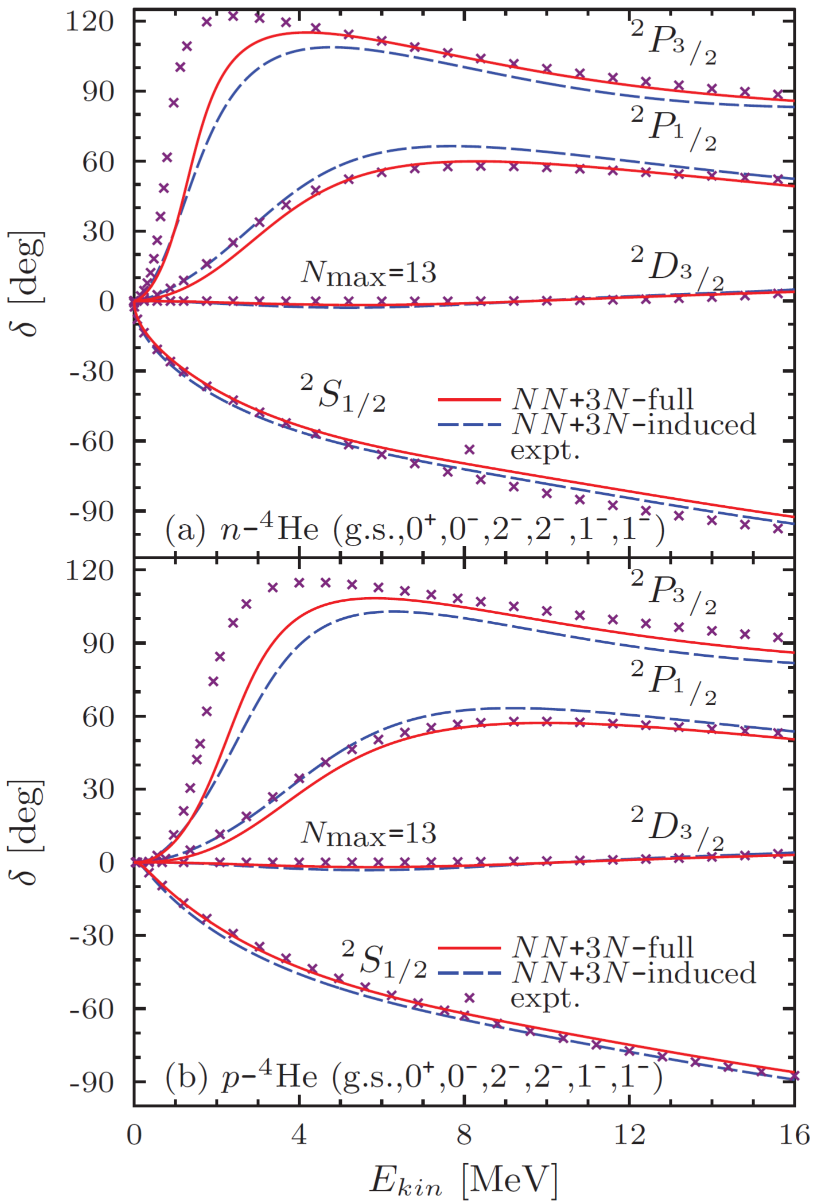


FIG. 10. (Color online) Comparison of the n-^{4}He (a) and p-^{4}He

PRC 88, 054622 (2013)

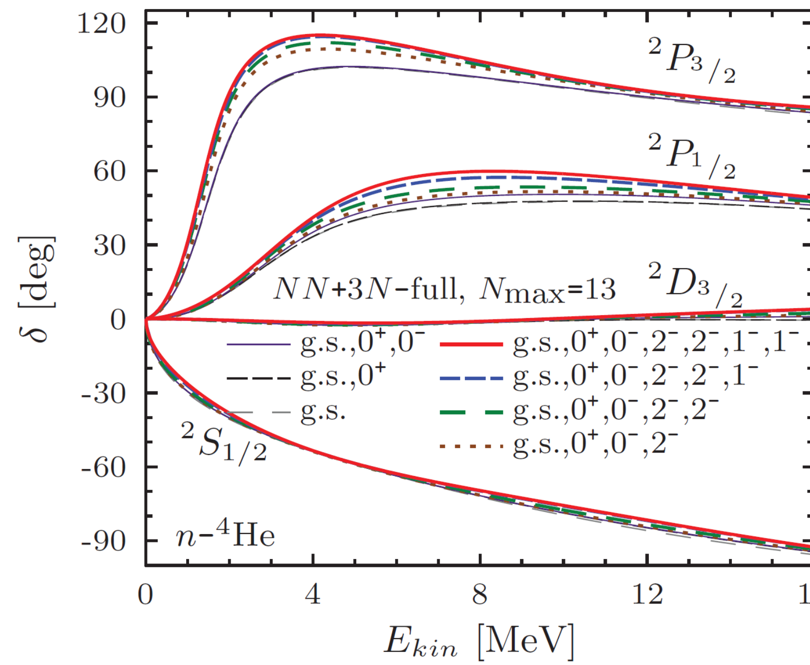


FIG. 5. (Color online) Dependence of the n-^{4}He phase shifts on the considered target eigenstates. Results with only the g.s. of ^{4}He (thin gray long-dashed lines) are compared to those obtained by including in addition up to the 0^+0 (thin black dashed lines), 0^-0 (thin violet lines), 2^-0 (thick brown dotted lines), 2^-1 (thick green long-dashed lines), 1^-1 (thick blue dashed lines), and 1^-0 (thick red lines) excited states of ^{4}He, respectively. The model space is truncated at $N_{\max} = 13$. Other parameters are identical to those of Fig. 2.

- he4+n elastic scattering

Ab-initio reactions for heavier nuclei

PRC 86, 021602R (2012)

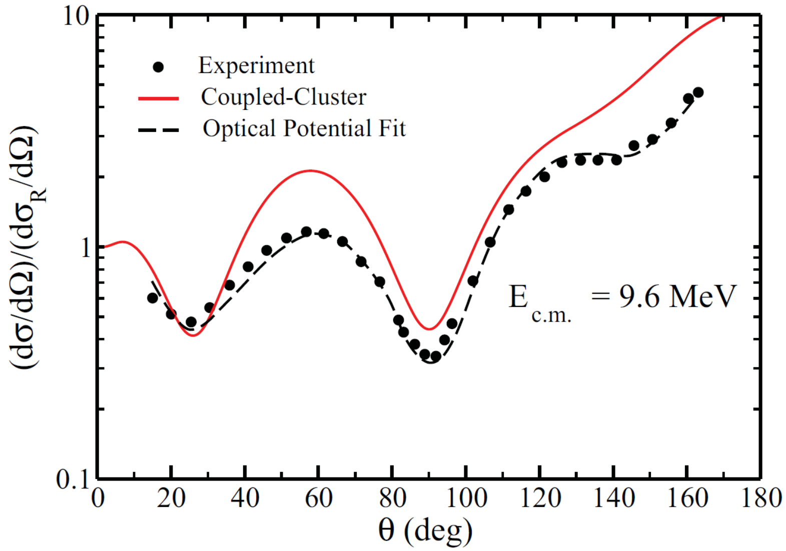


FIG. 5. (Color online) Differential cross section from coupled-cluster calculations divided by Rutherford cross section for elastic proton scattering on ^{40}Ca at $E_{cm} = 9.6$ MeV (solid line), experimental data (dots), and optical model potential fits (dashed line), taken from Ref. [31].

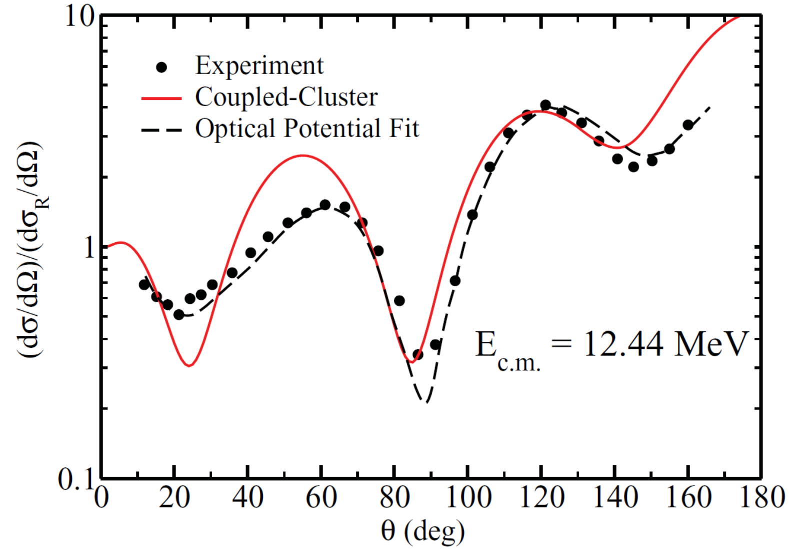
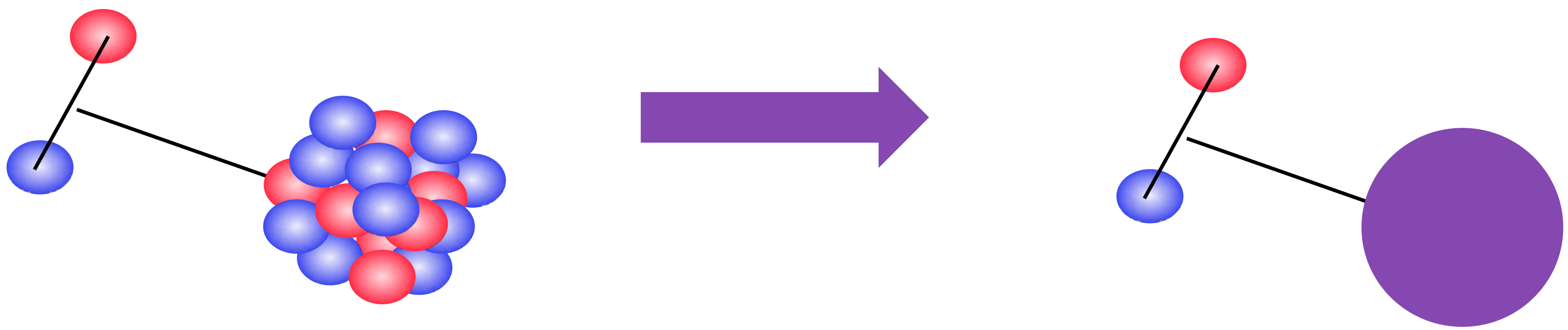


FIG. 6. (Color online) Same caption as in Fig. 5 except that the energy is $E_{cm} = 12.44$ MeV.

- ab-initio coupled cluster calculations
- single nucleon correlations insufficient

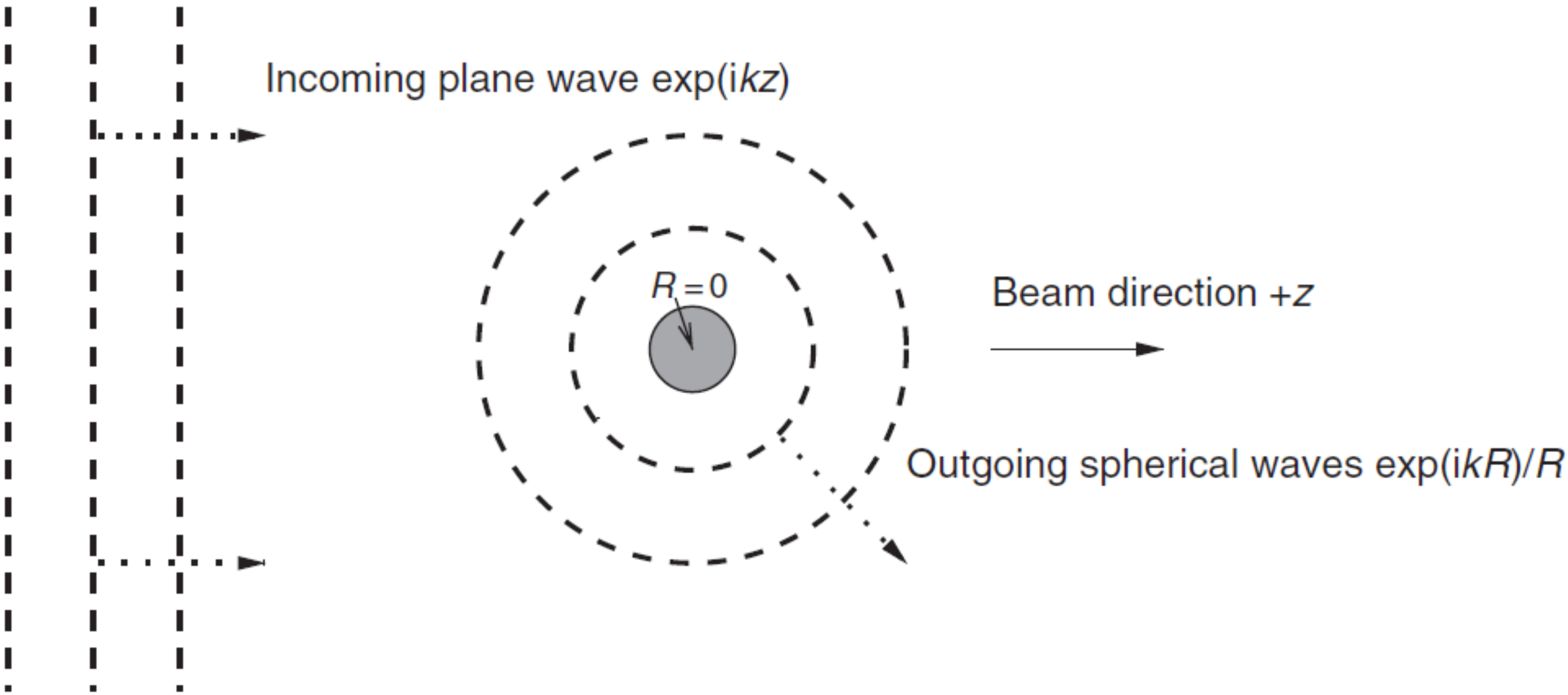
reducing the many body to a few body problem



- ❑ isolating the important degrees of freedom in a reaction
- ❑ keeping track of all relevant channels
- ❑ connecting back to the many-body problem

- ❑ effective nucleon-nucleus interactions (or nucleus-nucleus)
  (energy dependence/non-local)
- ❑ many body input

picture for scattering



classification of reactions

Direct reactions

transfer momentum is small compared to initial momentum
typically peripheral
short timescale (10^{-22} s)
E>10 MeV
mostly one step
final states keep memory of initial states

Resonance reactions

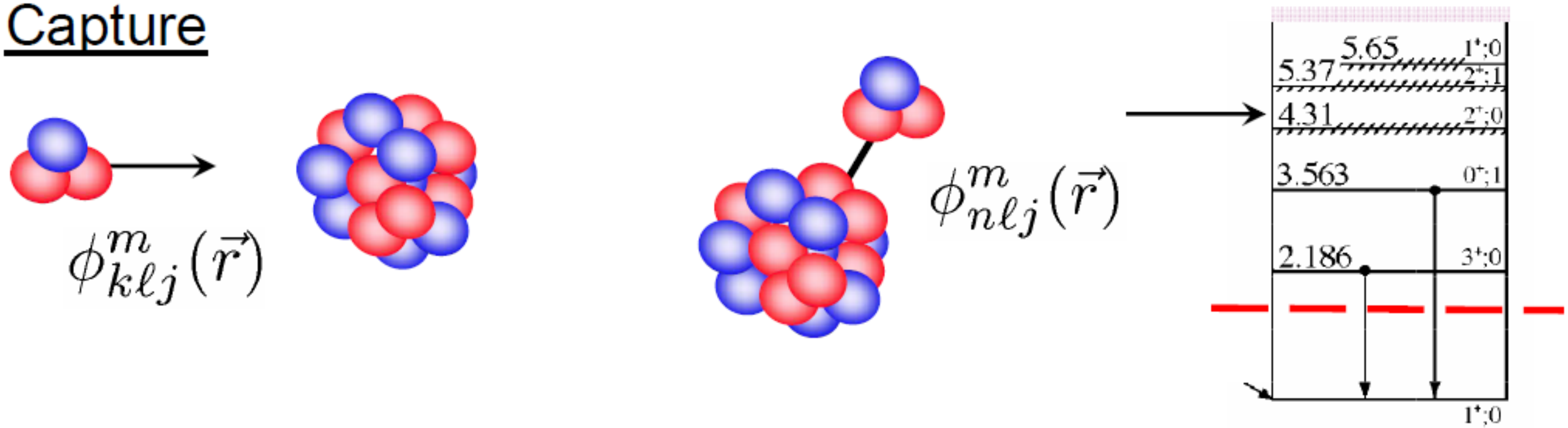
reactions that go through a resonance (peak in the cross section)
intermediate step in the reaction
longer time scale

Compound reactions

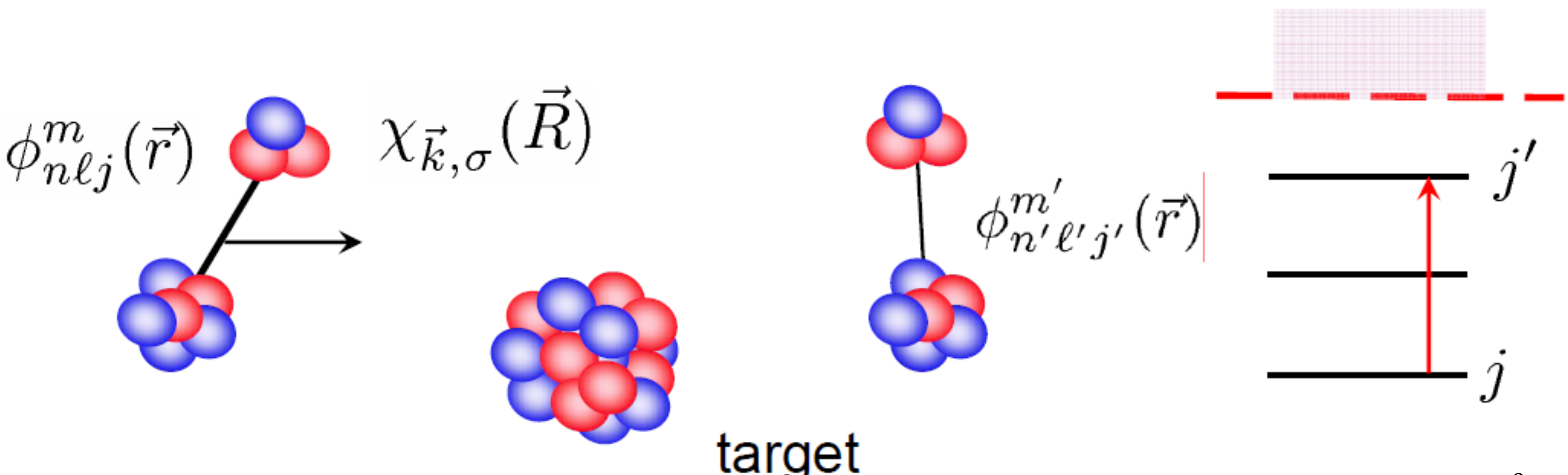
longer timescale
many steps in the reaction
all nucleons share the beam energy
loss of memory from the initial state
low energy reactions

direct reactions

Capture

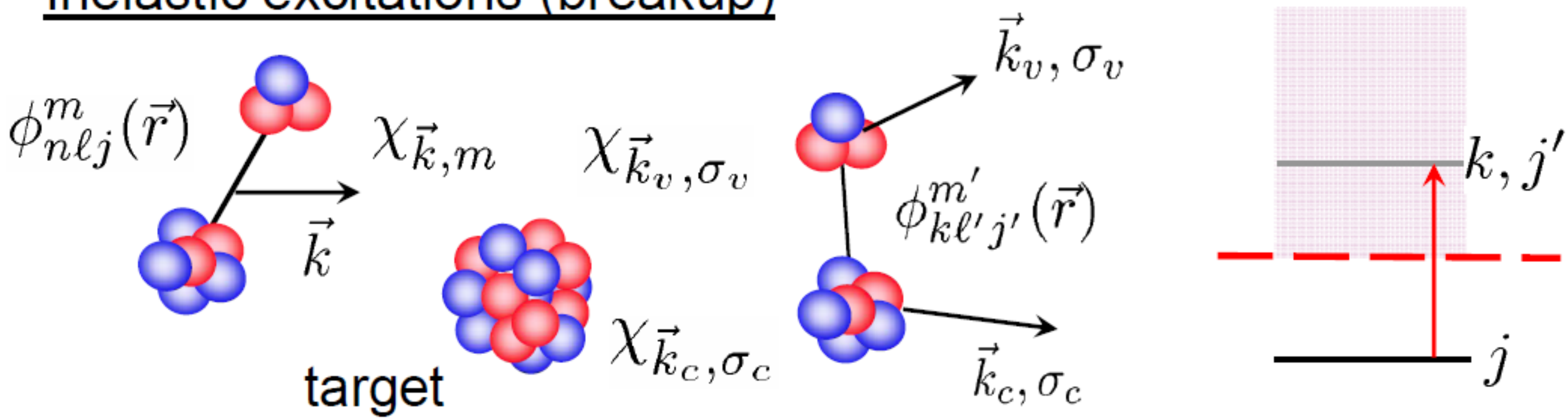


Inelastic excitations (bound to bound states)

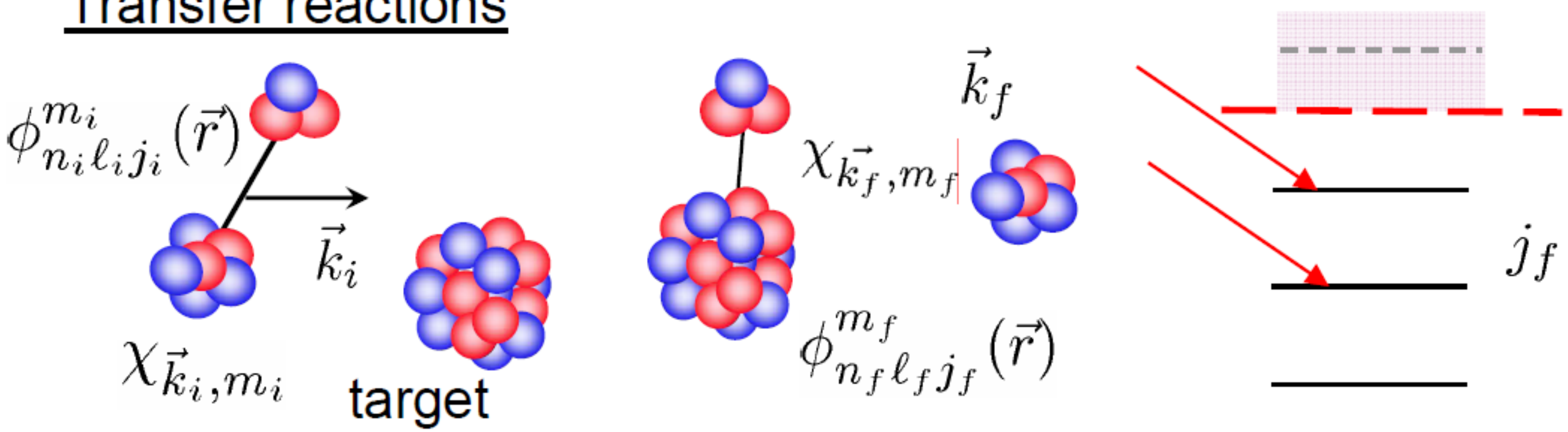


direct reactions

Inelastic excitations (breakup)



Transfer reactions



why do reactions? elastic

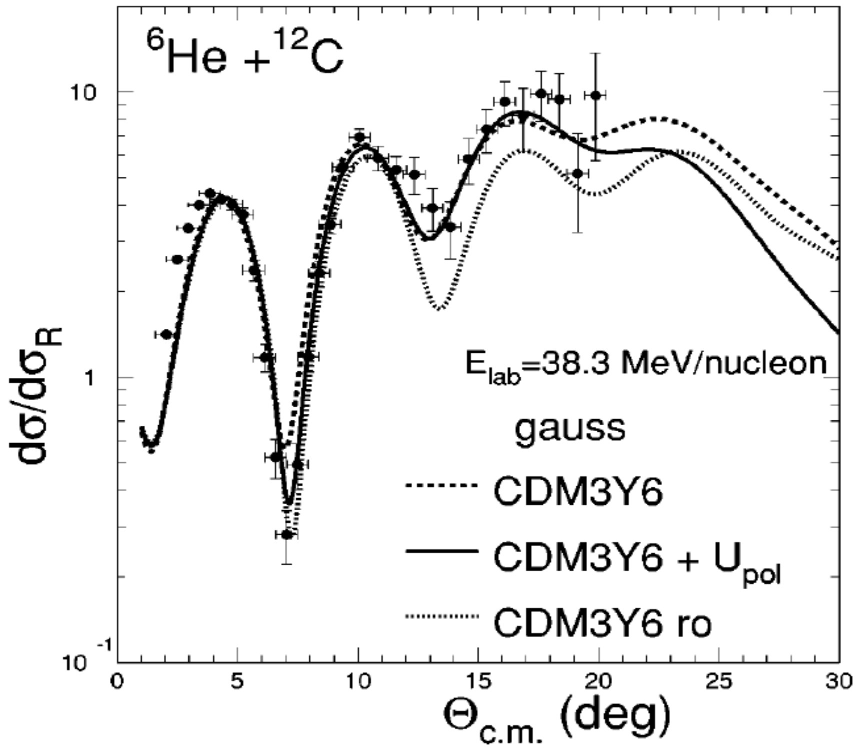
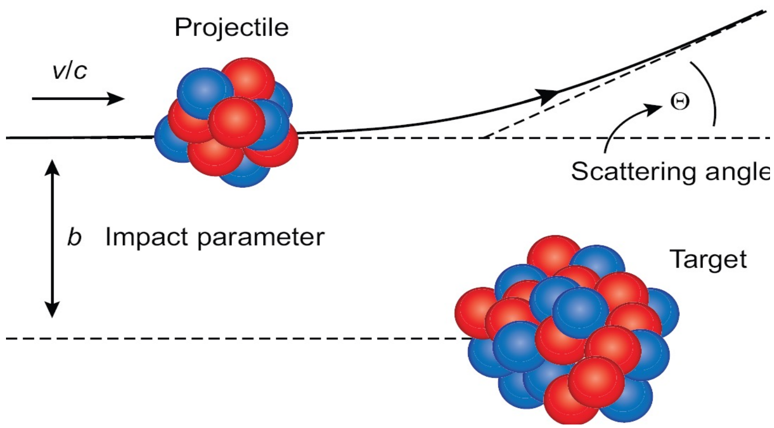


FIG. 10. Elastic scattering for ^{6}He+ ^{12}C at 38.3 MeV/nucleon in comparison with the OM results given by the real folded potential (obtained with the CDM3Y6 interaction and the Gaussian *ga* density for ^{6}He). The dashed curve is obtained with the unrenormalized folded potential only. The solid curve is obtained by adding a complex surface polarization potential to the real folded potential. Its parameters, and those of the imaginary part, are explained in the text. The dotted line is obtained by folding the CDM3Y6 interaction with the compact Gaussian density *ro*.

[Lapoux et al, PRC 66 (02) 034608]

traditionally used to extract optical potentials, rms radii, density distributions.

why do reactions? inelastic



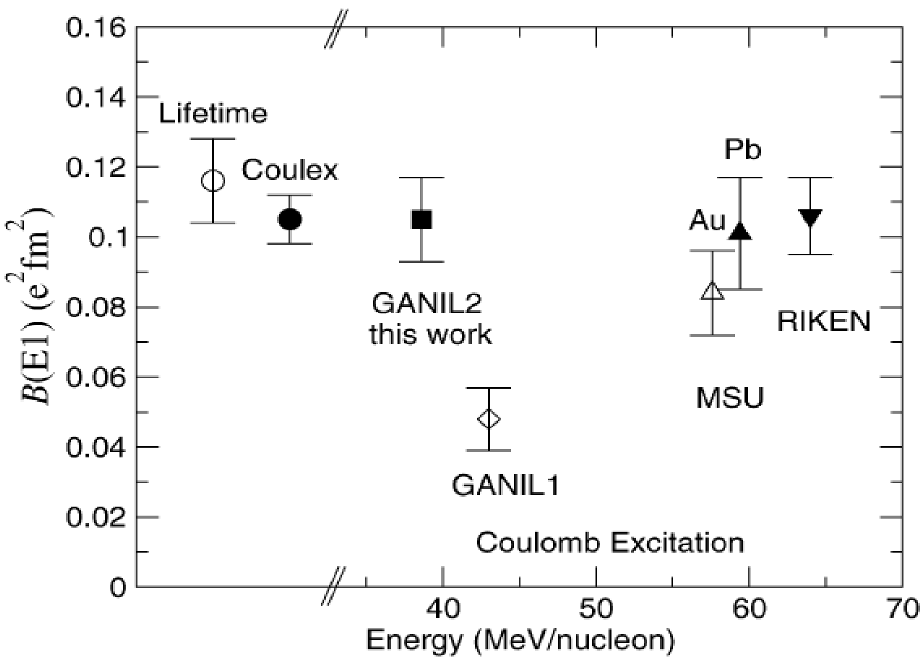
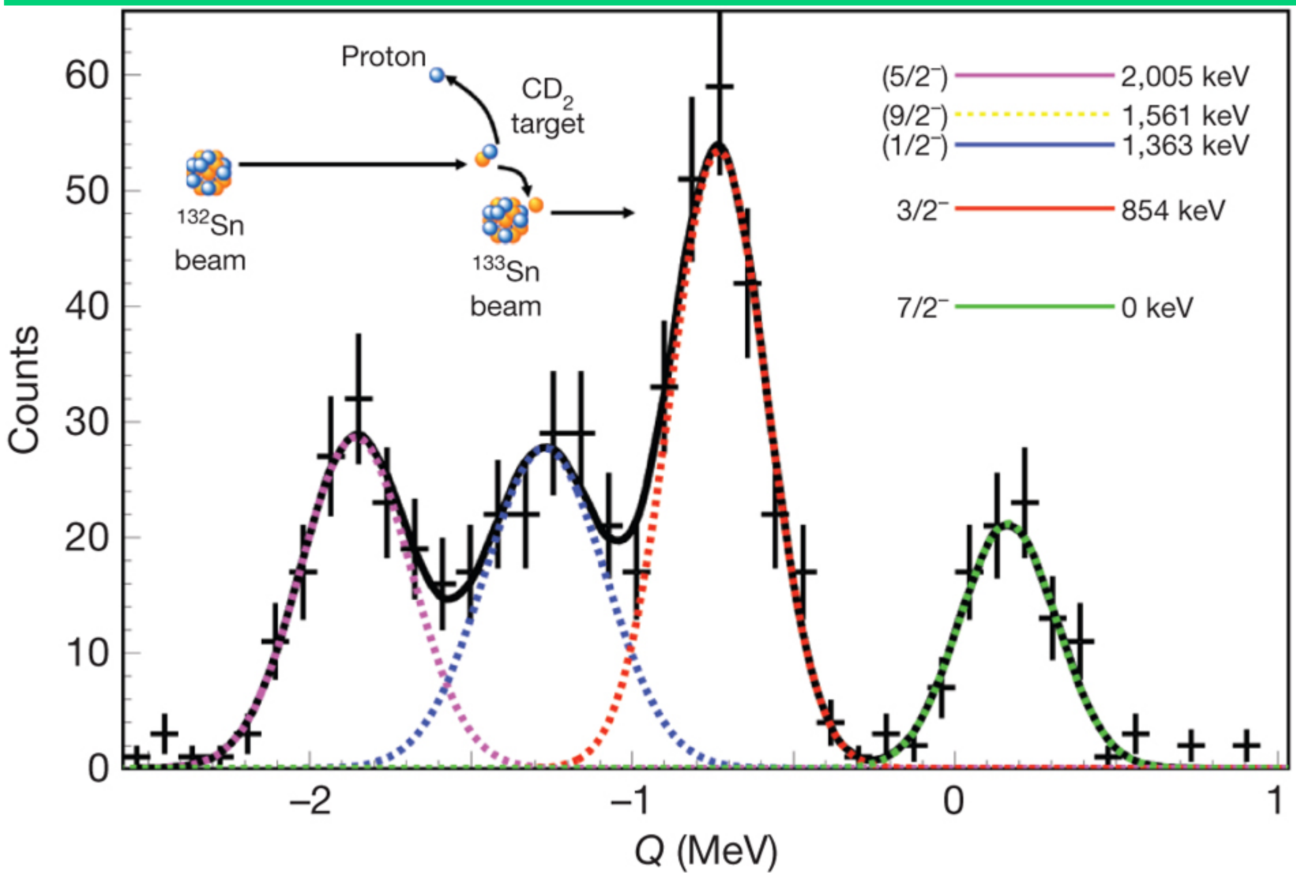


Fig. 2. Comparison of B(E1) values obtained from lifetime and Coulomb excitation measurements. The weighted average of lifetime measurements [3] (open circle) is plotted on the left along with the weighted average (solid circle) of three Coulomb excitation measurements (solid symbols). The individual Coulomb excitation measurements, GANIL (this work, square), MSU (up triangle) [6], RIKEN (down triangle) [7], and a previous GANIL experiment (diamond) [4], are plotted versus the beam energy.

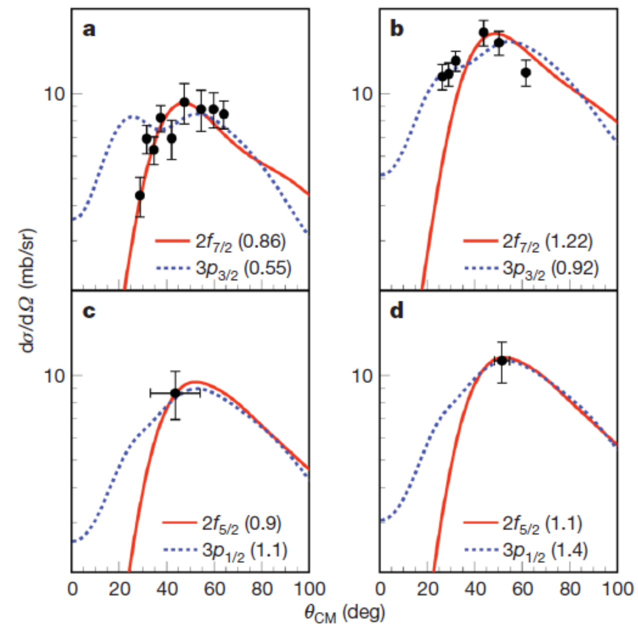
traditionally used to extract electromagnetic transitions or nuclear deformations

[Summers et al, PLB 650 (2007) 124]

why do reactions? transfer



d(^{132}Sn,^{133}Sn)p@5 MeV/u



traditionally used to extract spin,parity and spectroscopic factors

[K. Jones et al, Nature 465 (2010) 454]

why do reactions? transfer

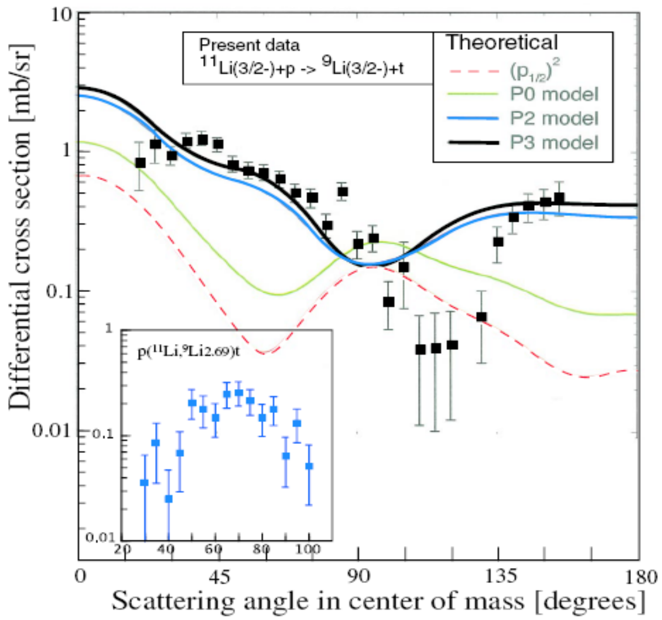


FIG. 3 (color online). Differential cross sections of the (p, t) reaction to the ground state of ^{9}Li and to the first excited state (insert). Theoretical predictions using four different wave functions were shown by curves. See the text for the difference of the wave functions.

^{11}Li(p,t)^{9}Li@ 3 A MeV

measured both ground state and excited state ^{9}Li

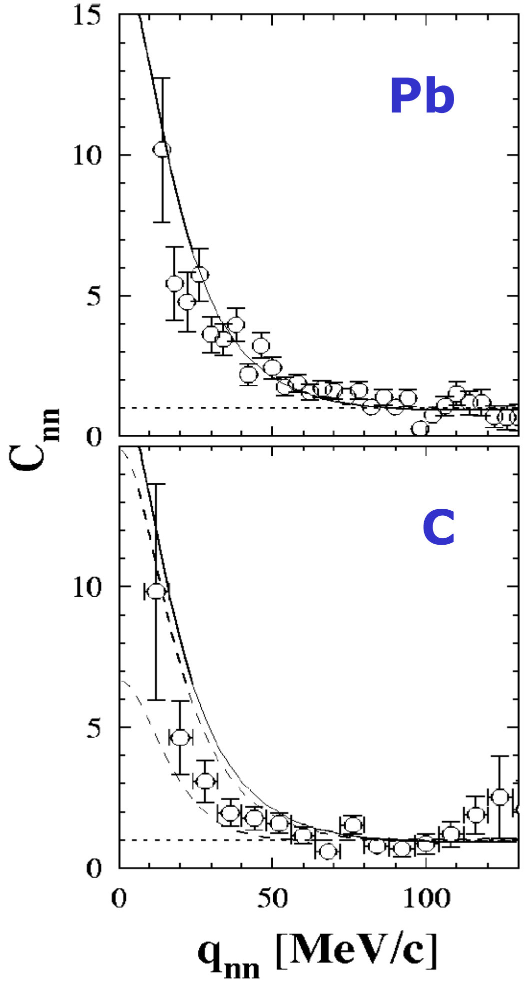
[Tanihata et al, PRL 100, 192502 (2008)]

traditionally used to study two nucleon correlations and pairing

why do reactions? breakup

two nucleon correlation function

$^{14}Be \rightarrow n+n+^{12}Be$



[Marques et al, PRC 64 (2001) 061301]

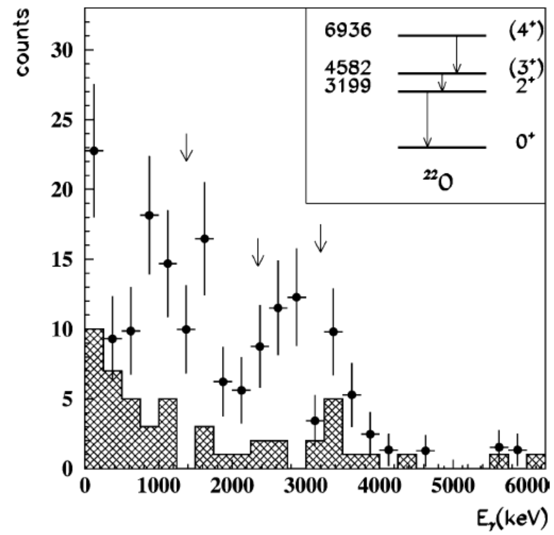
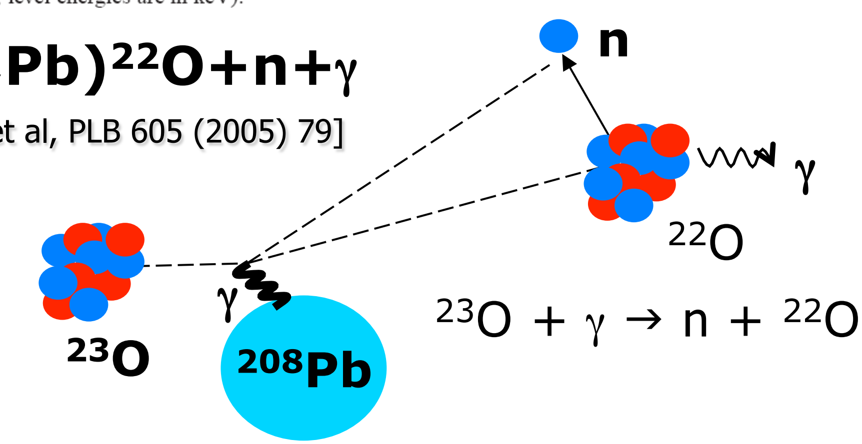


Fig. 1. Doppler corrected γ-ray spectra measured in coincidence with an ^{22}O fragment and one neutron for Pb (symbols) and C (shaded area) targets. Arrows indicate the strongest γ transitions as expected from the ^{22}O level scheme of Ref. [10] (partial level scheme shown as inset; level energies are in keV).

$^{23}O(Pb,Pb)^{22}O+n+\gamma$

[Nociforo et al, PLB 605 (2005) 79]



why do reactions? knockout

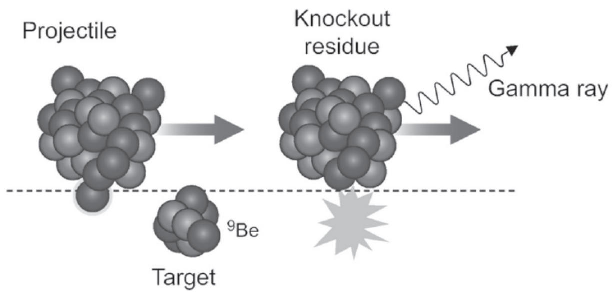
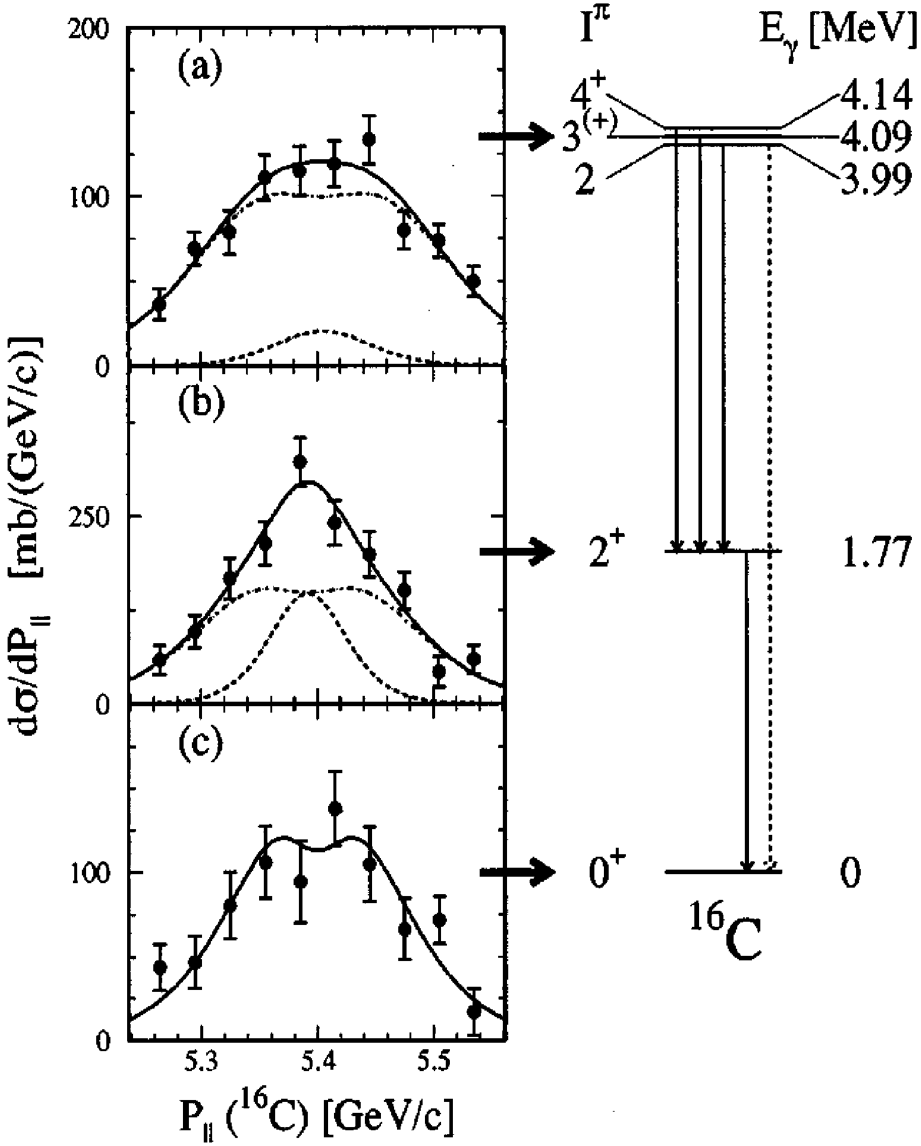


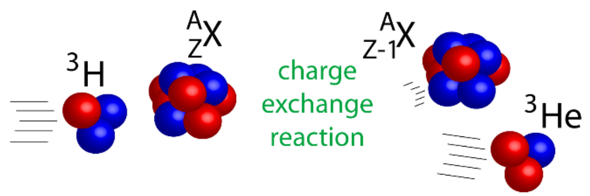
Fig. 14.9. Schematic of a nuclear knockout reaction. Reprinted from [3] with permission.

Includes elastic and inelastic breakup as well as transfer

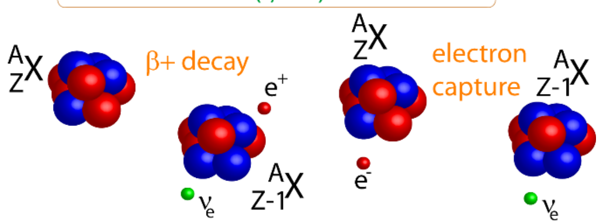
traditionally used to extract spin and parity as well as shell occupancy



why do reactions? Charge exchange



$$\left(\frac{d\sigma}{d\Omega}(q=0)\right)_{(t,^3He)} = \hat{\sigma}\, B(GT)$$



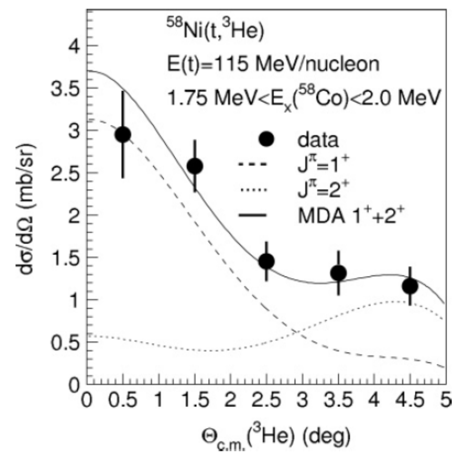


FIG. 5. The differential cross sections for the energy bin $1.75 < E_x(^{58}Co) < 2.0$ MeV and the result of the MDA (solid line) using a linear combination of 1^+ (dashed line) and 2^+ (dotted line) components. The error bars in the data are of statistical nature only.

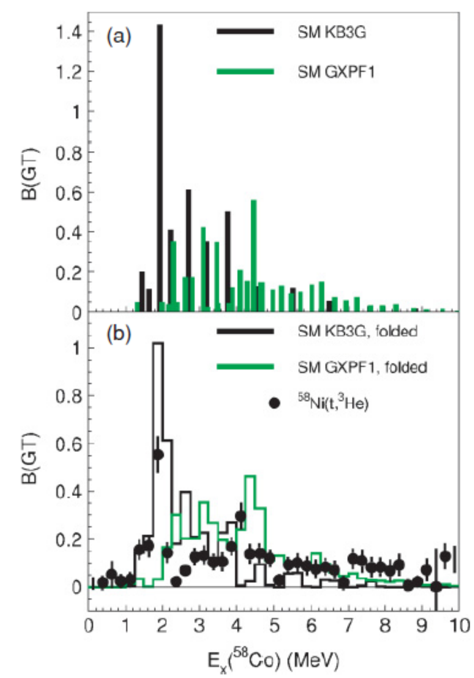


FIG. 6. (Color online) (a) Large-scale shell-model calculations for the Gamow-Teller strength distribution in ^{58}Co using the KB3G [69] interaction [37,38,70] (black) and GXPF1 [71,72] interaction [38] (gray, green online). (b) Gamow-Teller strength distribution extracted from the ^{58}Ni(t,^{3}He) data compared with the theoretical distributions that were folded with the experimental resolution (250 keV) and binned in the same manner as the data.

traditionally used to extract GT and F strengths

Cole et al., Phys. Rev. C 74, 034333

why do reactions? fusion

Fusion of Stable vs Unstable Nuclei

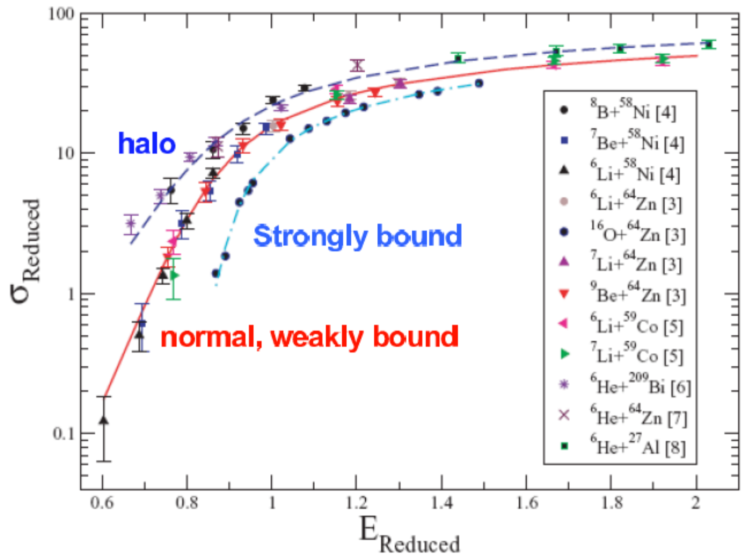


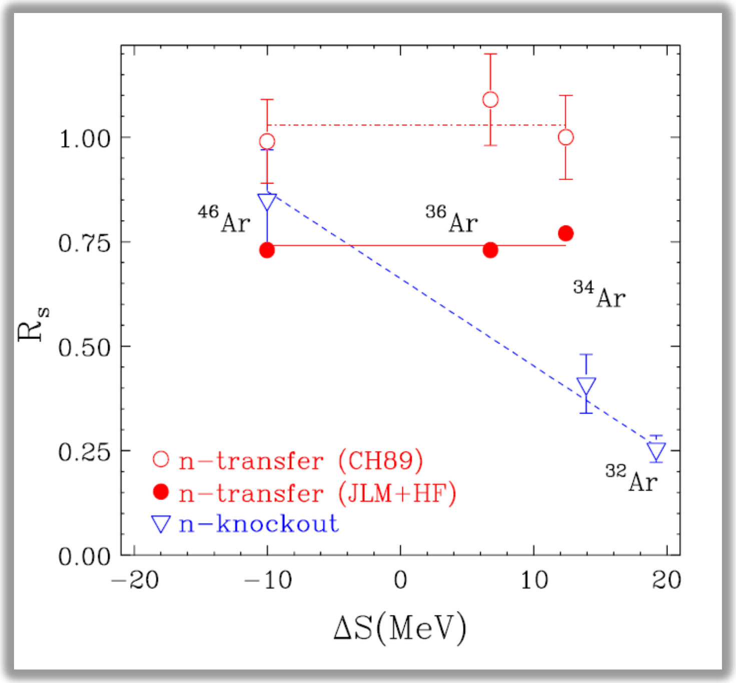
Fig. 8. Reduced cross sections for the fusion of halo, normal/weakly bound, and strongly bound nuclei. (Courtesy of J. Kolata).

After geometric effects are scaled out, fusion enhanced for halo nuclei!

Superheavies
Halos
Applications: energy

why reactions?

transfer versus knockout



[Jenny Lee et al, PRL 2009]

[Gade et al, Phys. Rev. Lett. 93, 042501]

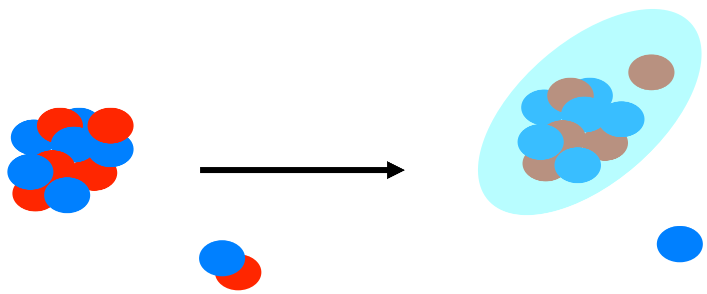
- shell structure
- correlations
- pairing
- weakly bound systems
- role of continuum
- ...

need accurate reaction models!

why do reactions? astrophysics

- direct measurement $^{14}C(n,\gamma)^{15}C$

- transfer reaction



$^{14}C(d,p)^{15}C$

- Coulomb dissociation