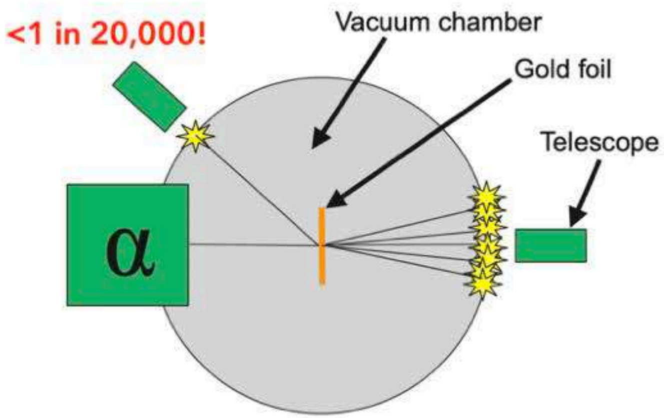
Nuclear Reactions Experiment - I



EBSS 2022

CALEM R. HOFFMAN
Physicist
Argonne National Laboratory

OVERVIEW

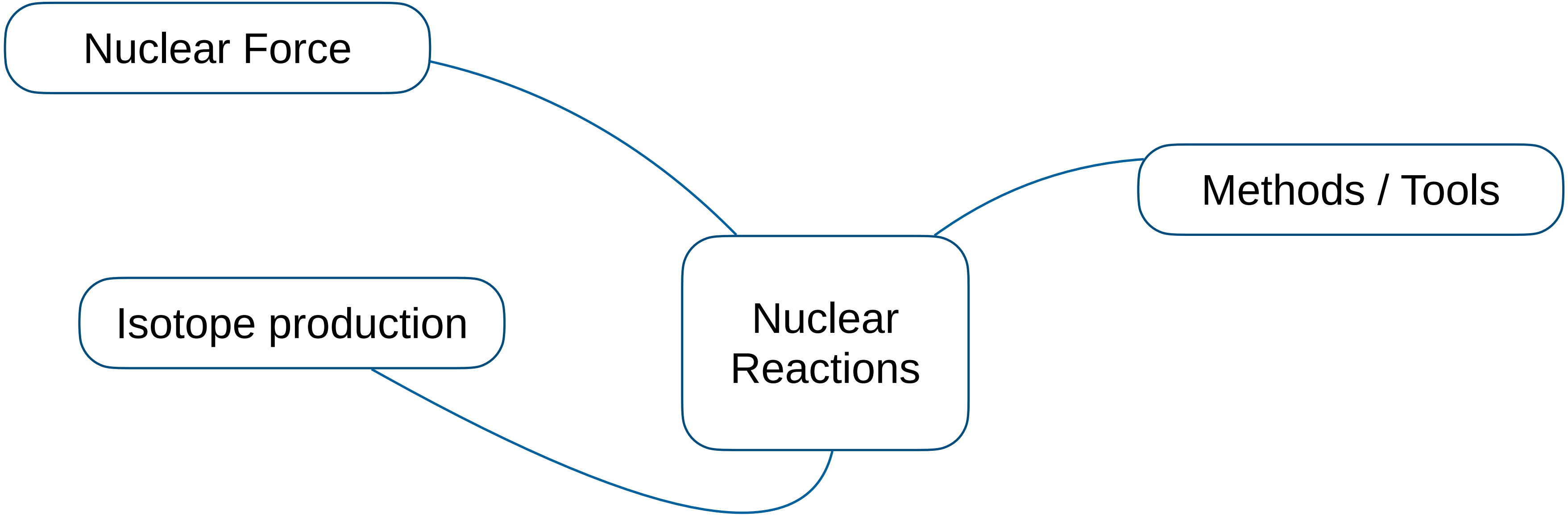
Lecture 1 Focus: Overview of Nuclear Reactions
Lecture 2 Focus: Example using single-particle transfer reactions

- Understanding different types / forms of reactions is key
  - Integrated into measurements, New physics directly, Isotope production
- Reaction Formalism
- Overview of some reaction types
- Example cases of complementary reactions

Lecture 1 Takeaways:

- Familiarity with reaction "language"
- List various reaction types & their general properties
- Link reaction method and/or probe to physics quantities of interest
- How multiple reactions are used to explore common physics goals

REACTIONS LINK VARIOUS ASPECTS OF NUCLEAR SCIENCE



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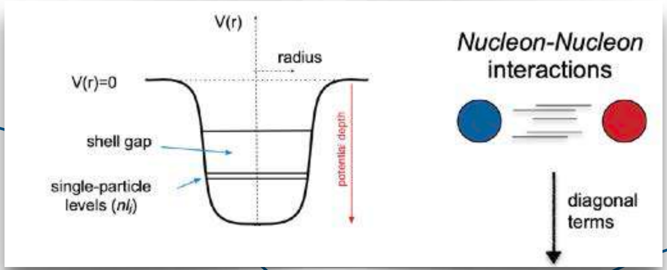


Nuclear Force

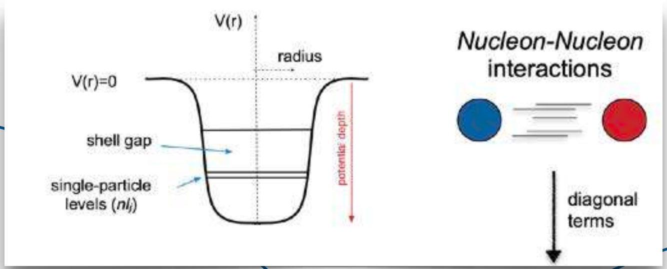
Methods / Tools

Isotope production

Nuclear Reactions

REACTIONS LINK VARIOUS ASPECTS OF NUCLEAR SCIENCE

Nuclear Force



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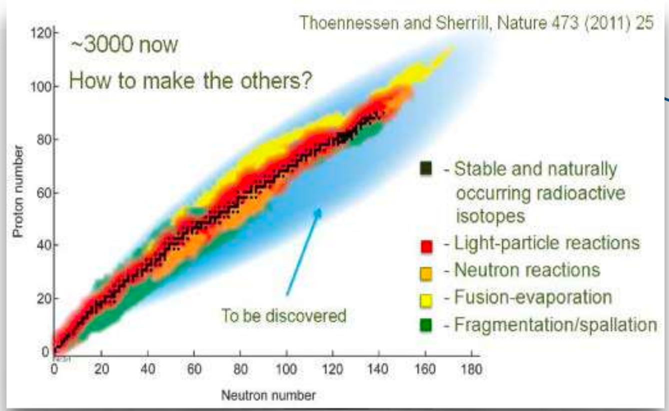

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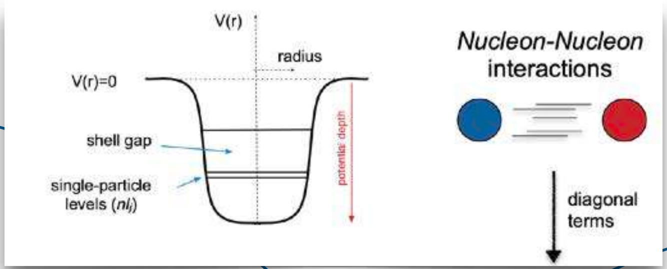

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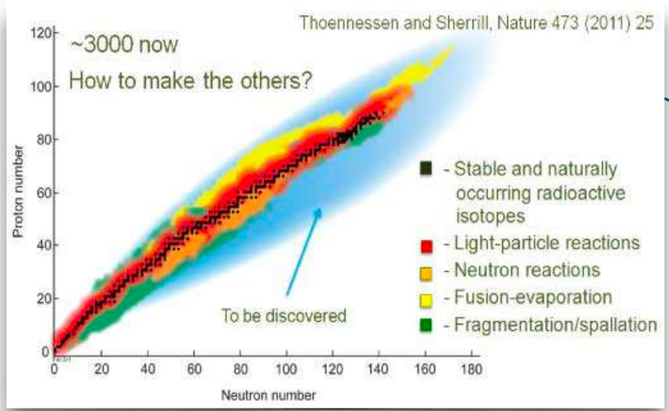
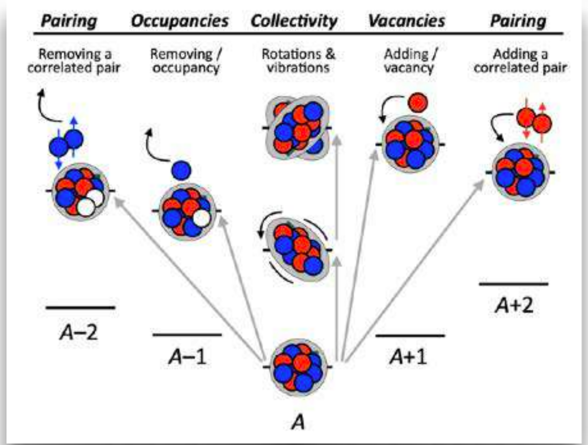
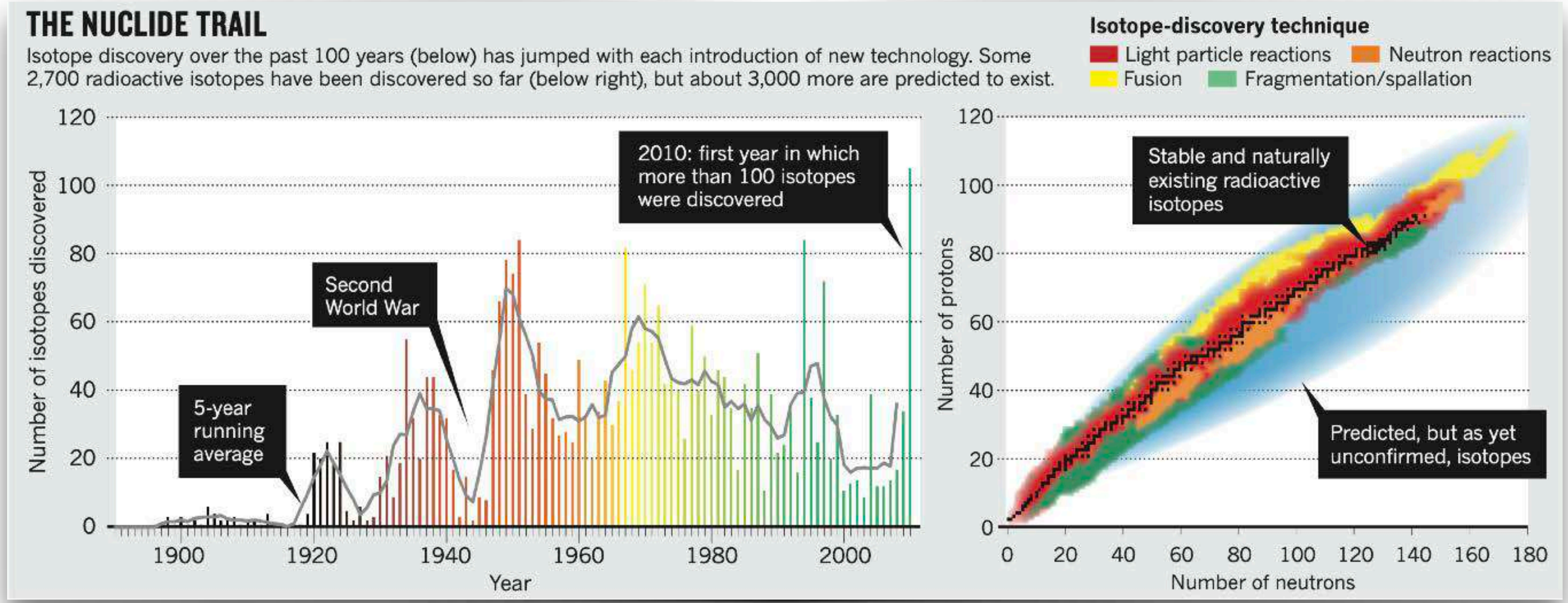




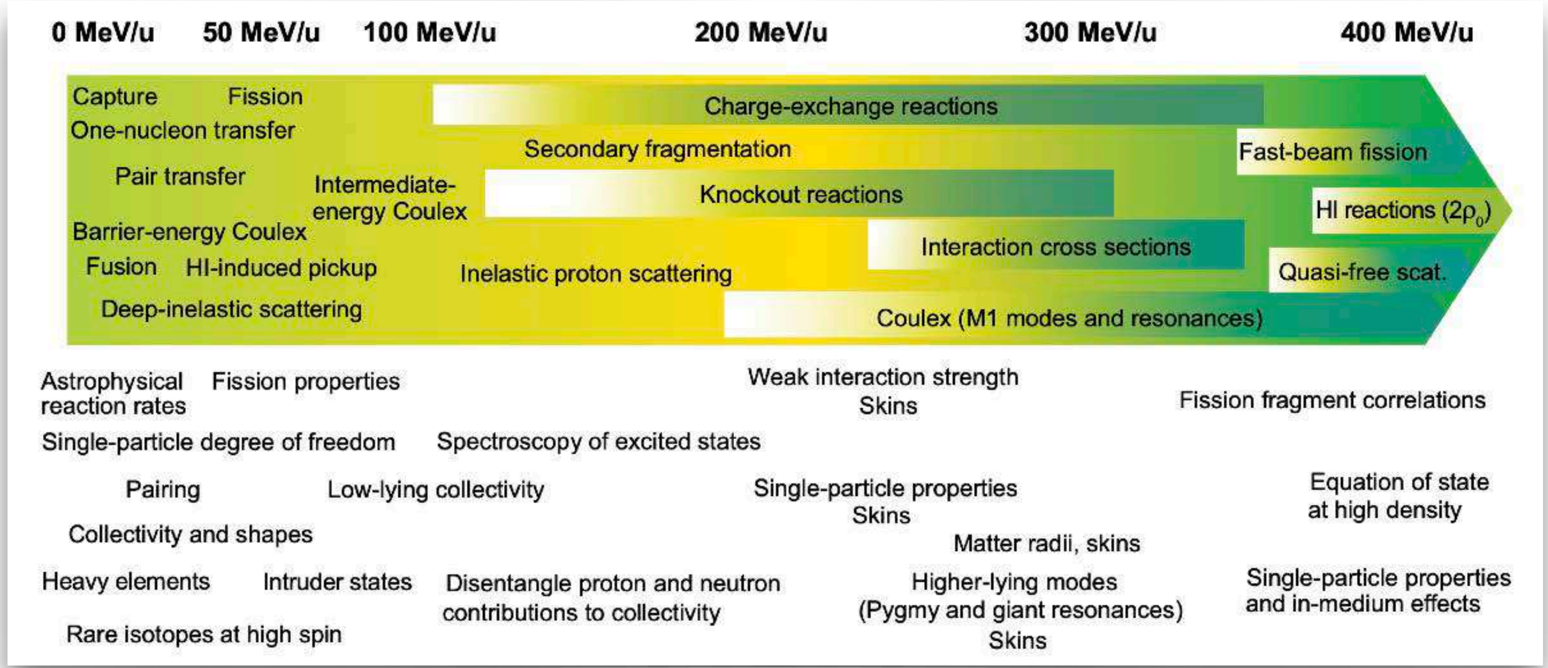
ISOTOPE DISCOVERY

Leveraging various reaction types / energies / facilities



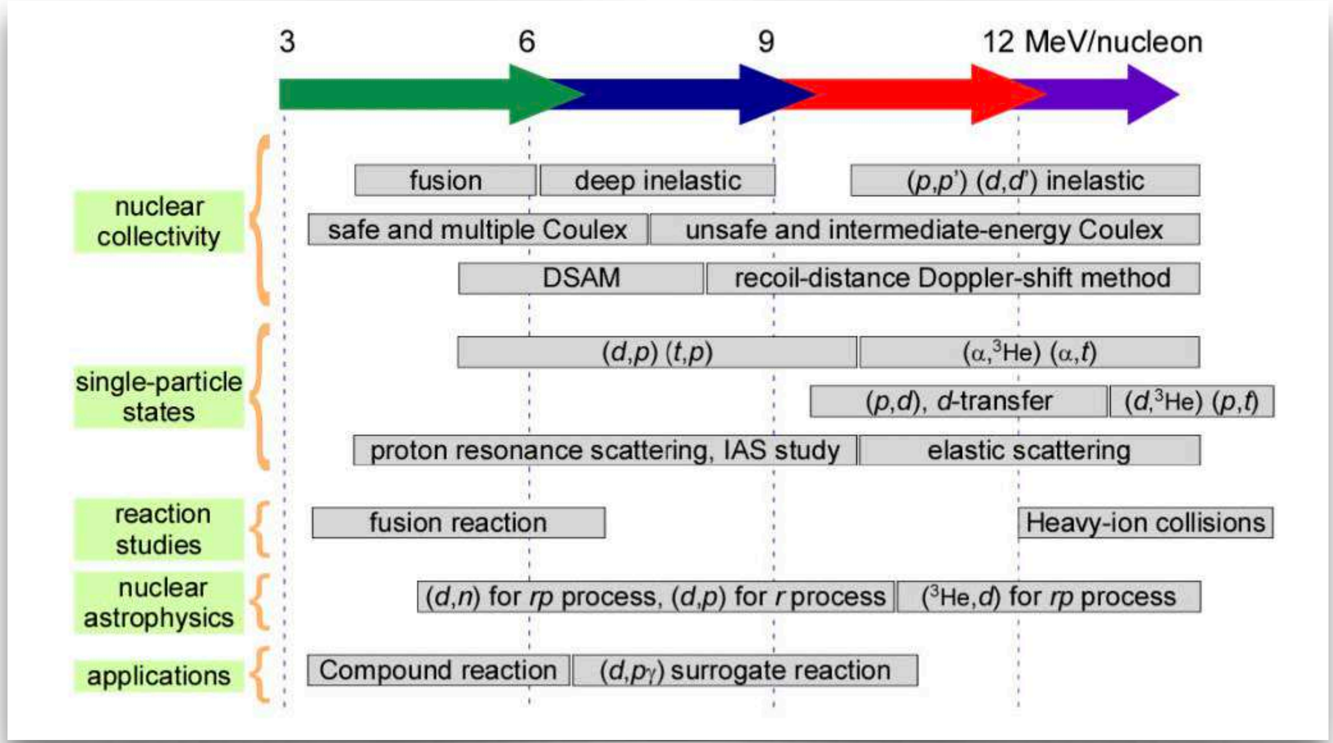
REACTION TYPES / ENERGIES / PHYSICS MOTIVATION

Many methods with overlapping science goals



BREAKDOWN IN COULOMB BARRIER REGION

Physics goals may be encompassed by various reaction types



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SOME BASIC REACTION FORMALISM / NOTATION

Pragmatic way of writing nuclear reactions

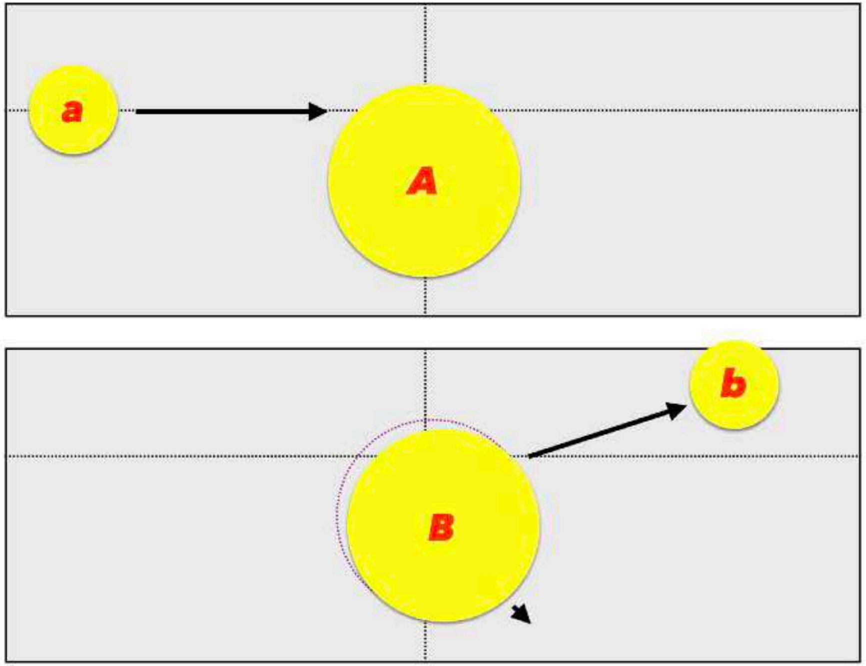
The ingredients

- Target (*A*)
- Projectile (*a*)
- Beam-like outgoing ion (*b*)
- Target-like outgoing ion (recoil) (*B*)

Other Considerations

- **Inverse kinematics [rare-isotope beams, MeV/u]**
- **near-Coulomb energies**
- **Low energy (<20 MeV/u) to Intermediate energy (50 - few hundred MeV/u)**

A(a,b)B



For most reactions it is the (a,b) of A(a,b)B that is used to label the reaction

REACTION TYPES

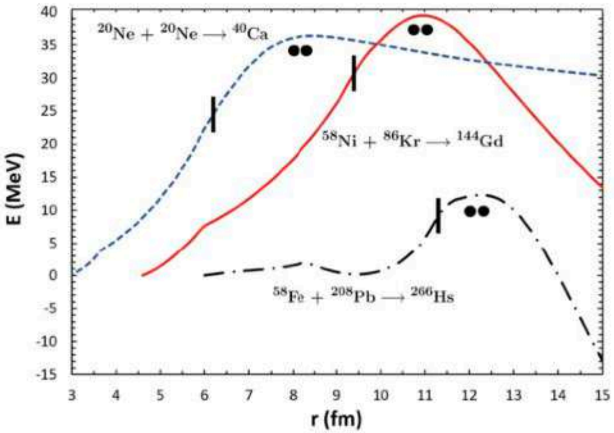
TYPES OF NUCLEAR REACTIONS

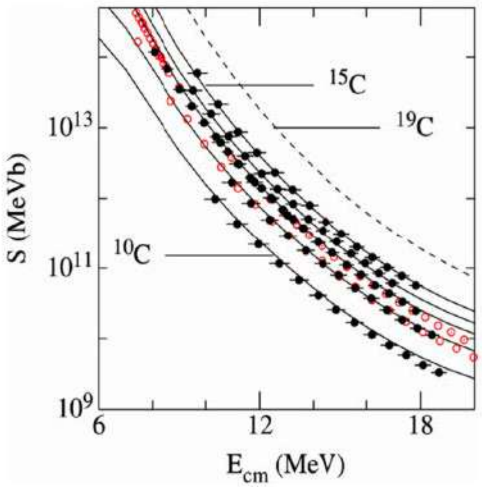
Beam energies range from eV/u to GeV/u

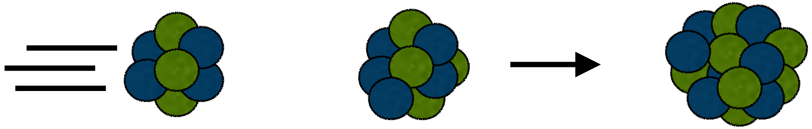
- Direct reactions
  - Knockout - single / multi-particle
  - Transfer - single / multi-nucleon / charge-exchange
- Scattering
  - Inelastic / Elastic / Resonance
- Fusion
  - Compound - Evaporation / Fission
- Capture
  - Neutron / Proton / Alpha / Induced reactions
- Others
  - Heavy-ion collisions / Fragmentation / Deep inelastic collisions / etc…

FUSION REACTIONS

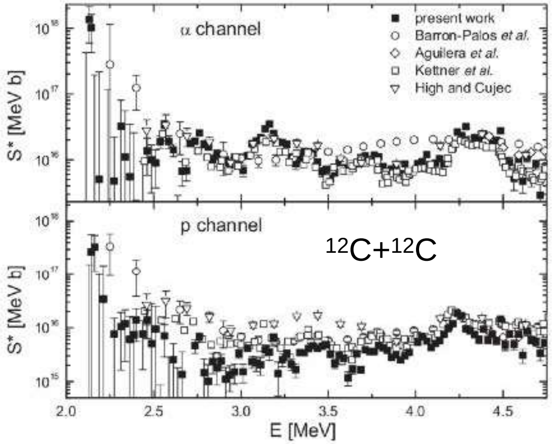
Fusion & fusion-fission: $^{12}C(^{A}C,x)$, $Th(^{15}C,X)$







Compound nucleus



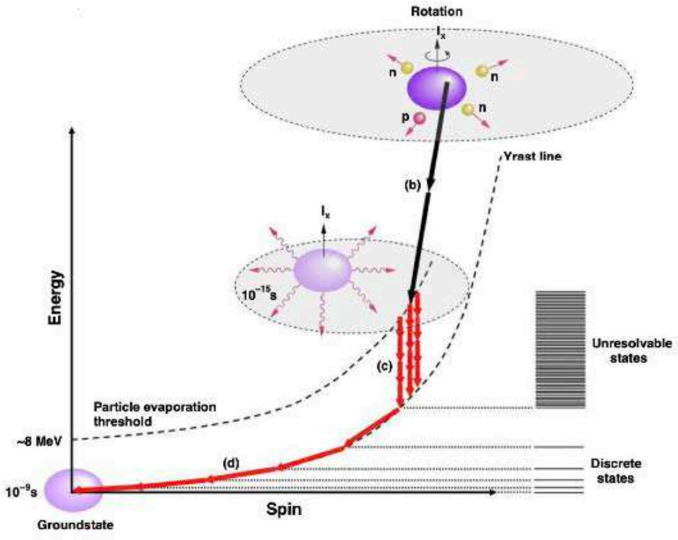
Extract: excitation functions, angular momenta
Deduce: barrier heights, fusion probabilities, S-factors
Tools: various cross section codes [HF approach / PACE / CASCADE / HIVAP / etc…]

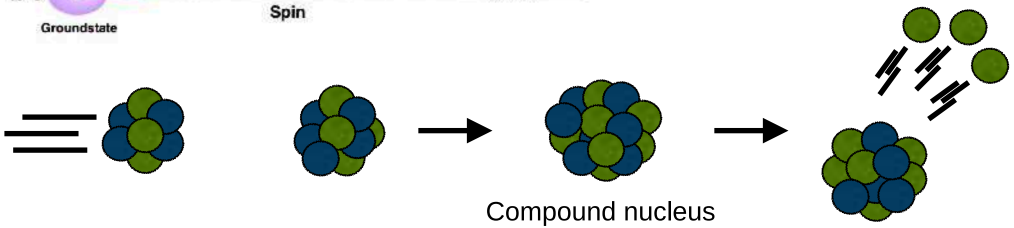
KEY POINTS

- <10 MeV/u
- No "memory" of formation
- Size & shape of barrier
- Relevance to stellar processes & heavy-element creation

FUSION REACTIONS

Fusion evaporation: $^{20}Ne(^{22}Ne,\alpha 2n)^{36}Ar$





Compound nucleus

Extract: Level & decay schemes, angular momenta, transition strengths
Deduce: nuclear shapes, entry distributions, deformation parameters
Tools: various fusion-evap codes [PACE / CASCADE / HIVAP / etc…]

KEY POINTS

- Compound has no “memory” of construction
- Population along yrast line
- Provides alignment
- Prolific tool in gamma-ray spectroscopy

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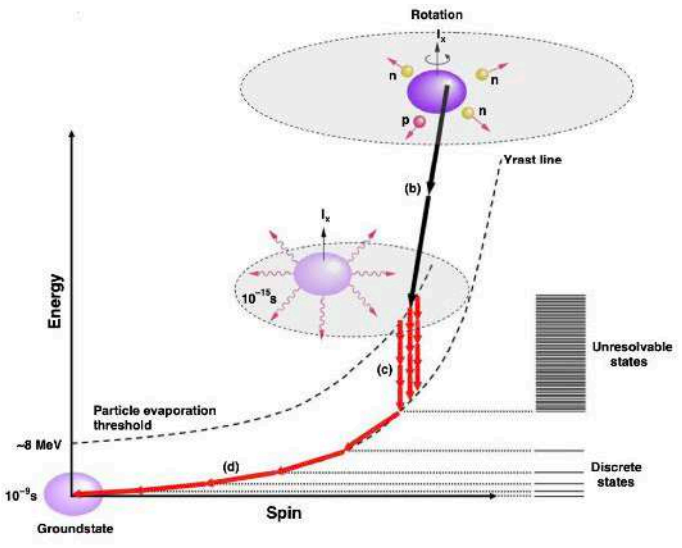
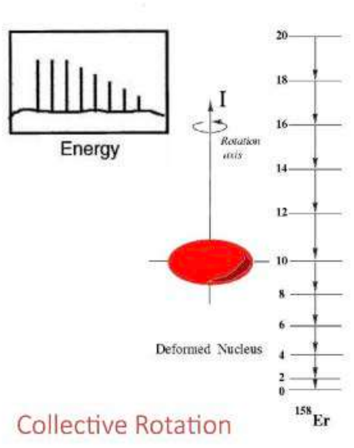
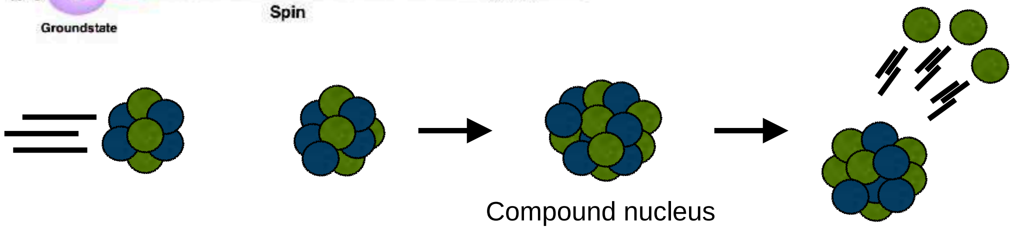
Fusion evaporation: ^{20}Ne(^{22}Ne,α2n)^{36}Ar







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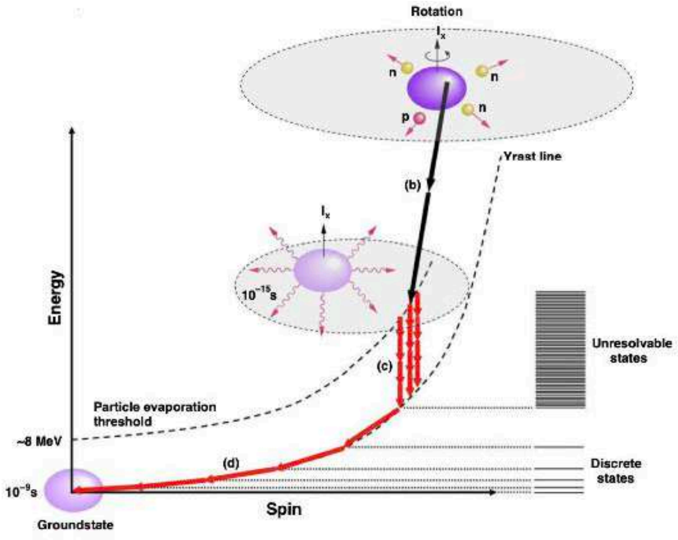

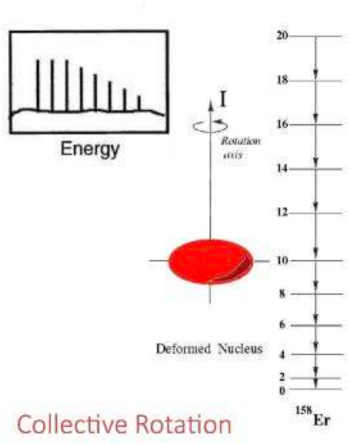

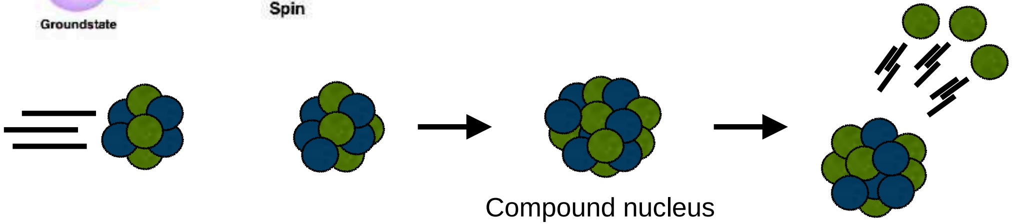

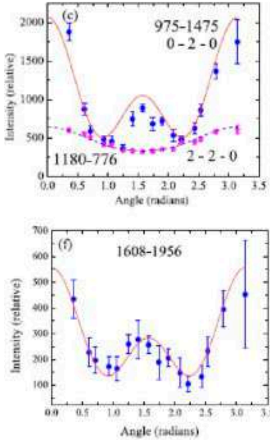

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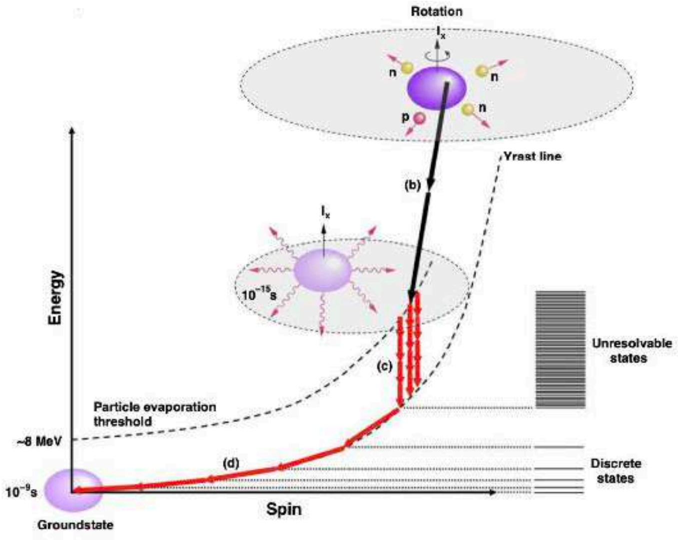

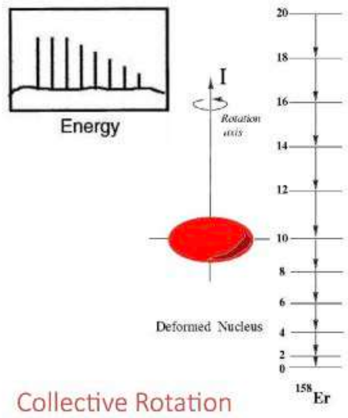

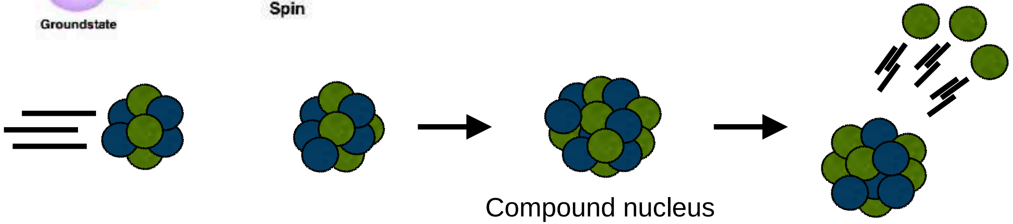

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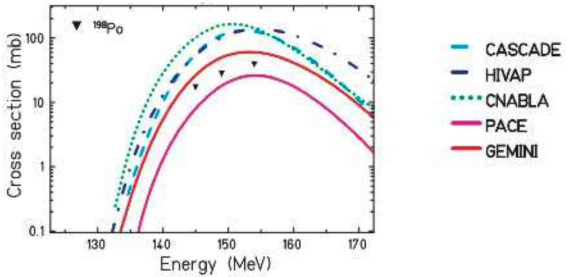

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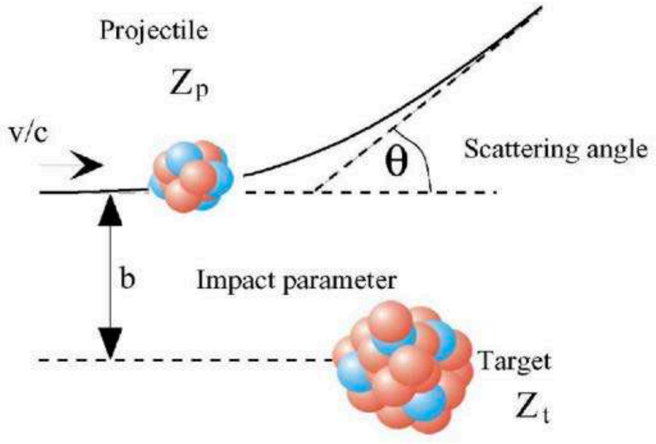
SCATTERING REACTIONS

Coulomb excitation & Coulomb dissociation



$$\sigma_{\pi\lambda} \approx \left(\frac{Z_{\text{pro}}e^2}{\hbar c}\right)^2 \frac{\pi}{e^2 b_{\min}^{2\lambda-2}} B(\pi\lambda, 0 \to \lambda) \begin{cases} 1/(\lambda-1) & \text{for } \lambda \geqslant 2 \\ 2\ln(b_a/b_{\min}) & \text{for } \lambda = 1 \end{cases}$$

Excitation of ^{34}Si to ^{34}SI*:
Extract: transition strengths
Deduce: deformation parameters

Reaction Rates for ^{26}Si(p,γ) from dissociation ^{27}P to ^{26}Si + p:
Extract: Survival probabilities, El strengths
Deduce: capture rates

KEY POINTS

- Safe < Coulomb barrier ~3 MeV/u
- Intermediate > Coulomb barrier
- Dissociation > 250 MeV/u
- Electromagnet probe (virtual photon flux)
  - Deformation
  - Capture rates
- Equipped for inverse kinematics

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SCATTERING REACTIONS

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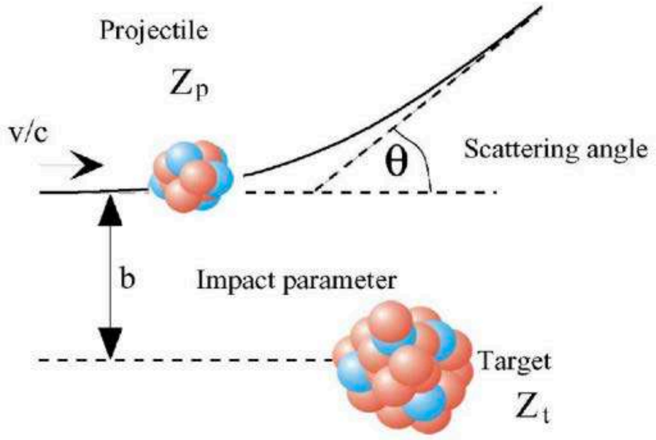

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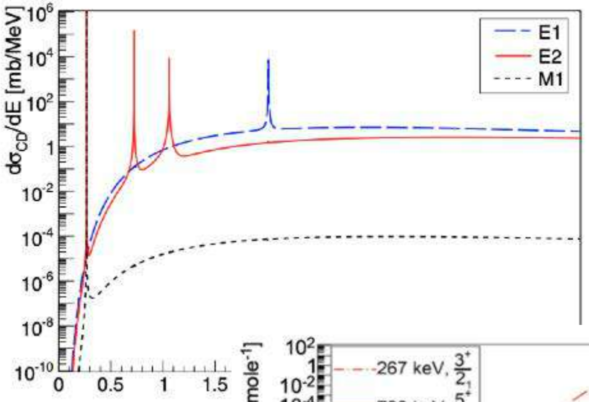
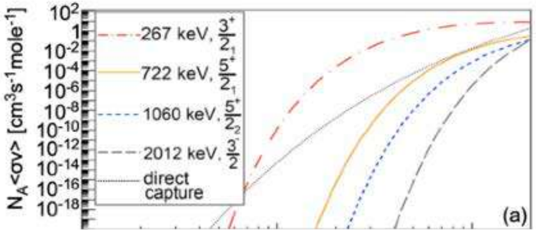
$$N_A\langle\sigma v\rangle^{\mathrm{tot}} = \sum_i N_A\langle\sigma v\rangle_i^{\mathrm{res}} + N_A\langle\sigma v\rangle^{\mathrm{dc}}$$





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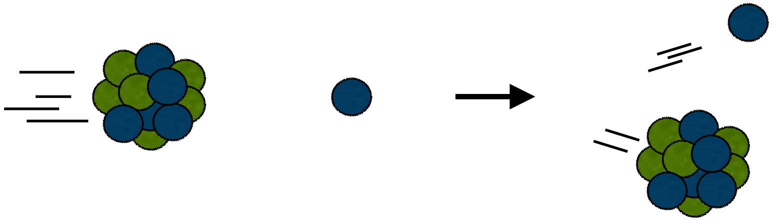
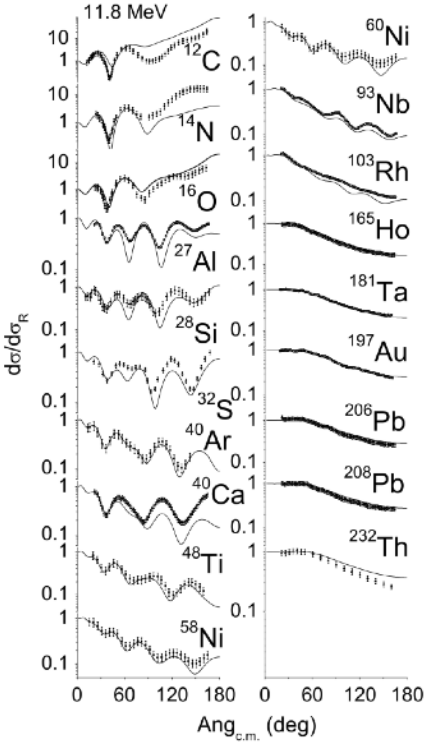
SCATTERING REACTIONS

Elastic & resonance scattering (p,p), (d,d), (α,α)





Extract: angular distributions, analog states
Deduce: sp states, optical model parameters, resonance/decay widths
Tools: R-Matrix, optical model calculations [DWBA, coupled channels, etc…]

KEY POINTS

- Few to hundreds MeV/u
- Sensitive to probe: proton, deuteron, alpha, etc.
- Scan in angle and/or energy
- Resonance params on analog states
  - sp structure
  - Widths
- Key in development of optical model description of nuclear potential

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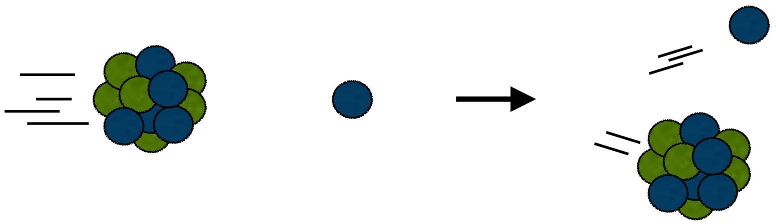

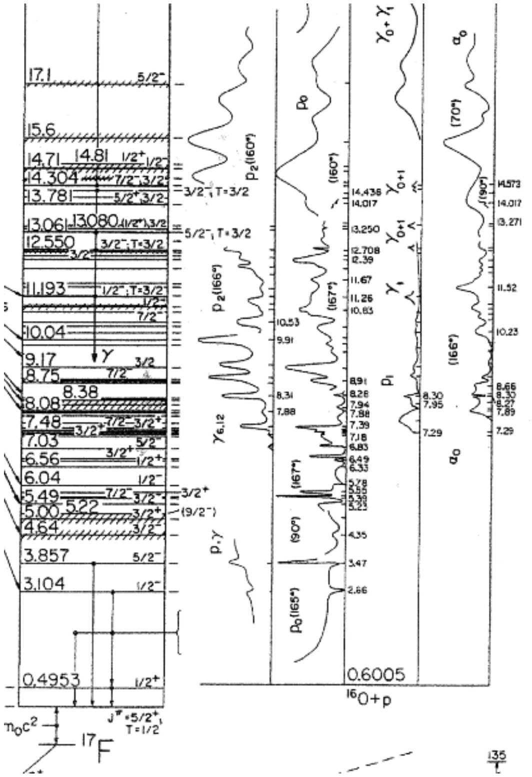

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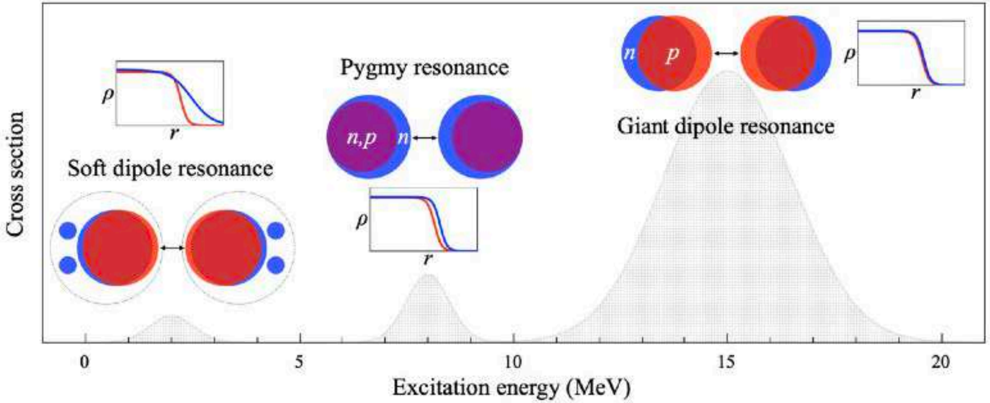
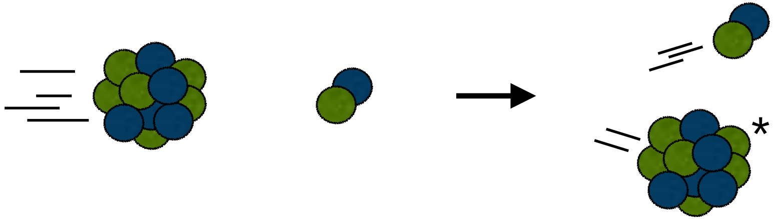
SCATTERING REACTIONS

Inelastic scattering: (p,p'), (d,d'), (α,α'), (^{12}C,^{12}C')





Extract: Distributions, resonance strengths
Deduce: unique excitation modes, clustering prob., isoscalar / isovector modes, deformation length
Tools: R-Matrix, optical model calculations [DWBA, CC, etc…]

KEY POINTS

- Few to 100's of MeV/u
- Selective to probe:
  - Proton - isovector
  - Deuteron - isoscalar
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- Cluster structures
- Collective features in nuclei

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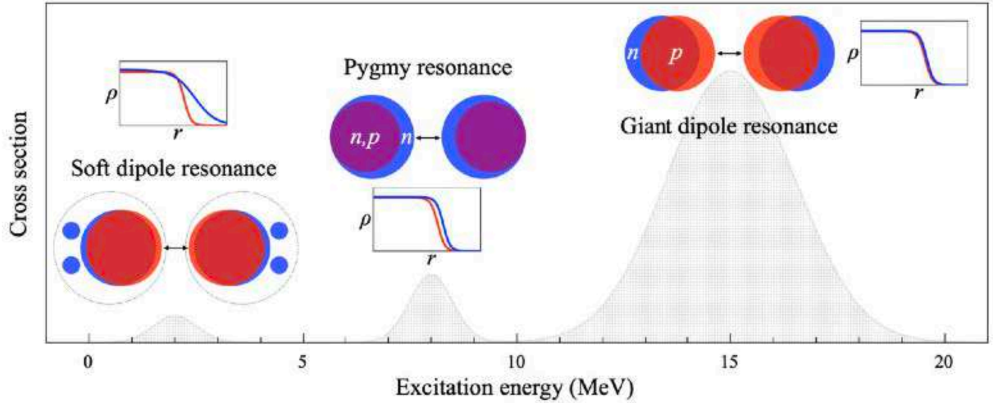

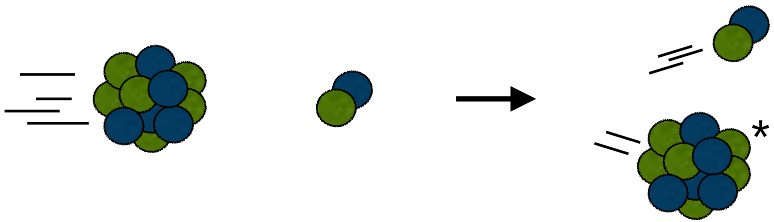

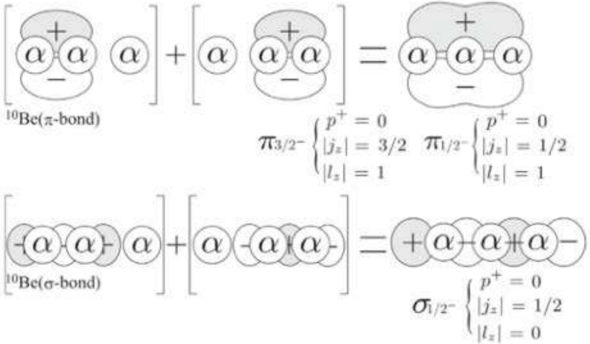

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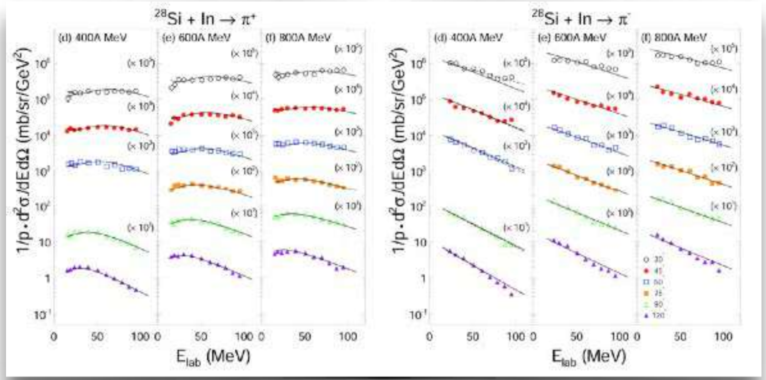
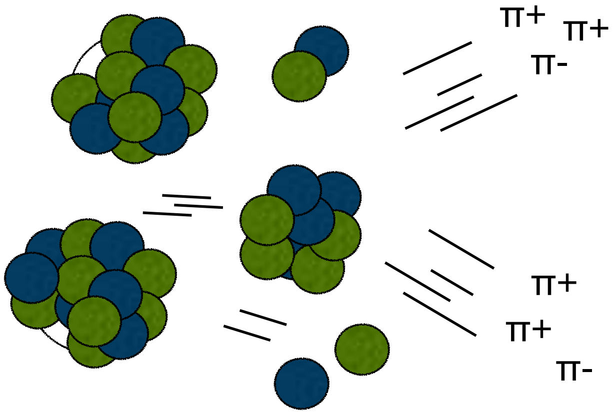
HEAVY-ION COLLISIONS

$^{A}Sn + {}^{A}Sn$, $^{A}Ni + {}^{A}Ni$





Extract: pion production, +/- asymmetry
Deduce: Symmetry energy, equation of state

KEY POINTS

- >350 MeV/u
- Pion production threshold >280 MeV
- Hot dense matter
  - Stars
- Pion production as a test of the symmetry energy

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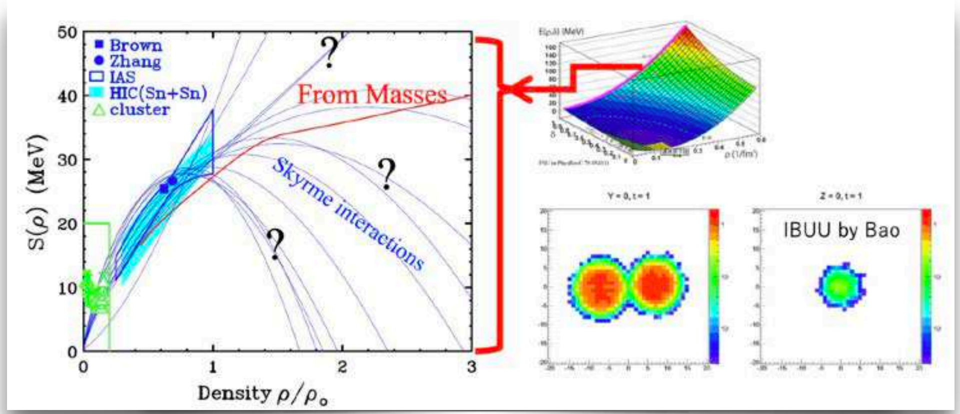

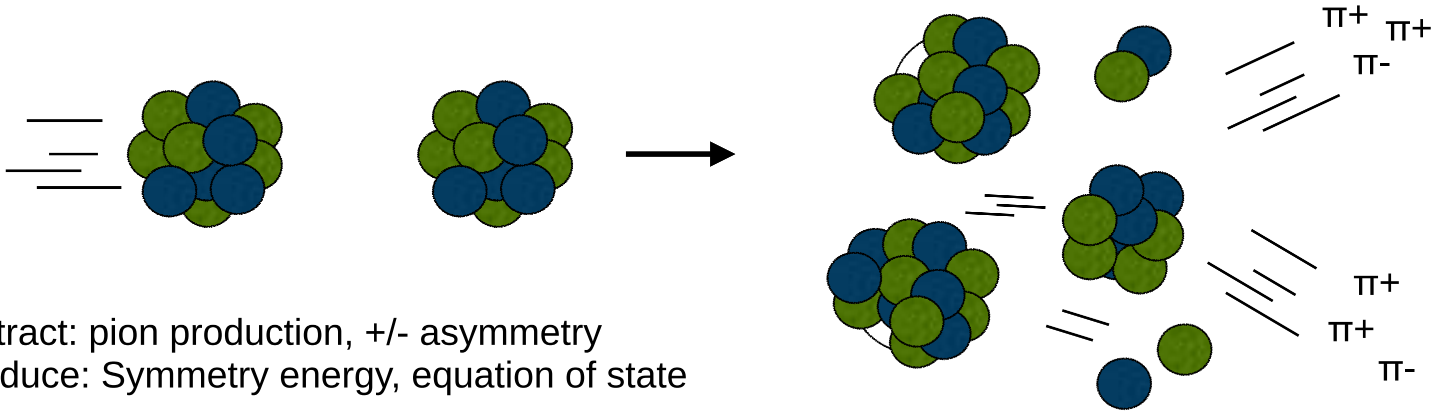

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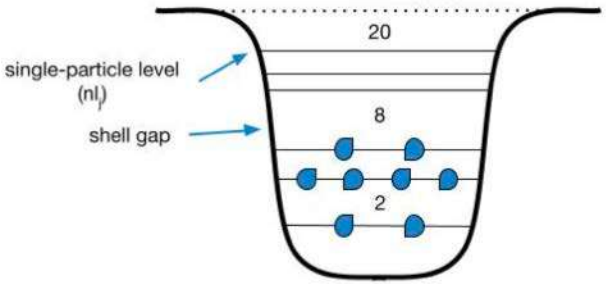
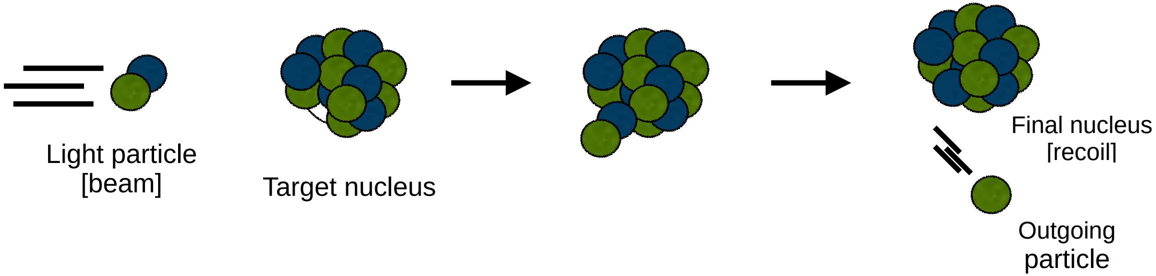
DIRECT REACTIONS

Single-nucleon transfer: (d,p), (^{3}He,d), (^{13}C,^{12}C)





Extract: orbital angular momenta, spectroscopic overlaps, energy centroids
Deduce: nucleon occupancies, single-particle energies, two-body matrix elements
Tools: Distorted wave Born approximation [DWBA], Coupled Channels, etc…]

KEY POINTS

- ~3 - 20 MeV/u
- Highly selective
- Direct probe of single-particle aspects
- Surrogate (p,γ) / (n,γ)
- resurgence in the RIB era
- Beam production

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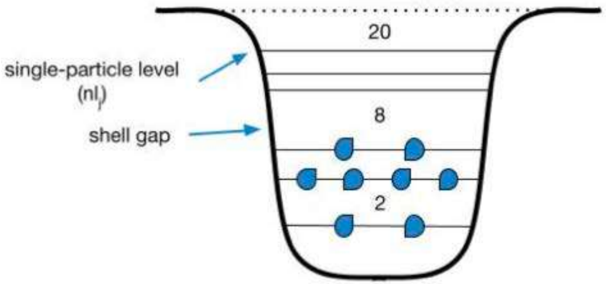
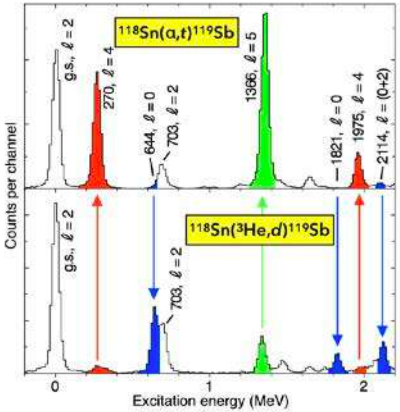
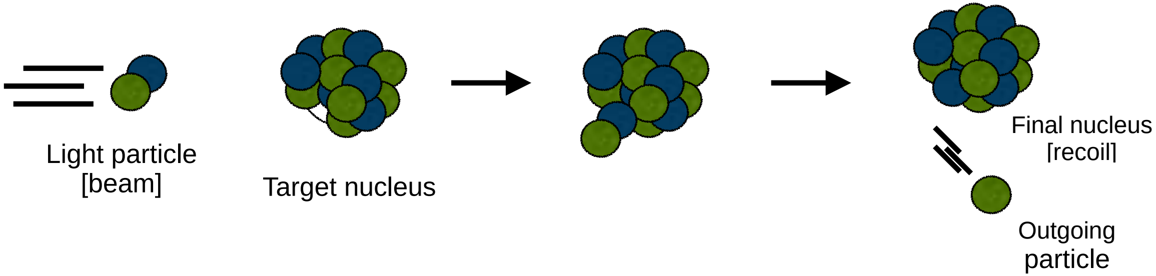
Single-nucleon transfer: (d,p), (^{3}He,d), (^{13}C,^{12}C)







Extract: orbital angular momenta, spectroscopic overlaps, energy centroids
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Tools: Distorted wave Born approximation [DWBA], Coupled Channels, etc…]

KEY POINTS

- ~3 - 20 MeV/u
- Highly selective
- Direct probe of single-particle aspects
- Surrogate (p,γ) / (n,γ)
- resurgence in the RIB era
- Beam production

DIRECT REACTIONS

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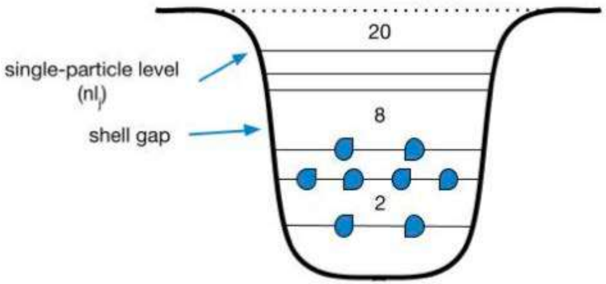

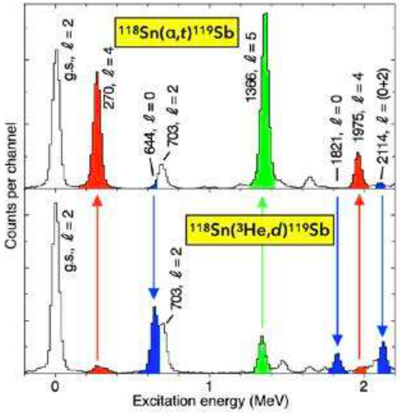

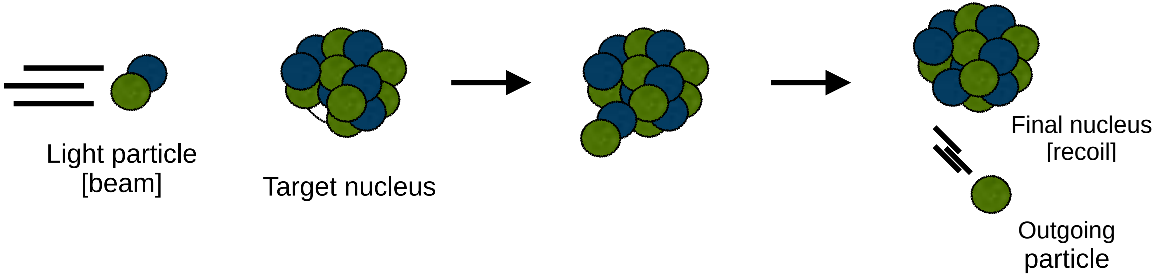

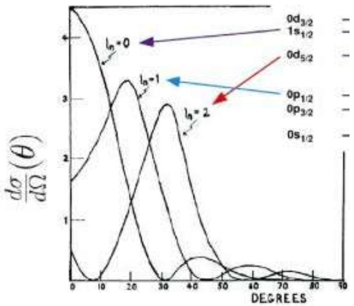

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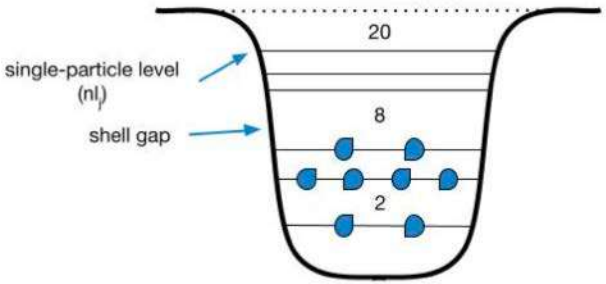

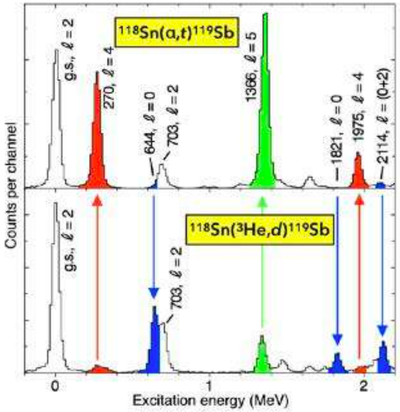

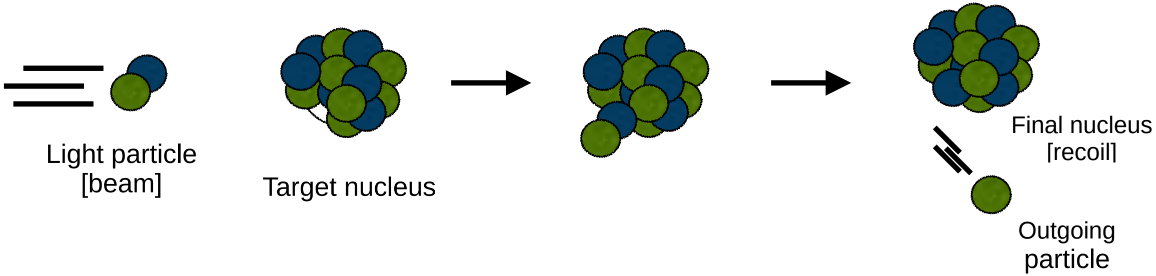

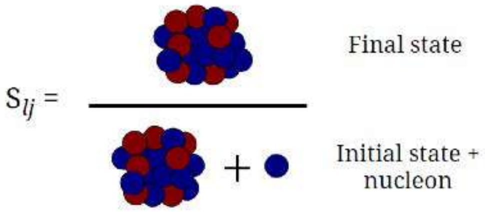

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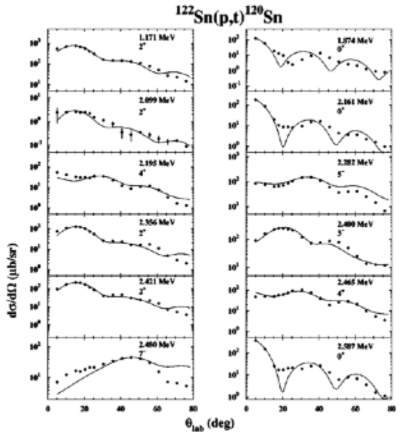
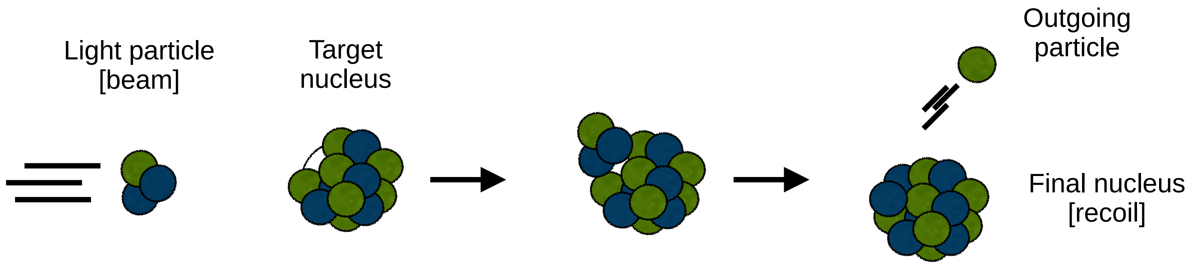
Multi-nucleon transfer e.g., (p,t), (^{7}Li,t), (^{6}Li,p)





Extract: final state angular momenta, spectroscopic overlaps, resonance widths
Deduce: resonance strengths, reaction rates, pair occupancies, collectivity
Tools: Distorted wave Born approximation [DWBA], Coupled Channels, etc…]

KEY POINTS

- ~3 - 20 MeV/u
- selective
- Alpha-like transfer: (α,γ), (α,X)
- Sensitive to paring (2n)
- Exploratory - cluster / rotational states
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DIRECT REACTIONS

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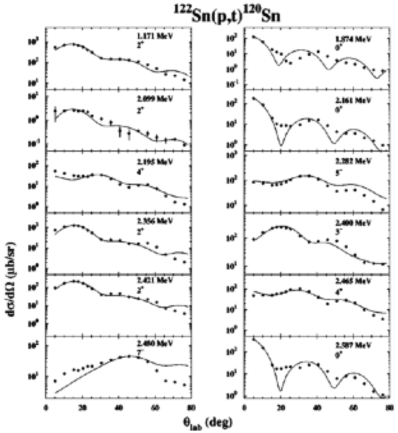

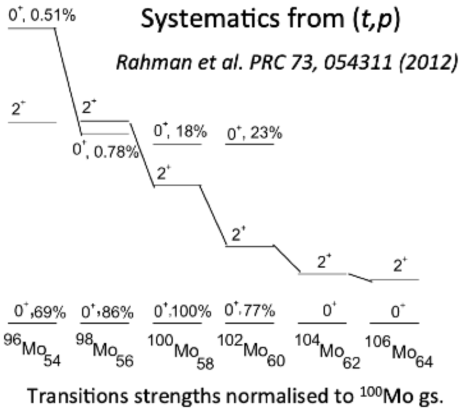

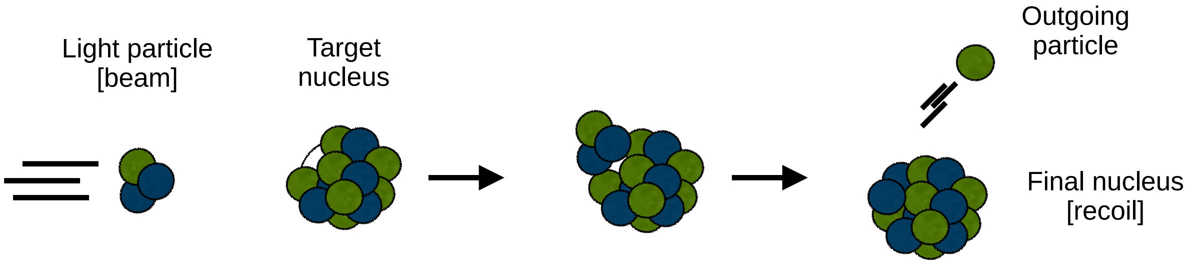

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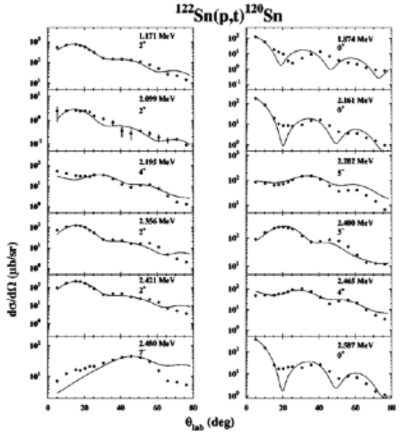

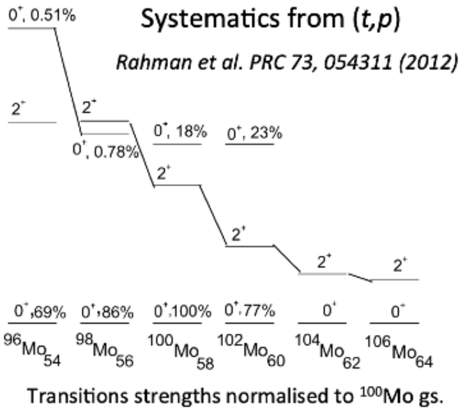

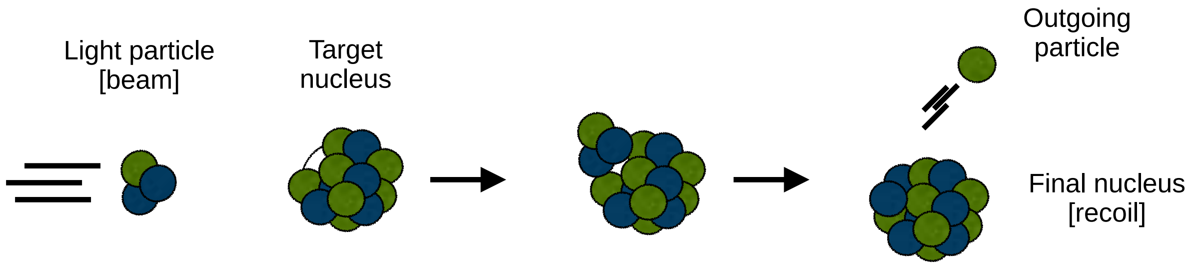

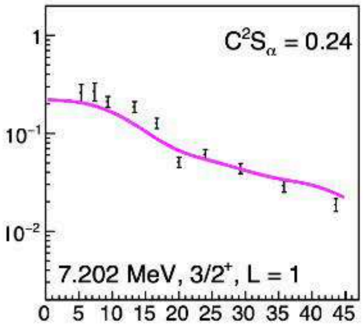

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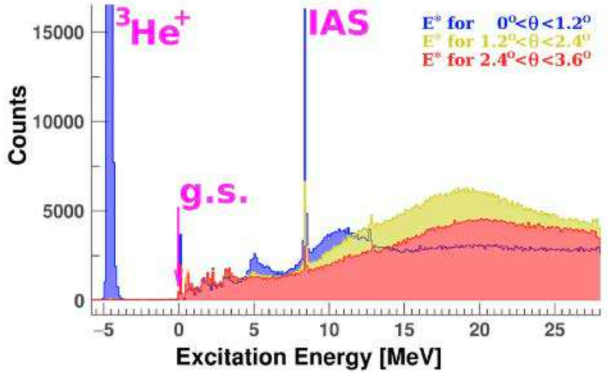
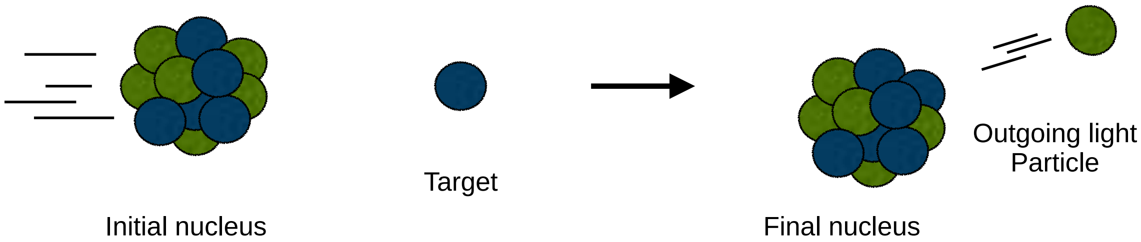
DIRECT REACTIONS

Charge-exchange: (p,n), (^{7}Li,^{7}Be)





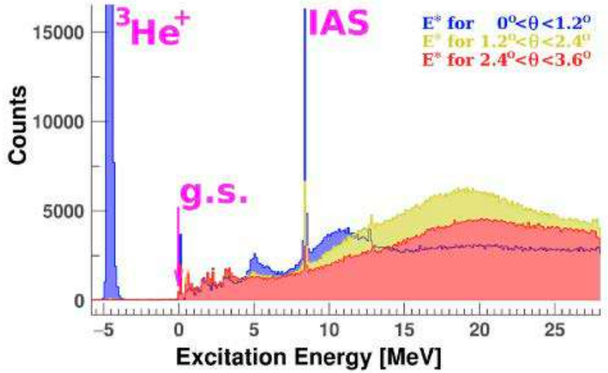
Extract: angular distributions, isobaric analog states
Deduce: Gamow-Teller strength distributions, level densities, g-strength functions
Tools: Distorted wave Born approximation [DWBA], Coupled Channels, etc…]

KEY POINTS

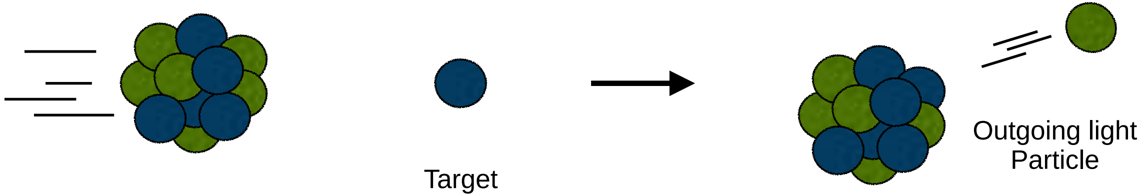
- ~5 - 400 MeV/u
- Isobaric analog states
- Gamow-Teller distributions
  - Astrophysics
  - Neutrino physics
- Beam production method

DIRECT REACTIONS

Charge-exchange: (p,n), (^7Li,^7Be)



$$B(GT_{\pm}) = \frac{1}{2J_i + 1} \left| \left\langle \Psi_f \left\| \sum_{j=1}^{A} \boldsymbol{\sigma}_j \boldsymbol{\tau}_{\pm,j} \right\| \Psi_i \right\rangle \right|^2$$



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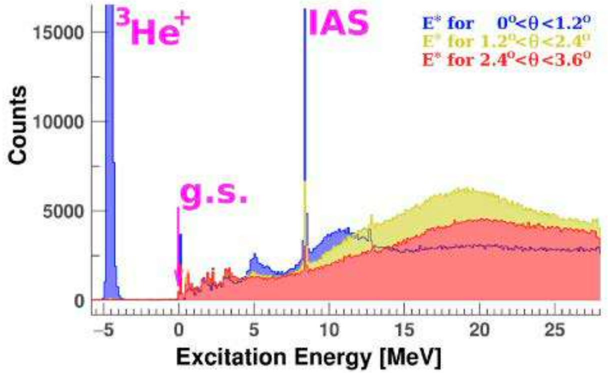

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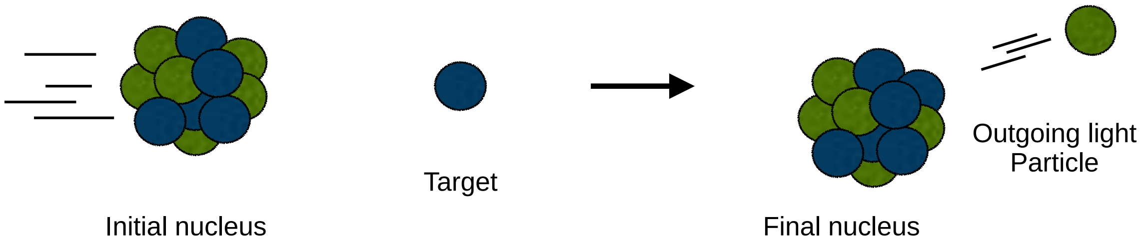

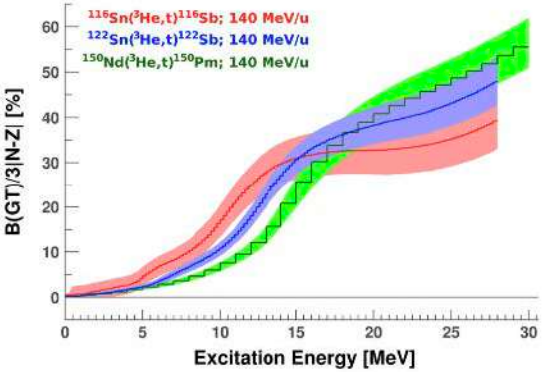

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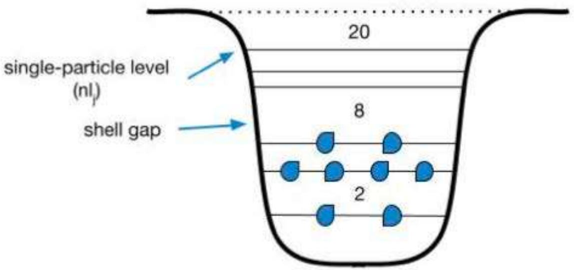
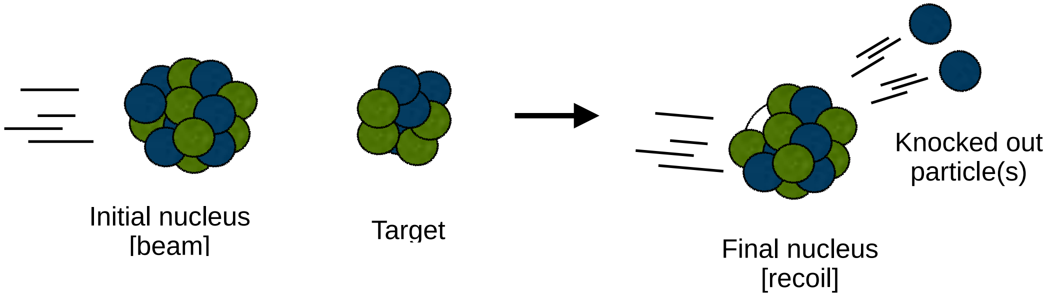
DIRECT REACTIONS

Quasi-free & nucleon knockout: (p,2p), (^{9}Be, -2p)





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KEY POINTS

- >50 MeV/u knockout
- >350 MeV/u quasi-free knockout
- selective to hole states
- Study of overlaps w/ established tools
- Pairing force
- Efficient in the RIB era

DIRECT REACTIONS

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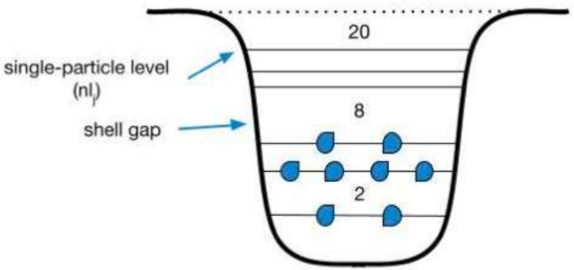

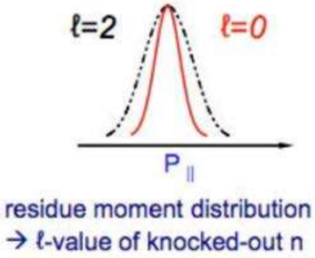

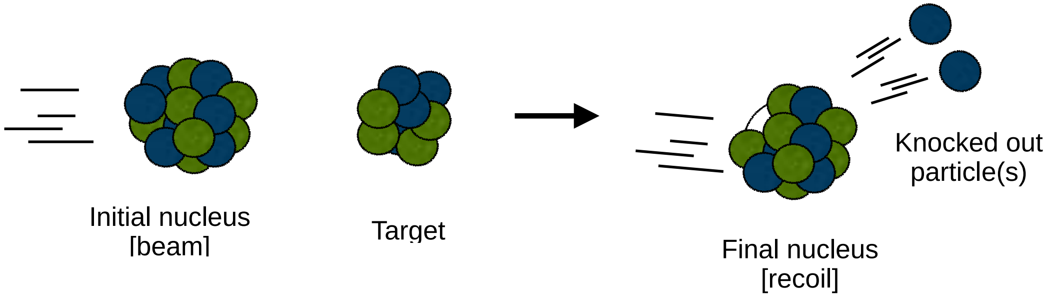

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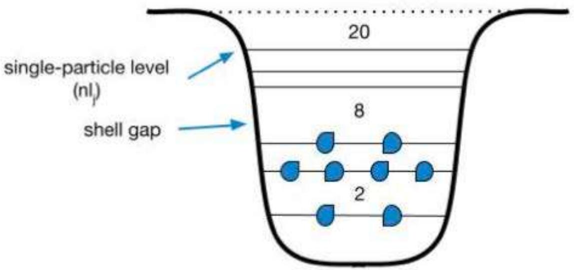

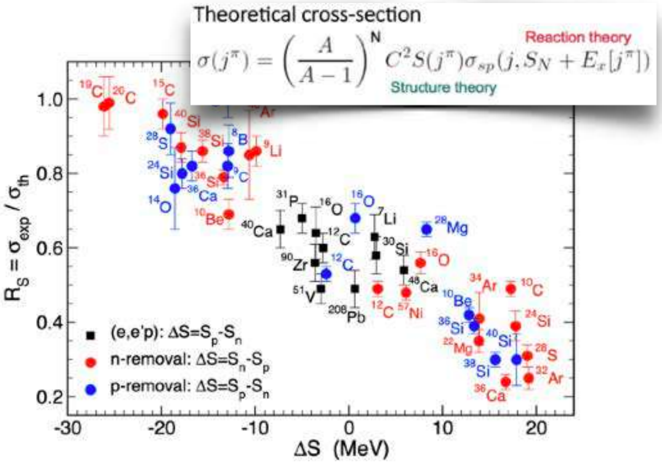

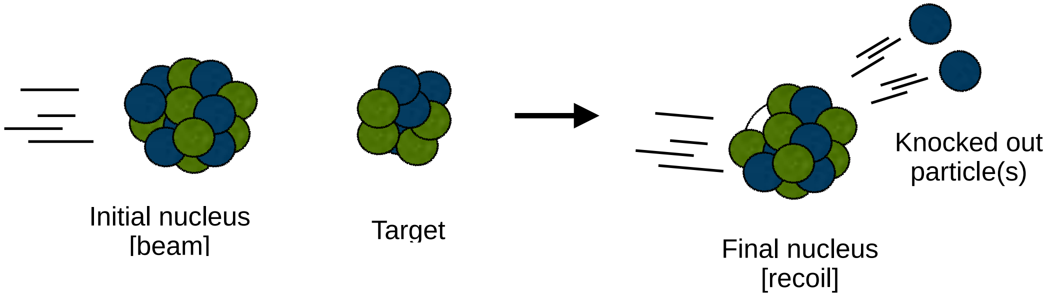

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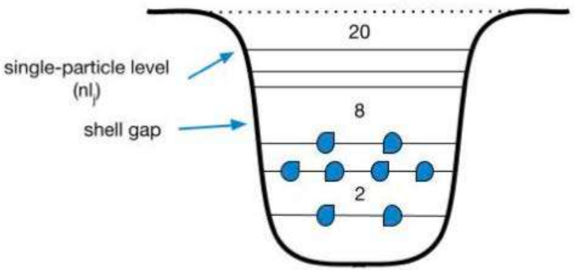

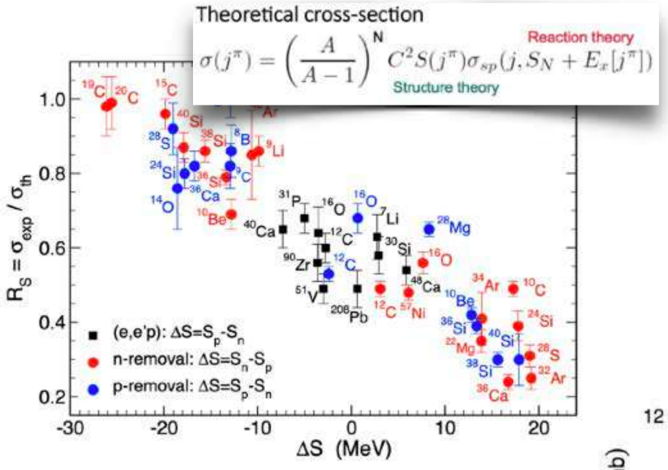

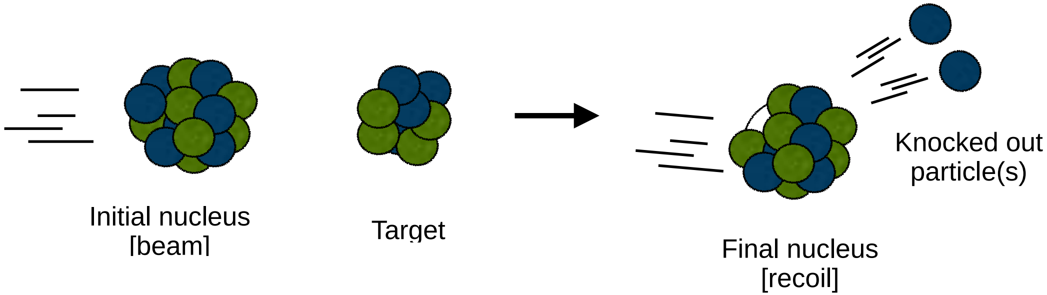

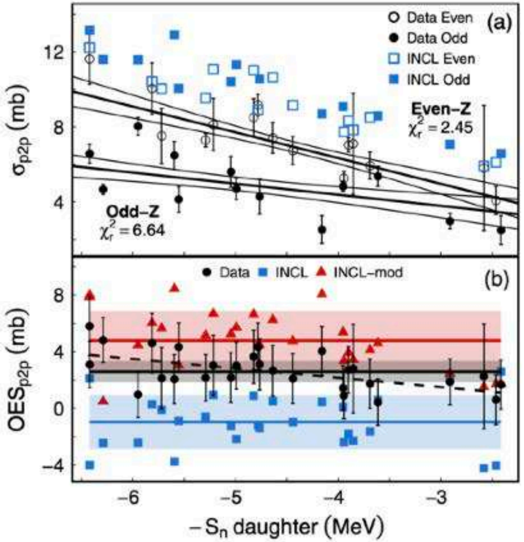

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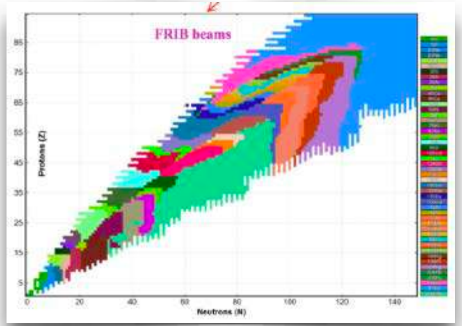
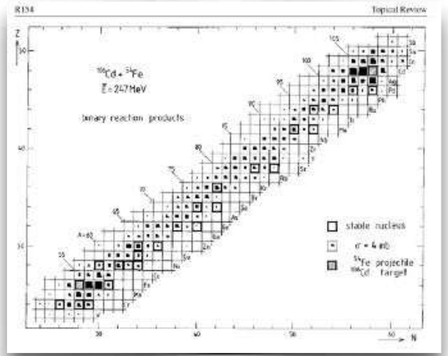
INTERMEDIATE ENERGY FRAGMENTATION

Create & populate isotopes at the extremes >100 MeV/u



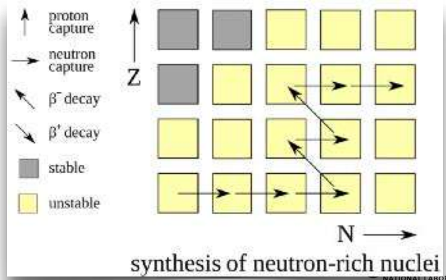
DEEP INELASTIC REACTIONS

Production of exotic nuclei via multi-nucleon removal + exchange



CAPTURE REACTIONS

p,n,α cross sections key to proliferation & astrophysics

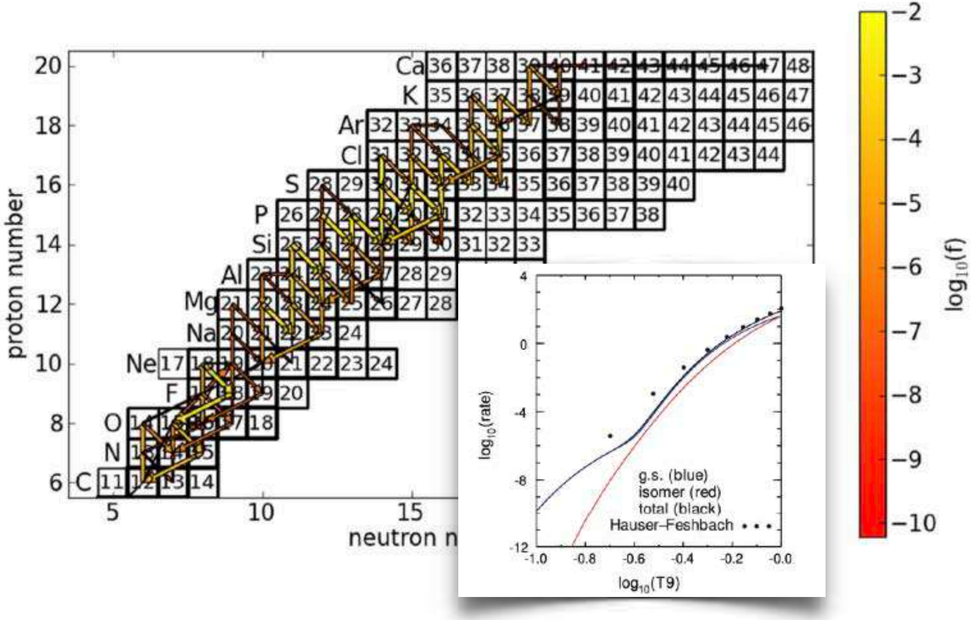


COMPLEMENTARITY OF NUCLEAR REACTIONS

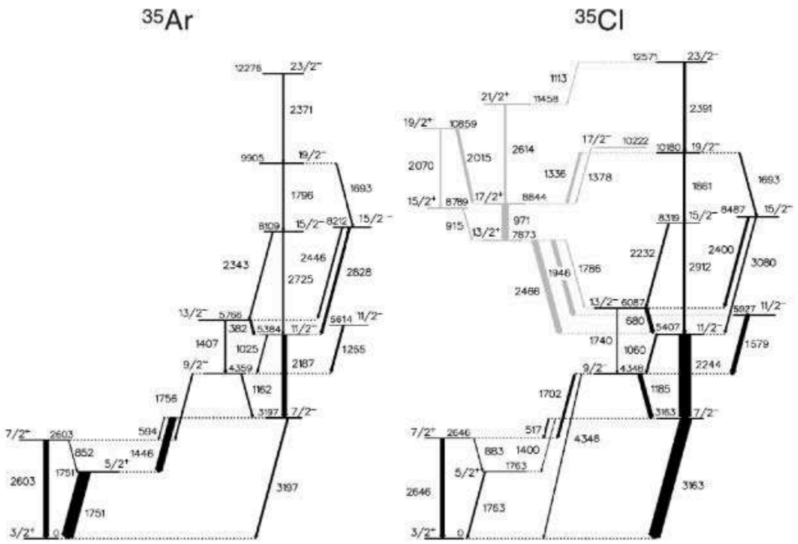
ISOMERIC BEAM PRODUCTION

Desire a beam of ^{34}Cl residing in either (or both) isomeric & ground states

^{34g,m}Cl(p,γ) rates influence ^{34}S production
in classical novae impacting solar grain classification



A=35 Mirror Pair
Partial Level & Decay Schemes



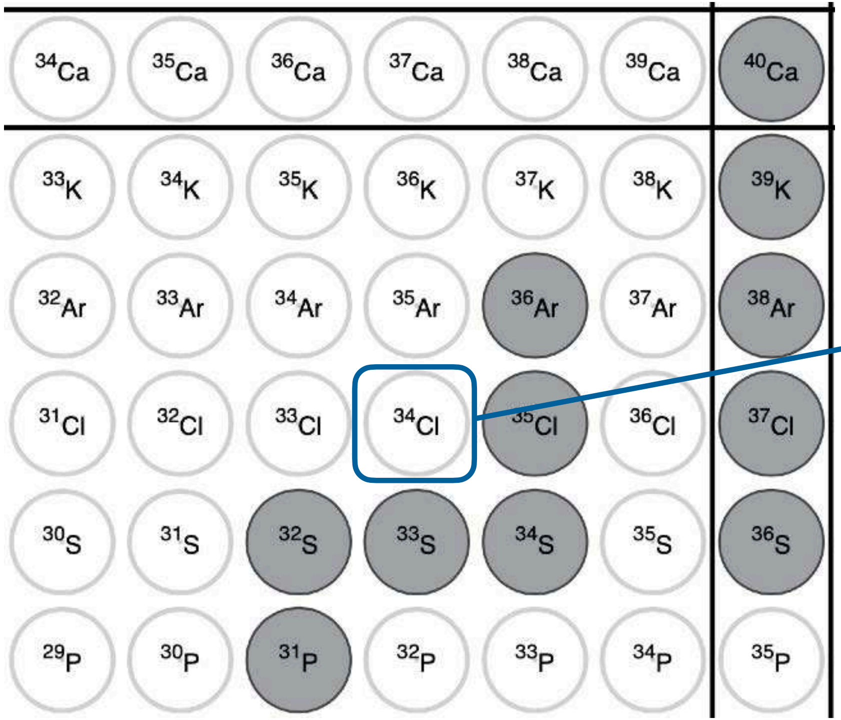
^{34g,m}Cl(d,p) mirror reaction is of interest

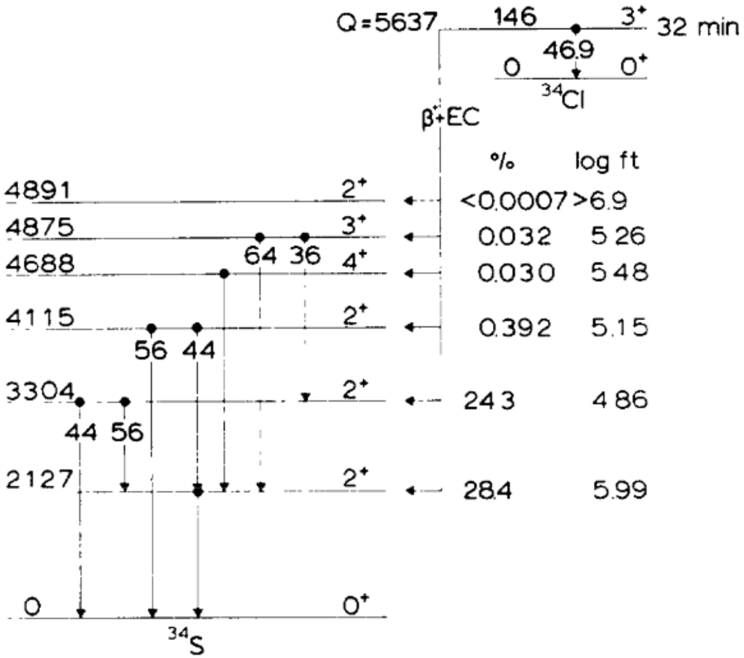
Argonne NATIONAL LABORATORY

ISOMERIC BEAM PRODUCTION

Sub-set of beam production options

^{34m,g}Cl (Z=17, N=17)





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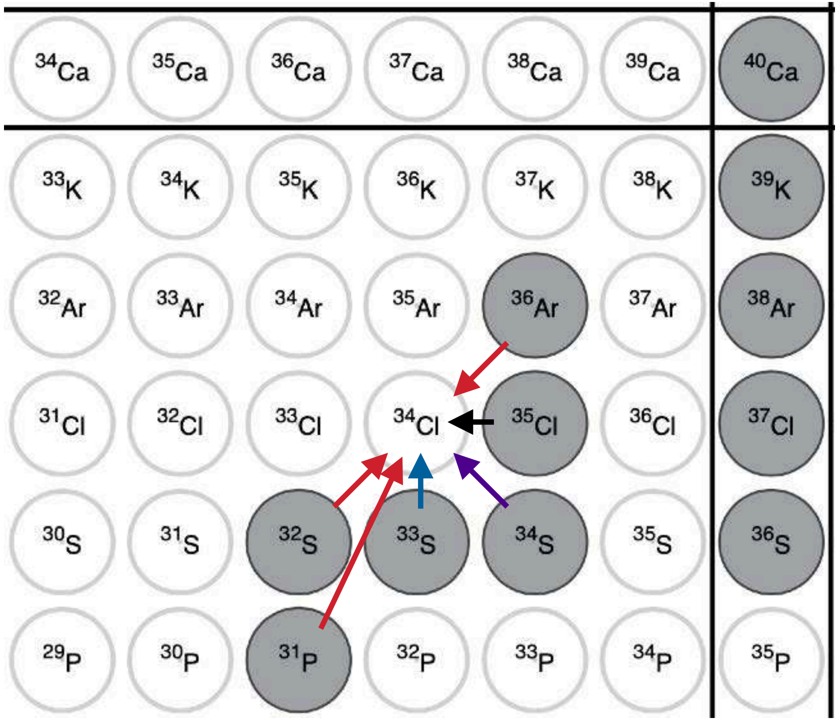
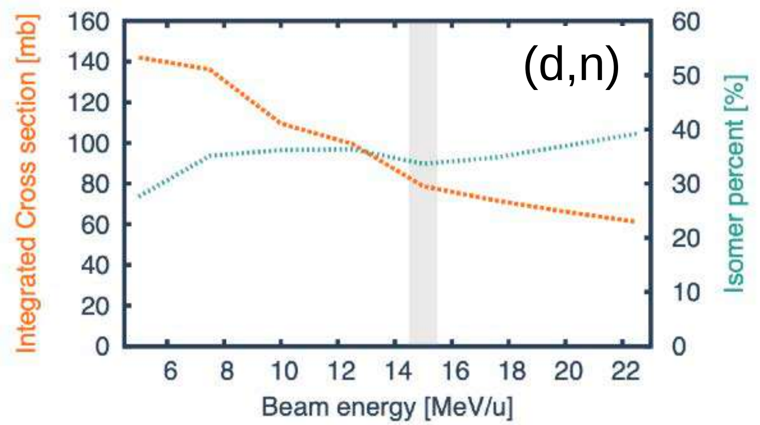


Transfer Reactions

- proton adding: (d,n), (^{3}He,d)
- Neutron removal: (d,t), (3He,α)
- Charge exchange: (p,n)
- Multi-nucleon: (d,α), (α,d), (α,n)



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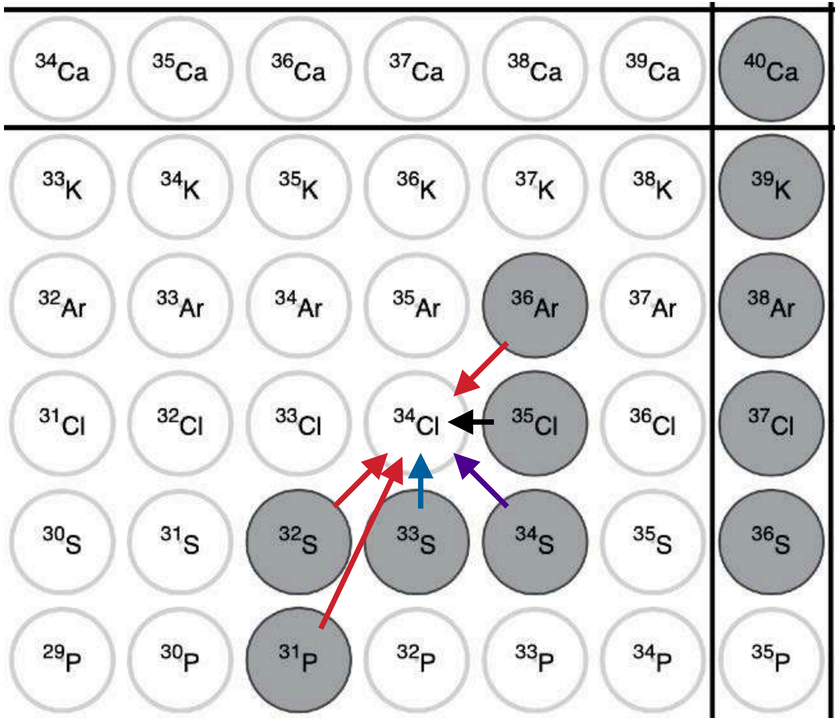

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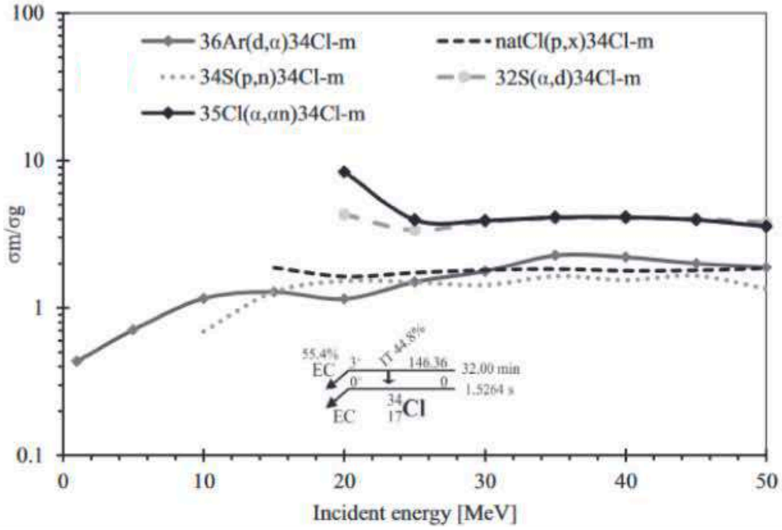

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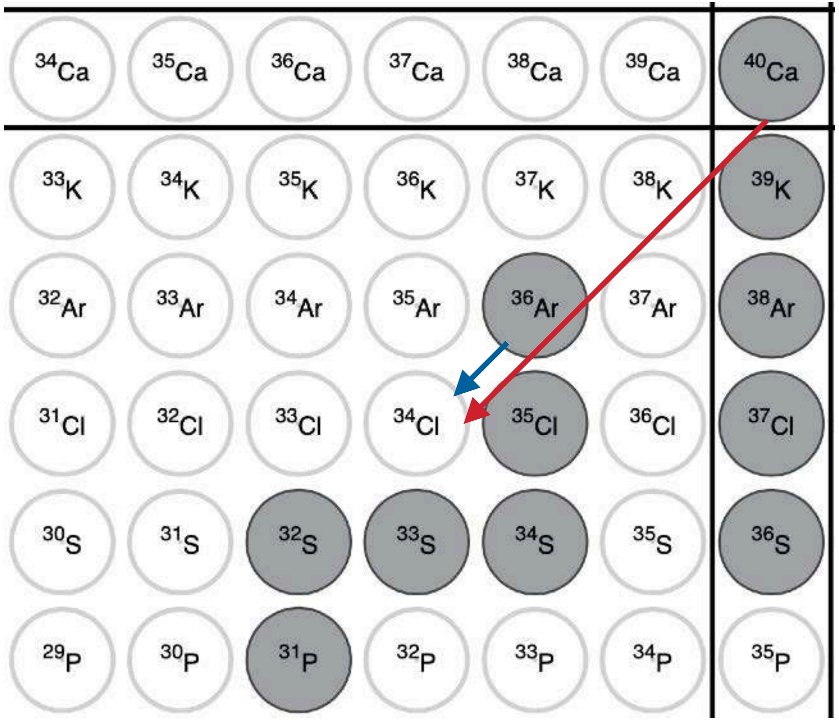
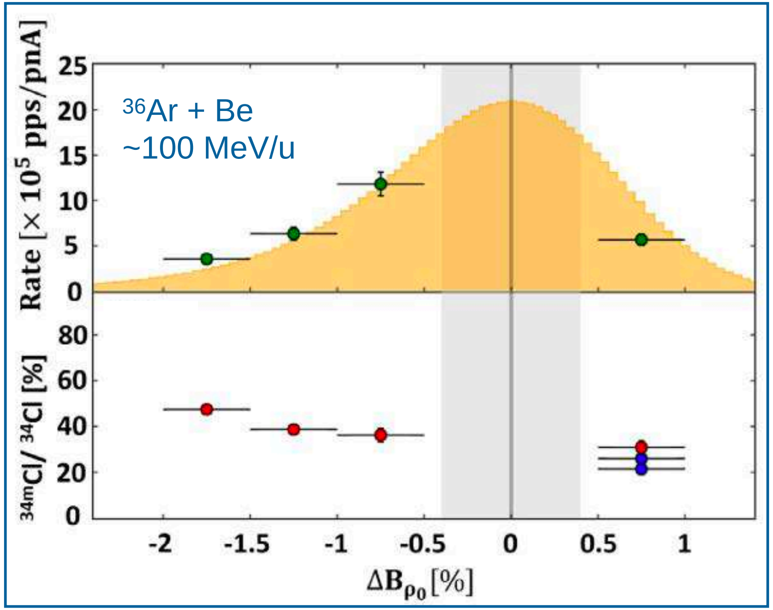


Fragmentation >100 MeV/u

- ^{36}Ar + Be: pn removal
- ^{40}Ca + Be: αpn removal



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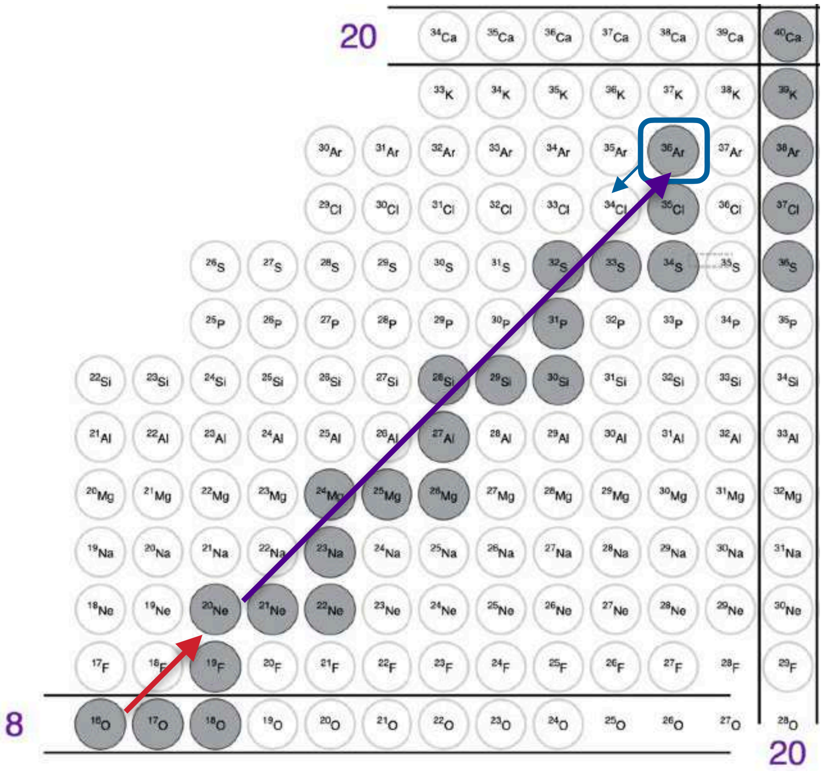
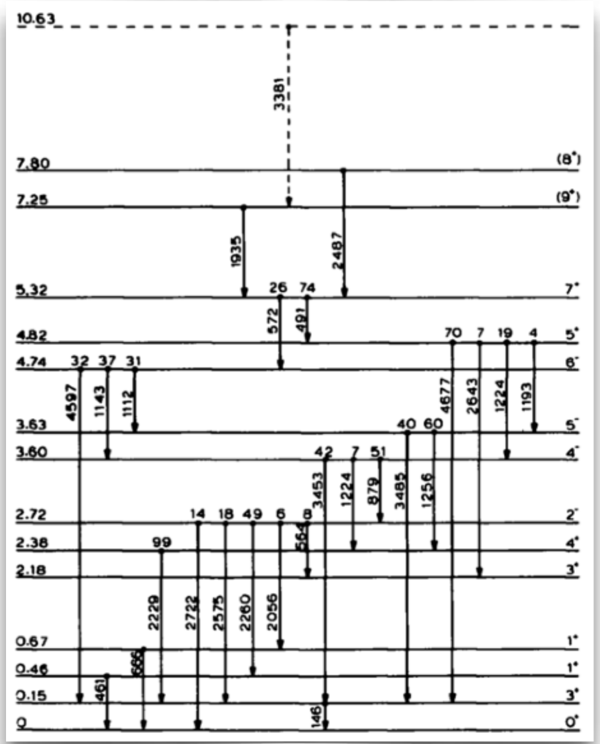


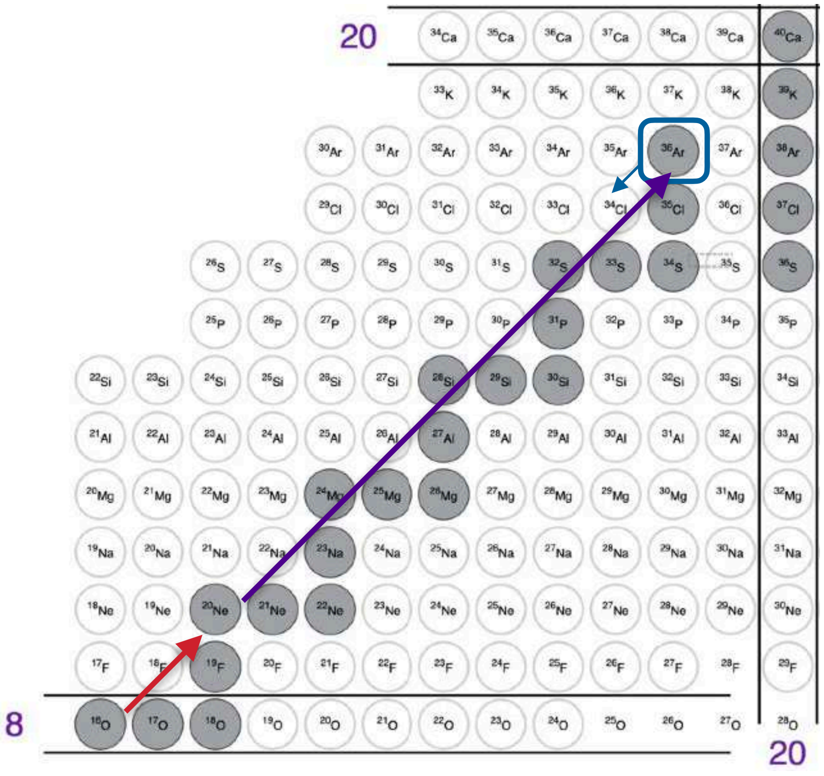
Fusion Evaporation

- $^{16}O(^{20}Ne,pn)$, $^{24}Mg(^{12}C,pn)$, $^{27}Al(^{12}C,\alpha n)$



ISOMERIC BEAM PRODUCTION

Sub-set of beam production options



Fusion Evaporation

- $^{16}O(^{20}Ne,pn)$, $^{24}Mg(^{12}C,pn)$, $^{27}Al(^{12}C,\alpha n)$

Other Possible Reactions:

- Resonance scattering $^{33}S(p,\gamma)$
- Electron capture
- Spallation

KEY ASTROPHYSICS REACTIONS RATES

Requires knowledge of resonance energies, spins, widths (overlaps), …

thermonuclear reaction rate:

$$\langle \sigma v \rangle = \sqrt{\frac{8}{\pi\mu}} \frac{1}{(kT)^{3/2}} \int_0^\infty \boxed{\sigma(E)} E e^{-E/kT} dE,$$

resonance capture

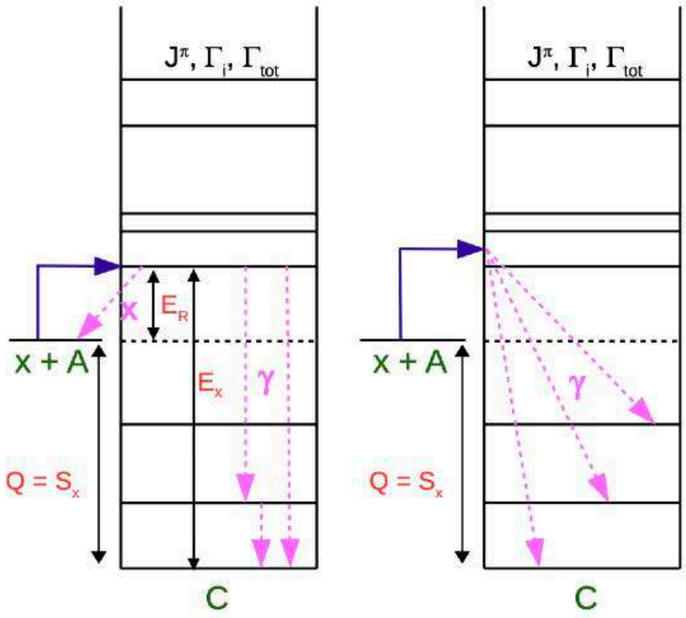
$$\boxed{\sigma(E)} = \frac{\lambda^2}{4\pi} \frac{2J_{C^*}+1}{(2J_A+1)(2J_x+1)} \frac{\Gamma_x \Gamma_y}{(E-E_r)^2+\Gamma^2/4}$$

partial width

$$\Gamma_x = C^2 S_x \times \Gamma_x^{s.p.}$$

s-factor

$$S(E) = \boxed{\sigma(E)} \times E \times e^{2\pi\eta},$$



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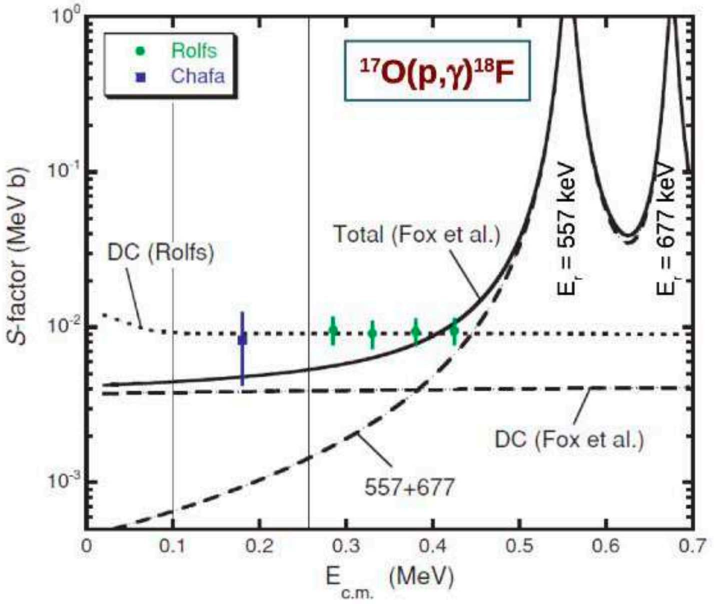
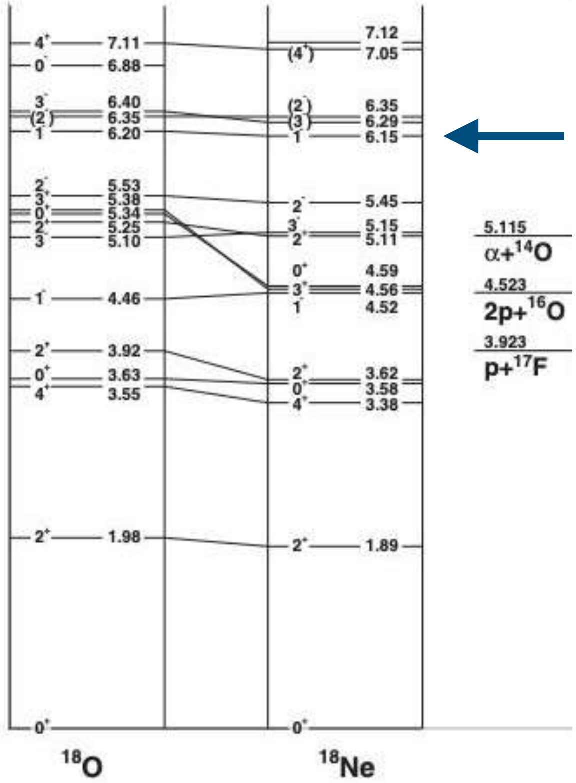
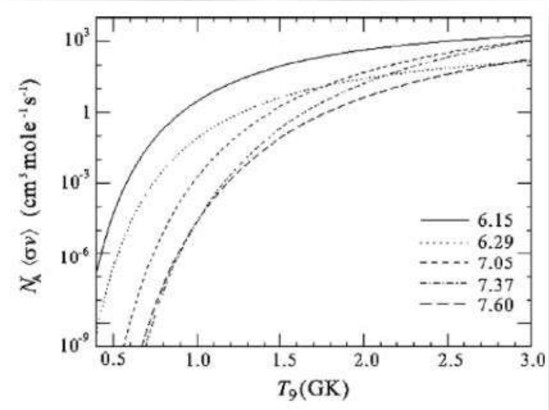


$^{14}O(\alpha,p)^{17}F$ REACTION RATE

hot-CNO breakout in type-I x-ray bursts





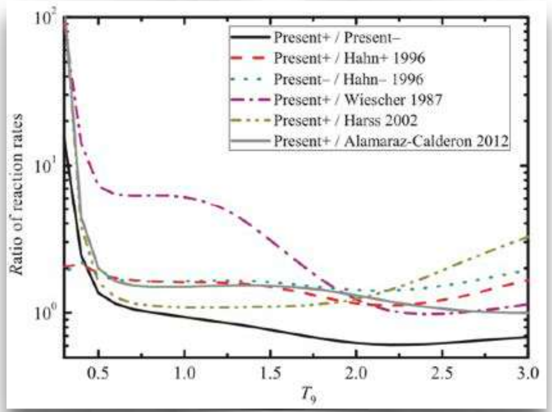
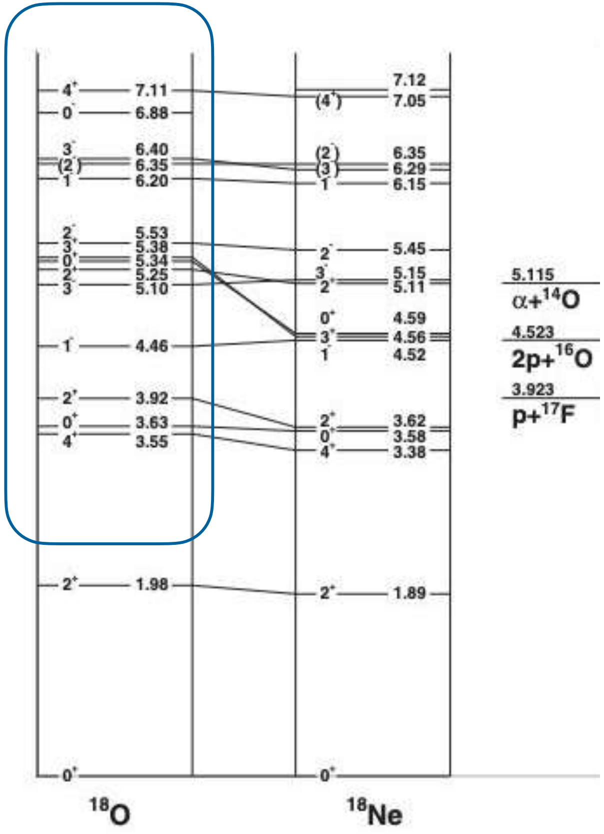


TABLE II. Resonance parameters adopted in the calculation of the $^{14}O(\alpha,p)^{17}F$ reaction rate.

E_x (MeV)[a]	E_{res} (MeV)[a]	J^π	Γ_α (eV)	Γ_p (keV)	$\Gamma_{p'}$ (keV)	Γ (keV)	$\omega\gamma$ (MeV)
5.153 ± 0.01	0.039	3^-	4.3×10^{-52}[a]	1.7[a]		$\leqslant 15$[a]	3.0×10^{-57}
6.150 ± 0.01	1.036	1^-	3.9 ± 1.0[b]	37.8 ± 1.9[c]	15.9 ± 0.7[c]	53.7 ± 2.0[c]	1.2×10^{-5}
6.286 ± 0.01	1.172	3^-	0.34[a]	20 ± 15[d]		20 ± 15[d]	2.4×10^{-6}
7.05 ± 0.03	1.936	4^+	22.6 ± 3.2[e]	90 ± 40[f]		90 ± 40[f]	2.0×10^{-4}
7.35 ± 0.02	2.236	2^+	40 ± 30[f]	70 ± 60[f]		70 ± 60[f]	2.0×10^{-4}
7.62 ± 0.02	2.506	1^-	1000 ± 120[f]	72 ± 20[f]	<2[f]	75 ± 20[f]	3.0×10^{-3}
7.94 ± 0.01	2.826	3^-	$(11 \pm 6.6) \times 10^3$[g]	35 ± 15[g]	9.0 ± 5.6[g]	55 ± 20[g]	6.2×10^{-2}

^{14}O(A,P)^{17}F REACTION RATE

hot-CNO breakout in type-I x-ray bursts



Exploring the mirror states in ^{18}O

- ^{17}O(d,p): neutron transfer
  - C^2S values of mirror state, E, π
- ^{16}O(t,p): 2n transfer
  - E, π of mirror levels
- ^{14}C(^{6}Li,d): alpha transfer
  - Alpha width of mirror state

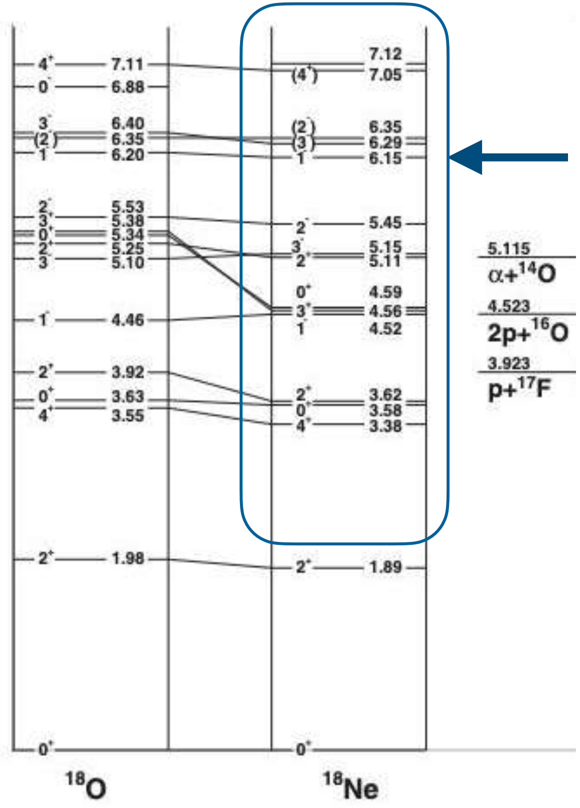
TABLE I. Results of the reaction ^{14}C(^{6}Li,d)^{18}O(6.20 MeV).

Quantity	Value	
$d\sigma/d\sigma$[a]	58.2(2.4) μb/sr	
After CN subtraction	45.2(5.5) μb/sr	
	$q=7$	$q=9$
S_α	0.23(4)	0.19(3)
$\Gamma_{\alpha sp}$(^{18}Ne) (eV)	17 eV	26 eV
Γ_α (^{18}Ne) (eV)	3.9(6)	4.9(8)
	3.9(1.0)[c]	4.9(1.2)[c]
Γ_α other (eV)[b]	3.2^{+5}_{-2}	

[a] At an incident energy of 20 MeV and a c.m. angle of 13.9°.
[b] Reference [6].
[c] Includes 20% target thickness uncertainty.

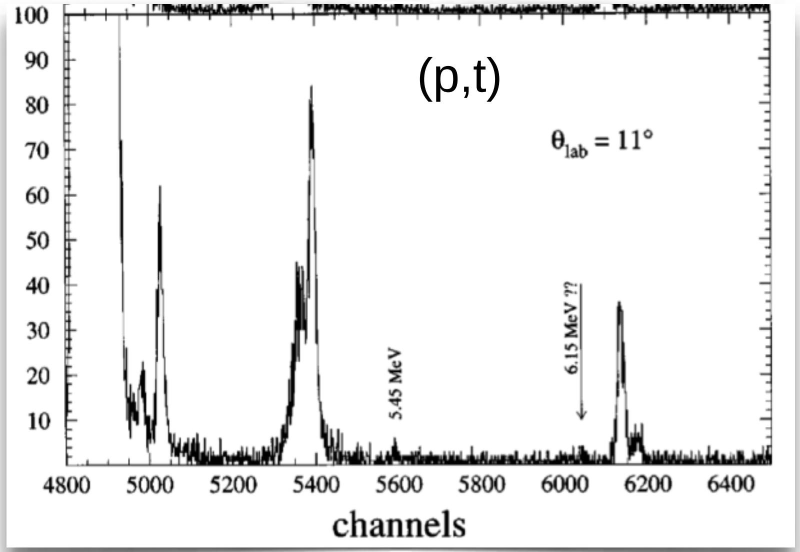
^{14}O(A,P)^{17}F REACTION RATE

hot-CNO breakout in type-I x-ray bursts



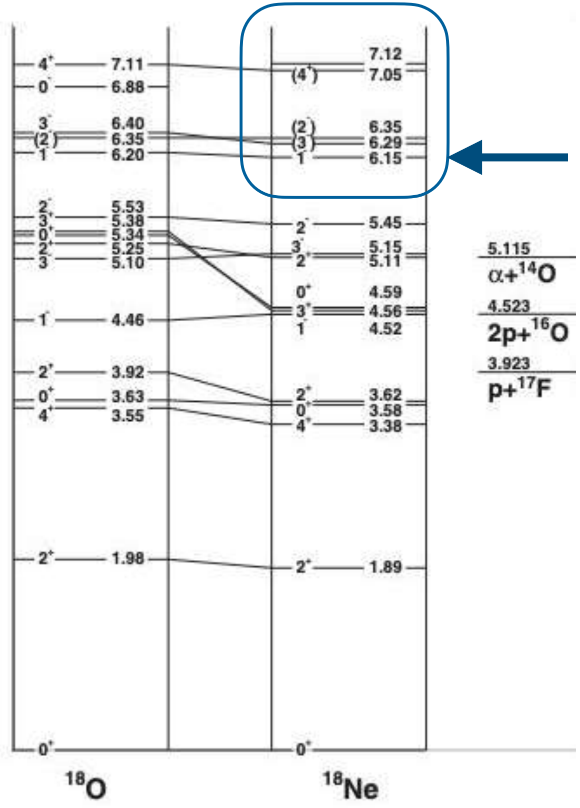
Multi-particle transfer reactions

- ^{16}O(^{3}He,n): 2p transfer
- ^{12}C(^{12}C,^{6}He): exotic transfer
- ^{20}Ne(p,t): -2n removal
  - Selective reactions
  - Determine resonance E, total widths (Γ), L(J), π



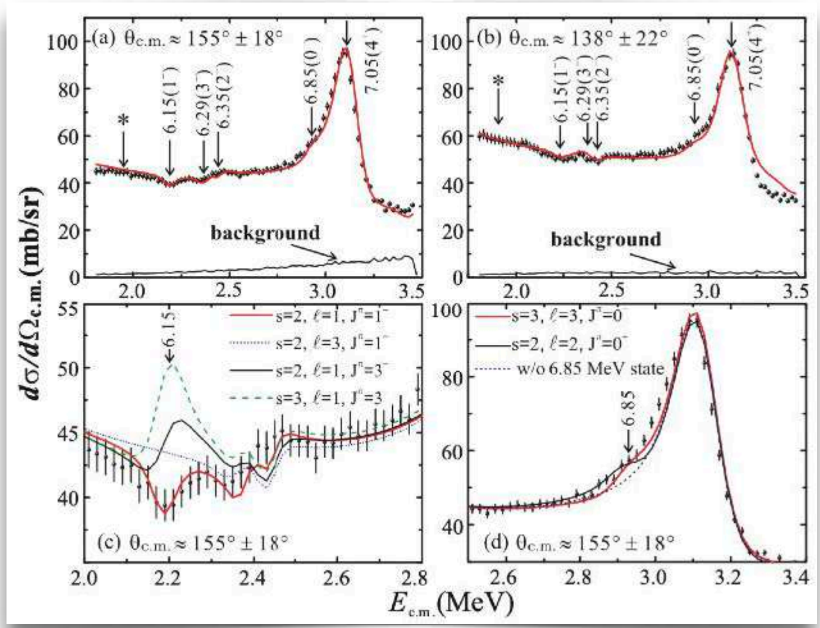
^{14}O(A,P)^{17}F REACTION RATE

hot-CNO breakout in type-I x-ray bursts



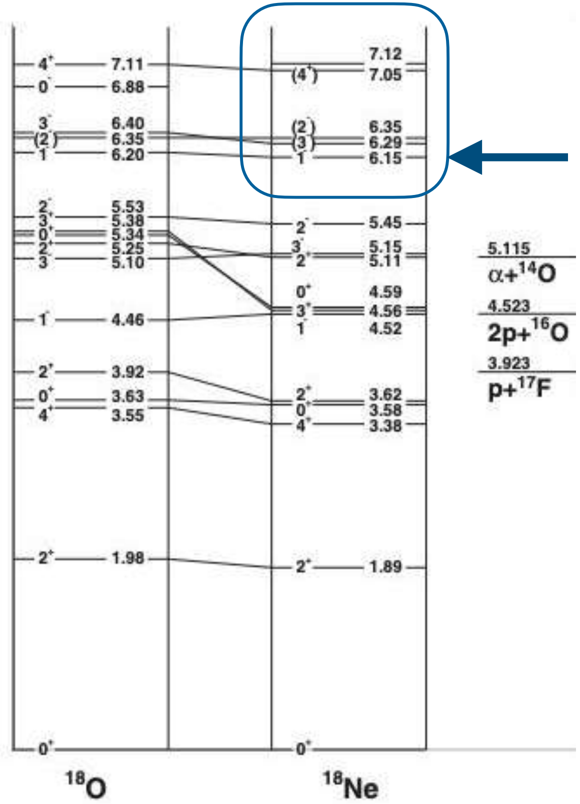
Elastic / resonance scattering

- ^{17}F(p,p): inverse proton scattering
  - (p,p') contributions
  - Determine resonance E, partial widths (Γ), L(J), π
  - R-Matrix interpretation



$^{14}O(\alpha,p)^{17}F$ REACTION RATE

hot-CNO breakout in type-I x-ray bursts



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- $^{17}F(p,p)$: inverse proton scattering
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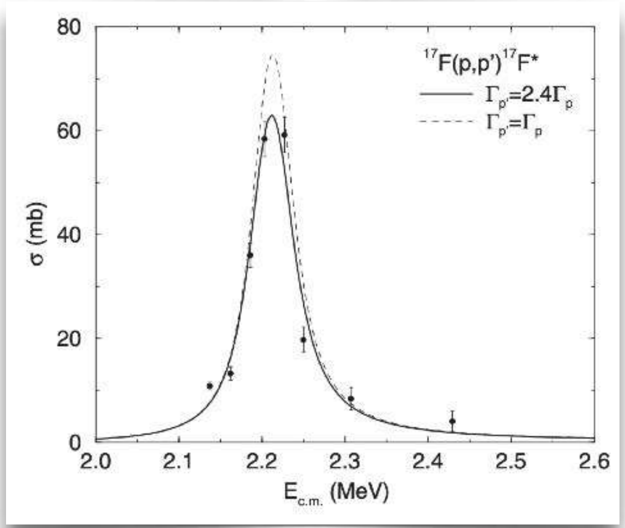
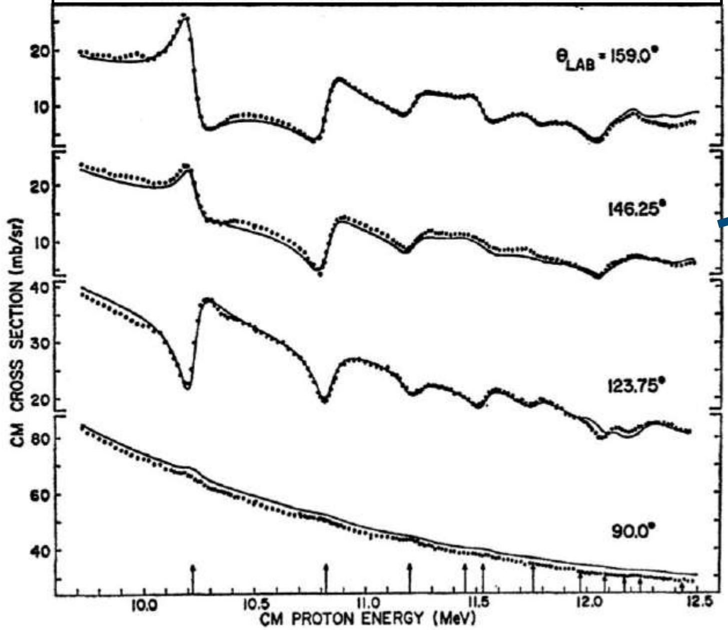


SINGLE-PARTICLE STRENGTHS

Complementary reactions: ^{136}Xe(p,p) and ^{136}Xe(d,p)

(p,p) ^{137}Xe analog states



^{136}Xe(p, p_0)^{136}Xe				
$E_R^{c.m.}$ (MeV)	$E_R^{c.m.}$ 10.195	l	j	S_{pp}
10.195	0.00	3	$\frac{7}{2}$	0.73
10.794	0.60	1	$\frac{3}{2}$	0.40
11.173	0.98	1	$\frac{1}{2}$	0.27
11.421	1.23	5	$\frac{9}{2}$	
11.498	1.30	3	$\frac{5}{2}$	0.26
11.724	1.53	3	$\frac{5}{2}$	0.15

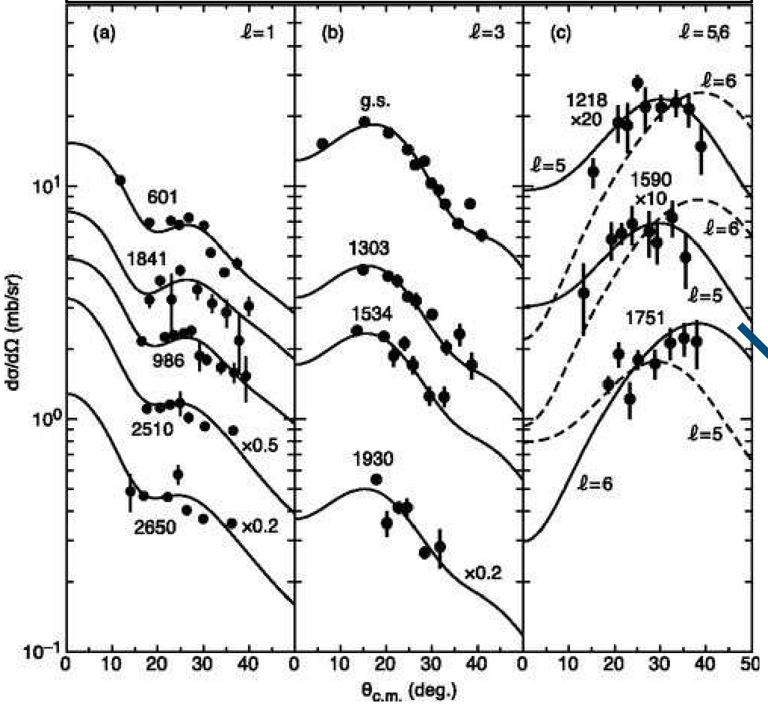
R-matrix analysis

- widths (Γ,γ) to spectroscopic overlaps (S)

SINGLE-PARTICLE STRENGTHS

Complementary reactions: ^{136}Xe(p,p) and ^{136}Xe(d,p)

(d,p) to final states in ^{137}Xe



DWBA analysis
- spectroscopic overlaps (S)

E (keV)	ℓ ($\hbar$)	J^π	$\sigma(\theta)$ (mb/sr)	C^2S
0.0[a]	3	$7/2^-$	18.8 (15°)	0.94
601[a]	1	$3/2^-$	10.6 (12°)	0.52
986[a]	1	$1/2^-,3/2^-$	2.2 (17°)	0.35
1218[a]	5	$9/2^-$	1.1 (33°)	0.43
1303[a]	3	$5/2^-$	4.4 (15°)	0.22
1534[a]	3	$5/2^-,7/2^-$	2.2 (20°)	0.12

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SINGLE-PARTICLE STRENGTHS

Complementary reactions: $^{136}Xe(p,p)$ and $^{136}Xe(d,p)$

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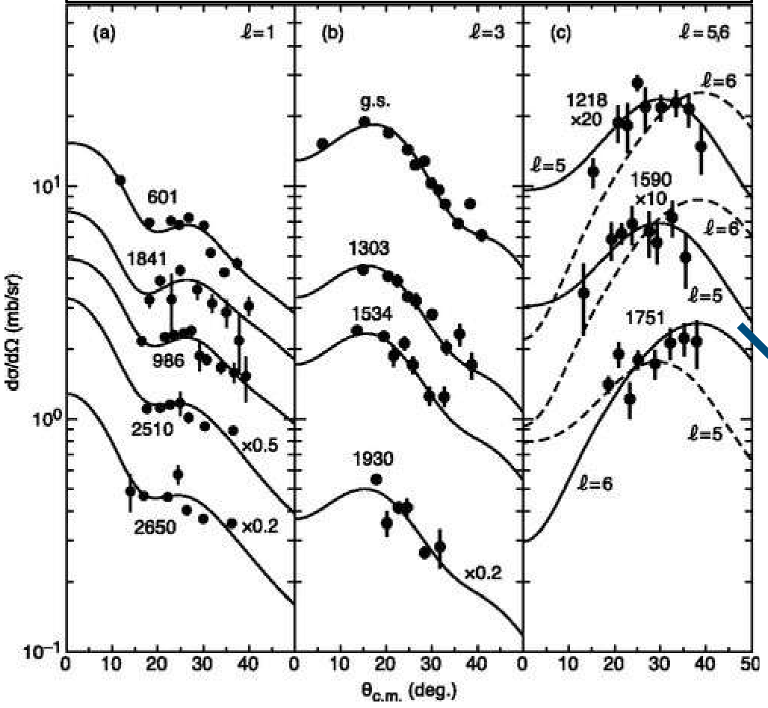

$^{136}Xe(p, p_0)^{136}Xe$

$E_R^{c.m.}$ (MeV)	$E_R^{c.m.}$ 10.195	l	j	S_{pp}
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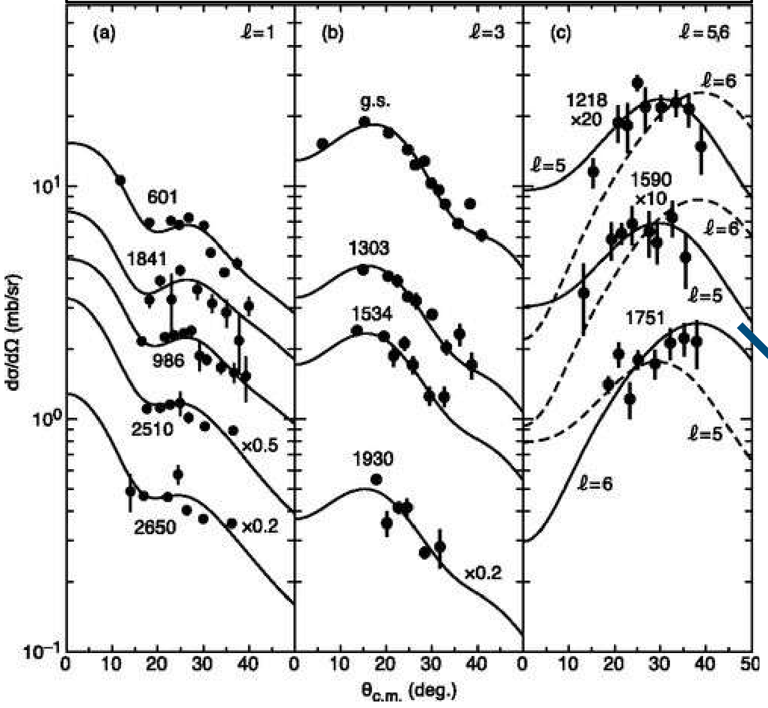
(d,p) to final states in ^{137}Xe



$E_R^{c.m.}$ (MeV)	$E_R^{c.m.}$ − 10.195	l	j	S_{pp}
	^{136}Xe(p, p_0)^{136}Xe			
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Spp

0.94
0.52
0.35
-
0.34
0.19

CONCLUDING REMAKES ON LECTURE I

- Understanding different types / forms of reactions is key
  - Integrated into measurements, New physics directly, Isotope production
- Reaction Formalism
- Overview of some reaction types
- Example cases of complementary reactions

Lecture 1 Takeaways:

- Familiarity with reaction “language”
- List various reaction types & their general properties
- Link reaction method and/or probe to physics quantities of interest
- How multiple reactions are used to explore common physics goals

RESOURCES

Less than complete set of links / references: crhoffman@anl.gov

Review

Low energy nuclear physics with active targets and time projection chambers

D. Bazin[a,b,*], T. Ahn[c], Y. Ayyad[a], S. Beceiro-Novo[b], A.O. Macchiavelli[d], W. Mittig[a,b], J.S. Randhawa[a]

PHYSICAL REVIEW C 90, 025803 (2014)

Examination of the role of the $^{14}O(\alpha,p)^{17}F$ reaction rate in type-I x-ray bursts

J. Hu,[1,2] J. J. He,[1,*] A. Parikh,[3,4,†] S. W. Xu,[1,5] H. Yamaguchi,[2] D. Kahl,[2] P. Ma,[1] J. Su,[6] H. W. Wang,[7] T. Nakao,[2] Y. Wakabayashi,[8] T. Teranishi,[9] K. I. Hahn,[10] J. Y. Moon,[11] H. S. Jung,[11,‡] T. Hashimoto,[12] A. A. Chen,[13] D. Irvine,[13] C. S. Lee,[11] and S. Kubono[1,8]

PHYSICAL REVIEW C 93, 045811 (2016)

Coulomb dissociation of ^{27}P at 500 MeV/u

J. Marganiec,[1,2,3,*] S. Beceiro Novo,[4,5] S. Typel,[2] C. Langer,[5,6,7] C. Wimmer,[7] H. Alvarez-Pol,[4] T. Aumann,[1,2] K. Boretzky,[2] E. Casarejos,[4,8] A. Chatillon,[2] D. Cortina-Gil,[4] U. Datta-Pramanik,[9] Z. Elekes,[10] Z. Fulop,[10] D. Galaviz,[11] H. Geissel,[2] S. Giron,[2] U. Greife,[12] F. Hammache,[13] M. Heil,[2] J. Hoffman,[2] H. Johansson,[14] O. Kiselev,[2] N. Kurz,[2] K. Larsson,[14] T. Le Bleis,[2,15] Yu. A. Litvinov,[2] K. Mahata,[2] C. Muentz,[7] C. Nociforo,[2] W. Ott,[2] S. Paschalis,[1,16] R. Plag,[2] W. Prokopowicz,[2] C. Rodríguez Tajes,[4] D. M. Rossi,[5,2,17] H. Simon,[2] M. Stanoiu,[2] J. Stroth,[7] K. Sümmerer,[2] A. Wagner,[18] F. Wamers,[1,2] H. Weick,[2] and M. Wiescher[19]
(R3B Collaboration)

Transfer reactions as a tool in Nuclear Astrophysics

Faïrouz Hammache[1,*] and Nicolas de Séréville[1,*]

Experimental study of the ^{34m}Cl beam production at intermediate energies

O.A. Shehu[a,1], B.P. Crider[a,*], T. Ginter[b], C.R. Hoffman[c], T.H. Ogunbeku[a], Y. Xiao[a,b], K.L. Childers[b,d], P. Chowdhury[e], C. Fry[b,f,2], E. Lamere[e], R. Lewis[b,d], S.N. Liddick[b,d], B. Longfellow[b,f,3], S. Lyons[b,4], S.K. Neupane[g], D. Pérez-Loureiro[g,5], C.J. Prokop[b], A.L. Richard[b,3], U. Silwal[a,6], D.P. Siwakoti[a,7], D.C. Smith[a], M.K. Smith[b]

Measurements of Fusion Reactions of Low-Intensity Radioactive Carbon Beams on ^{12}C and their Implications for the Understanding of X-Ray Bursts

P. F. F. Carnelli, S. Almaraz-Calderon, K. E. Rehm, M. Albers, M. Alcorta, P. F. Bertone, B. Digiovine, H. Esbensen, J. O. Fernández Niello, D. Henderson, C. L. Jiang, J. Lai, S. T. Marley, O. Nusair, T. Palchan-Hazan, R. C. Pardo, M. Paul, and C. Ugalde

Phys. Rev. Lett. **112**, 192701 – Published 14 May 2014

Single-nucleon knockout reactions at fragmentation beam energies

J. A. Tostevin*

Department of Physics, School of Physics and Chemistry, University of Surrey, Guildford, Surrey, GU2 7XH, United Kingdom

Evaluation of fusion-evaporation cross-section calculations

B. Blank[a,b,*], G. Canchel[a], F. Seis[a,1], P. Delahaye[c]

[a] Centre d'Etudes Nucléaires de Bordeaux Gradignan, 19 Chemin du Solarium, CS10120, F-33175 Gradignan Cedex, France
[b] ISOLDE/CERN, EP Department, CH-1211 Geneve 23, Switzerland
[c] Grand Accélérateur National d'Ions Lourds, Bd Henri Becquerel, BP 55027, 14076 CAEN Cedex 05, France

Gamow–Teller strength distributions of ^{116}Sb and ^{122}Sb using the (^{3}He, t) charge-exchange reaction

C. A. Douma[1,4], C. Agodi[2], H. Akimune[3], M. Alanssari[4], F. Cappuzzello[2,5], D. Carbone[2], M. Cavallaro[2], G. Colò[6,7], F. Diel[8], H. Ejiri[9], D. Frekers[4], H. Fujita[9], Y. Fujita[9], M. Fujiwara[9], G. Gey[9], M. N. Harakeh[1], K. Hatanaka[9], F. Hattori[3], K. Heguri[3], M. Holl[4], A. Inoue[9], N. Kalantar-Nayestanaki[1], Y. F. Niu[10,11], P. Puppe[4], P. C. Ries[12], A. Tamii[9], V. Werner[12], R. G. T. Zegers[13,14,15], K. Zuber[16]

Sub-Coulomb α Transfers on ^{12}C and the $^{12}C(\alpha,\gamma)^{16}O$ S Factor

C.R. Brune,[1] W.H. Geist,[1,*] R.W. Kavanagh,[2] and K.D. Veal[1,*]
[1] University of North Carolina, Chapel Hill, North Carolina 27599-3255 and Triangle Universities Nuclear Laboratory, Durham, North Carolina 27708-0308
[2] W.K. Kellogg Radiation Laboratory, California Institute of Technology, Pasadena, California 91125
(Received 17 June 1999)

PHYSICAL REVIEW LETTERS **122**, 162503 (2019)

Prominence of Pairing in Inclusive (p,2p) and (p,pn) Cross Sections from Neutron-Rich Nuclei

N. Paul,[1,2,*] A. Obertelli,[3,1,2] C. A. Bertulani,[4] A. Corsi,[1] P. Doornenbal,[2] J.L. Rodriguez-Sanchez,[1,5] G. Authelet,[1]

LETTER

An increase in the $^{12}C + ^{12}C$ fusion rate from resonances at astrophysical energies

RESOURCES

Less than complete set of links / references: crhoffman@anl.gov

https://people.nscl.msu.edu/~zegers/ebss2011/cizewski.pdf (J. Cizewski of Rutgers, NSCL 2011) ...10th in EBSS series

http://www.phy.anl.gov/atlas/EBSS2012/NuclearReactions-ExperimentI.pptx (L. Trache of Texas A&M, ANL 2012) ... 11th
http://www.phy.anl.gov/atlas/EBSS2012/NuclearReactions-ExperimentII.pptx

http://fribusers.org/documents/2013/ebssLectures/reactions1.pdf (Grigory Rogachev of FSU, LBNL 2013) ... 12th
http://fribusers.org/documents/2013/ebssLectures/reactions2.pdf
http://fribusers.org/documents/2013/ebssLectures/reactions3.pdf

http://fribusers.org/documents/2014/ebssLectures/hoffman_1.pdf (Calem Hoffman of Argonne, ORNL 2014) ... 13th
http://fribusers.org/documents/2014/ebssLectures/hoffman_2.pdf

http://aruna.physics.fsu.edu/ebss_lectures/F_Lecture2.pdf (Ben Kay of Argonne, FSU 2015) ... 14th

https://people.nscl.msu.edu/~iwasaki/EBSS2016/reaction_1.pdf (Alan Wuosmaa of UConn, NSCL 2016) ... 15th
https://people.nscl.msu.edu/~iwasaki/EBSS2016/reaction_2.pdf
https://people.nscl.msu.edu/~iwasaki/EBSS2016/reaction_3.pdf

http://www.phy.anl.gov/ebss2017/ebss-2017-zegers.pdf (Remco Zegers of NSCL, ANL 2017) ... 16th

THE END