Nuclei in the Cosmos School
2025

EXPERIMENTAL NUCLEAR PHYSICS

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NASA/Space Telescope Science Institute

Outline

Outline

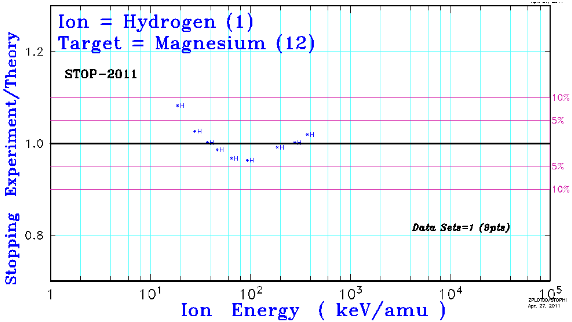
1. Absolute cross sections
2. Astrophysical S factors
3. Transfer measurements - finer points
   - Potential models
   - Target effects
   - Asymptotic Normalization Coefficiencts
4. Mirror states
5. Inverse kinematics experiments

Resonance strength measurement

$$\omega\gamma = \frac{2}{\lambda_r^2}\epsilon_r \frac{I_{\max}}{N_b B \eta W}$$

There are several quantities in this equation that are hard to determine

- ϵ_r: depends on
  - stopping powers
  - assumptions about target composition
  - target stability
- Stopping powers
  - SRIM.org
  - Be careful to check where measurements are available
  - e.g. 1 MeV protons in magnesium
- e.g. what is the molecular model you're using?



Beam current

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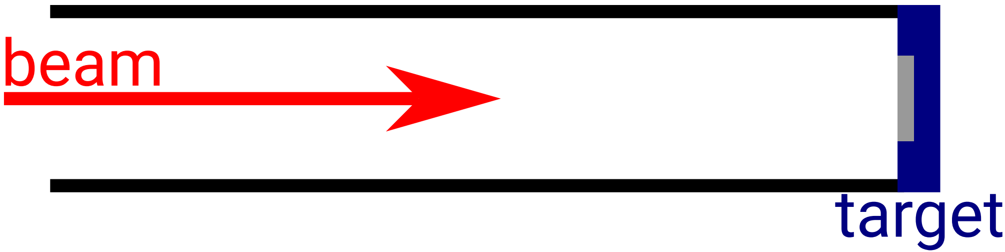

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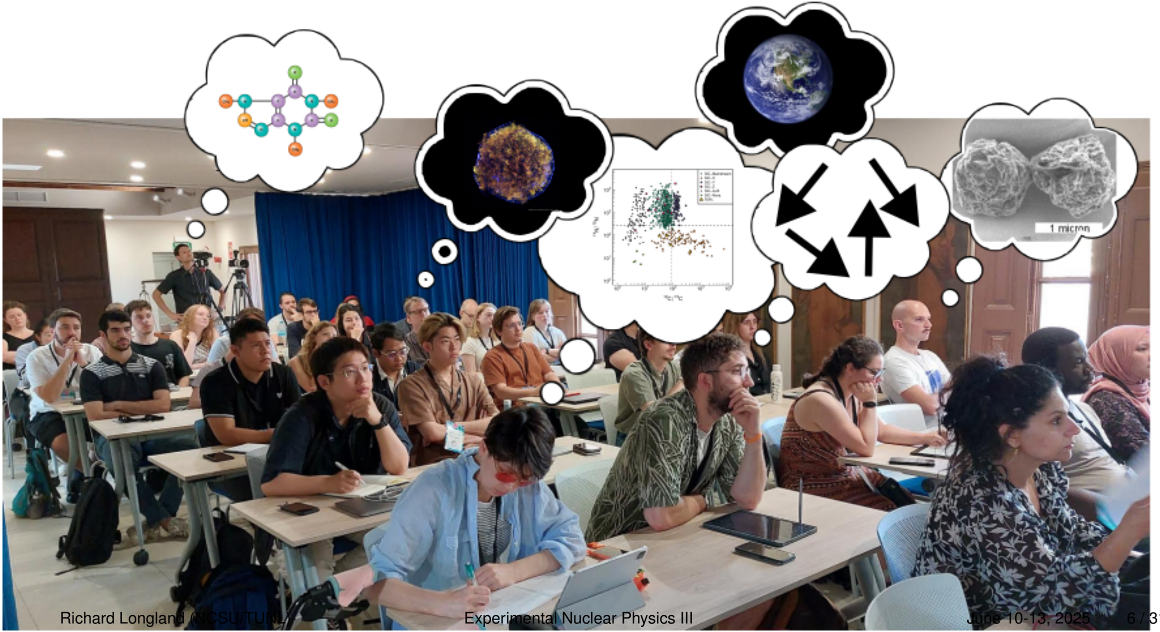

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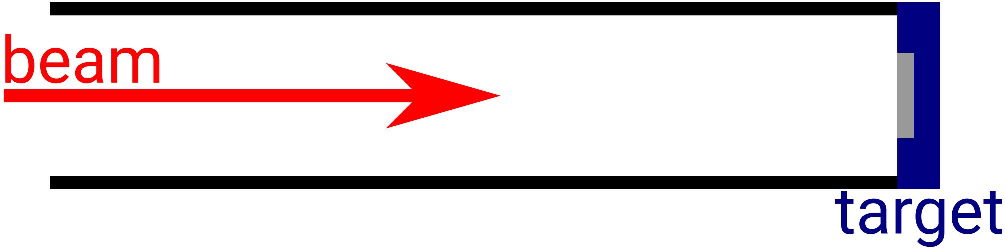

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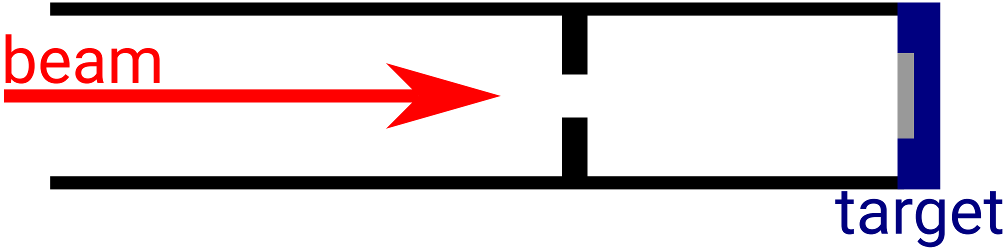

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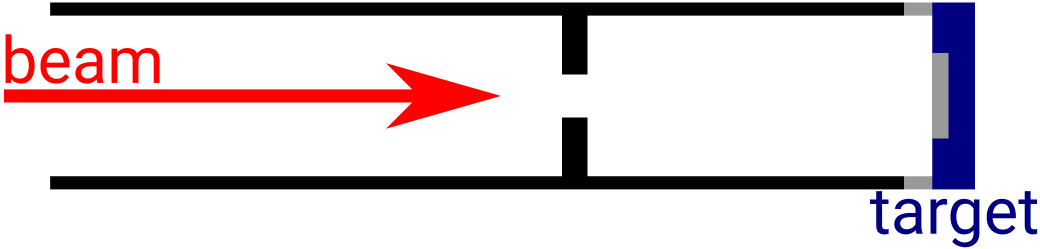

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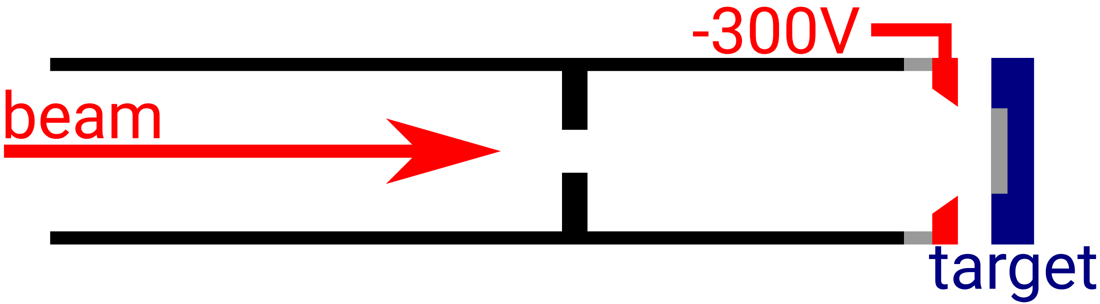
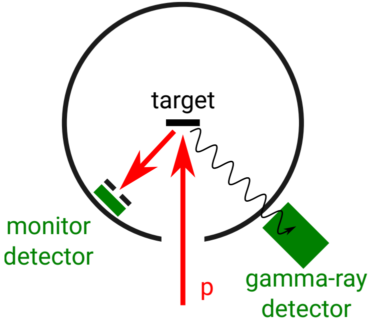


Performing measurements relative to Rutherford scattering

- Low-energy: beam scatters according to Rutherford



- Resonance strength from integrated yield

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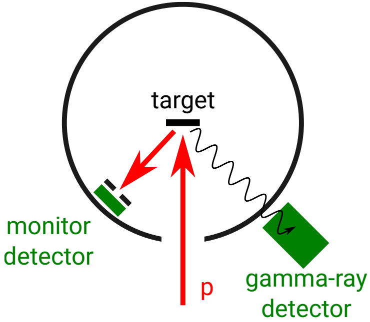

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- Yield from Rutherford scattering

$$Y_{\text{Ruth}} = \frac{N_{p'}}{N_p \Omega_{\text{mon}}} = \int_{E_0-\Delta E}^{E_0} \frac{\sigma(E)}{\epsilon(E)} dE \approx \sigma n_t$$

- Yield from reaction

$$A = \frac{1}{B_\gamma \eta_\gamma W_{\gamma(\theta)}} \int \frac{N_\gamma(E)}{N_p(E)} dE$$

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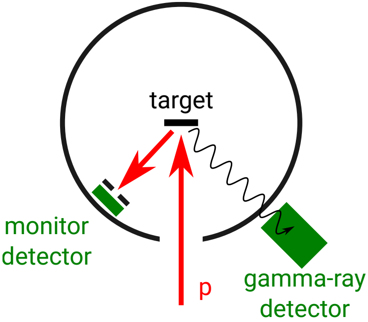

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- Yield from reaction

$$A = \frac{1}{B_\gamma \eta_\gamma W_{\gamma(\theta)}} \int \frac{N_\gamma(E)}{N_p(E)} dE$$

- Combining everything above

$$\omega\gamma = \frac{2}{\lambda_r^2}\frac{1}{B_\gamma \eta_\gamma W_\gamma(\theta)} \Omega_{\text{mon}} \int \frac{N_\gamma(E)}{N_{p'}} \sigma_{\text{Ruth}} dE$$

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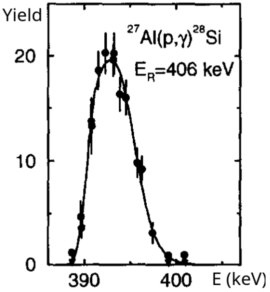
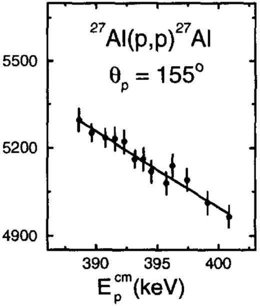
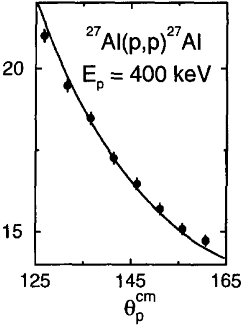
Powell et al., Nucl. Phys. A 644 (1998) 263







Absolute resonance strengths

Reaction	E_r^{lab}	$\omega\gamma$ (eV)	Uncertainty	Ref.
^{23}Na(p,γ)^{24}Mg	512	8.75 (120) × 10^{-2}	14%	a
^{23}Na(p,α)^{20}Ne	338	7.16 (29) × 10^{-2}	4.1%	d
^{30}Si(p,γ)^{31}S	620	1.89 (10)	5.3%	a
^{18}O(p,γ)^{19}F	151	9.77 (35) × 10^{-4}	3.6%	b
^{27}Al(p,γ)^{28}Si	406	8.63 (52) × 10^{-3}	6.0%	c

a) Paine and Sargood Nucl. Phys. A 331 (1979) 389
b) Panteleo et al., Phys. Rev. C 104 (2021) 025802
c) Powell et al., Nucl. Phys. A 644 (1998) 263
d) Rowland et al., Phys. Rev. C 65 (2002) 064609
And many more

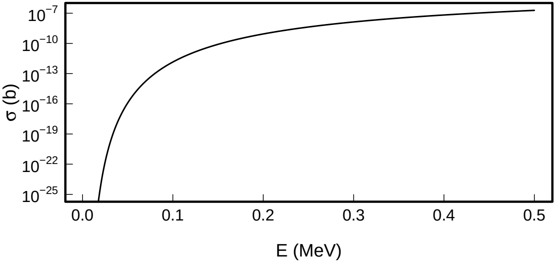
Outline

Astrophysical S factor

Please remember: S factor is a visual/convenience tool!

- Back to ^{16}O(p,γ)^{17}F reaction

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



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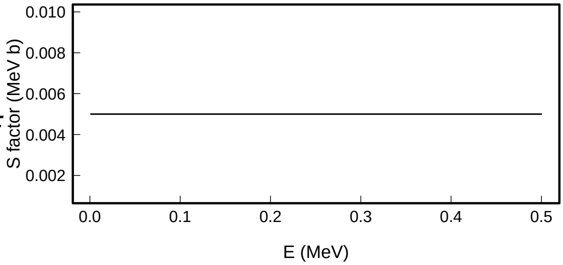

- Remove 1/E and s-wave Coulomb barrier tunneling

$$\sigma(E) \equiv \frac{1}{E} e^{-2\pi\eta} S(E)$$

$$2\pi\eta = \frac{2\pi}{\hbar} \sqrt{\frac{\mu}{2E}} Z_0 Z_1 e^2$$

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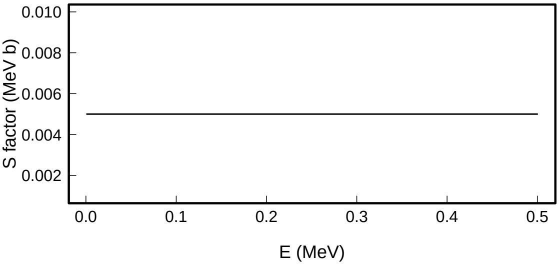

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- S is Astrophysical S Factor

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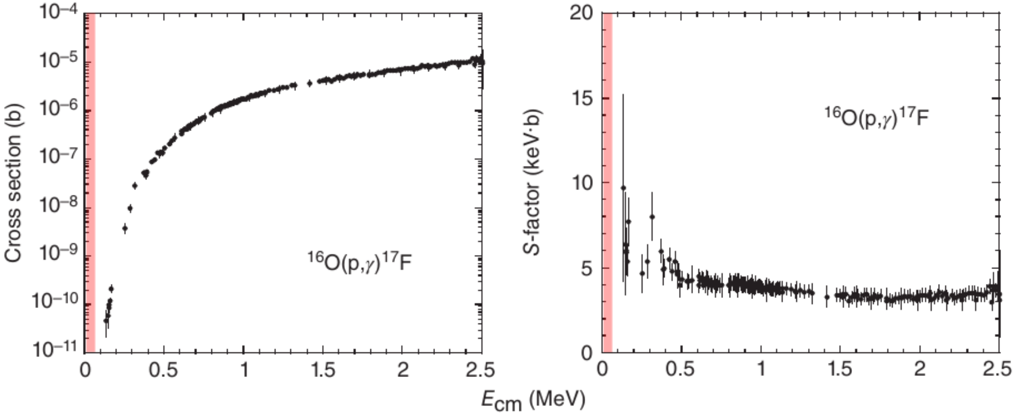
Astrophysical S factor

- Extrapolating and visualizing the cross section is much easier in terms of the astrophysical S factor.
- Recall that Gamow window is about 30 ± 15 keV



Iliadis, Nuclear Physics of Stars (2nd ed) 2015

Astrophysical S Factor

- Warning: When calculating S factor from experimental data, you *must* use the correct effective energy

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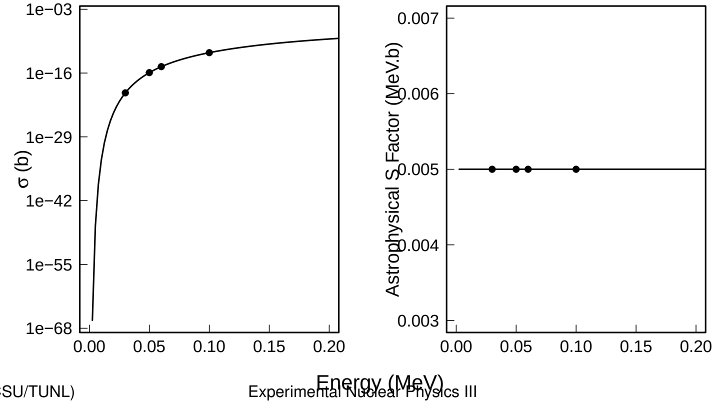

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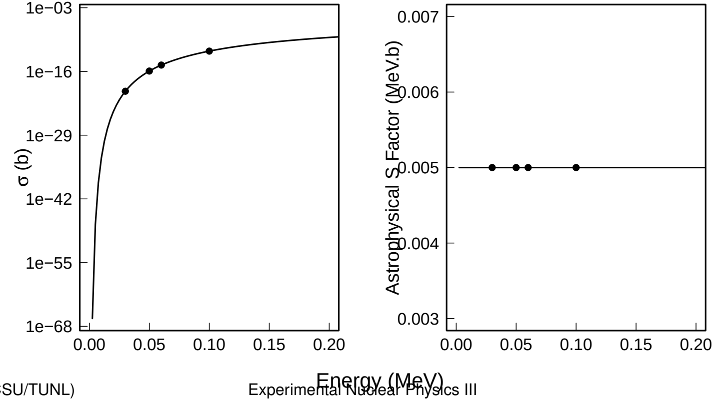

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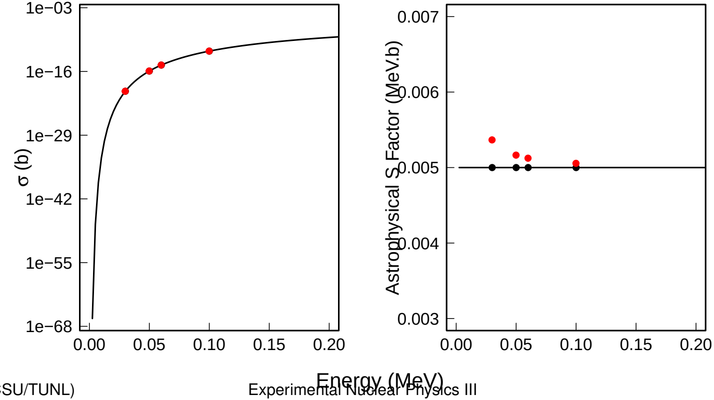
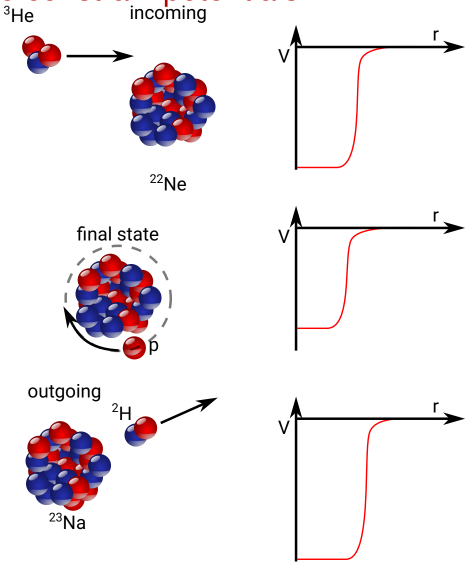


Outline

Using elastic scattering to constrain potentials



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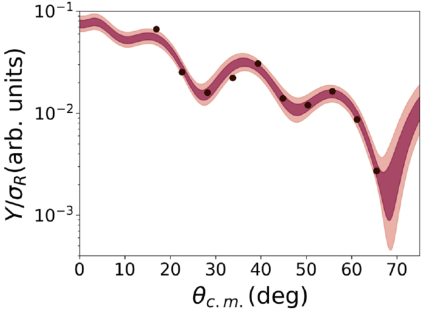

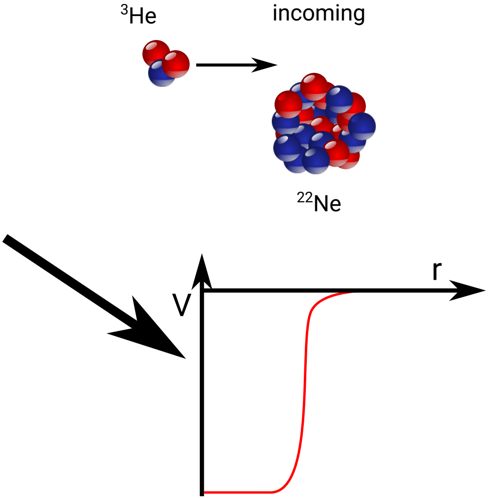

e.g., Marshall et al., Phys. Rev. C 107 (2023) 035806

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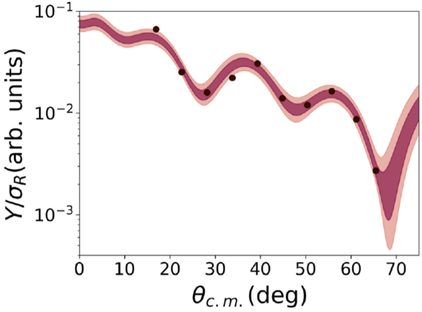

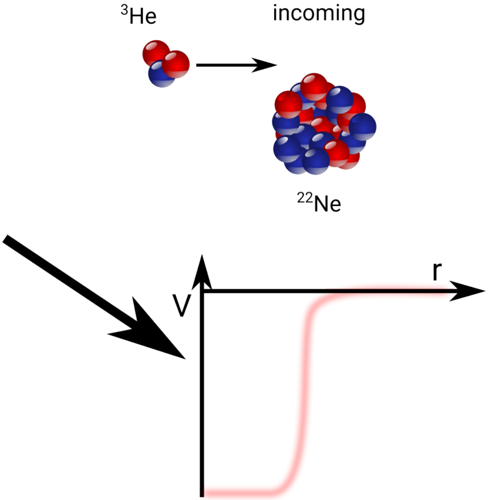

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Target effects in transfer measurements

- How do we know how much neon is in there?
- From Tuesday we know

$$\frac{dY}{d\Omega} = \frac{d\sigma}{d\Omega}\frac{\Delta E}{\epsilon_{\text{eff}}}$$

- ΔE and ϵ_{eff} are both target effects $\equiv A$

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- Transfer

$$\frac{d\sigma}{d\Omega} = \frac{dY}{d\Omega}A$$

- Elastic scattering

$$\frac{d\sigma}{d\Omega_e} = \frac{dY}{d\Omega_e}A$$

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$$\frac{d\sigma}{d\Omega} = \frac{dY}{d\Omega}A$$

- Elastic scattering

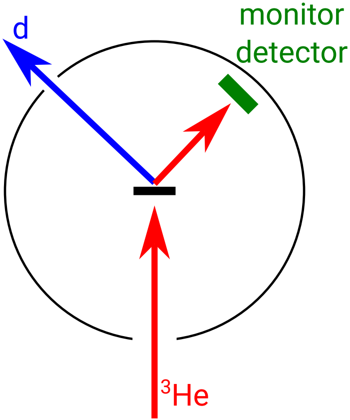
$$\frac{d\sigma}{d\Omega}_e = \frac{dY}{d\Omega}_e A$$

- We also know that elastic scattering approaches Rutherford scattering at 0°

$$\frac{d\sigma}{d\Omega}_{\text{Ruth}} = \left(\frac{Z_0 Z_1 e^2}{4E}\right)^2 \frac{1}{\sin^4(\theta/2)}$$

- Use elastic scattering and Rutherford scattering to find A

Targetry



- What is neon leeches out during our experiment?
- Use a monitor detector
  - Fixed angle
  - Does not change throughout experiment
  - Measured elastically-scattered beam
  - Used to normalize *A* from previous slide

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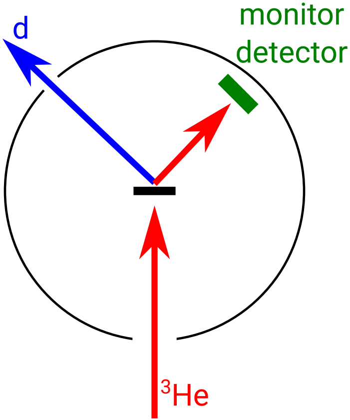

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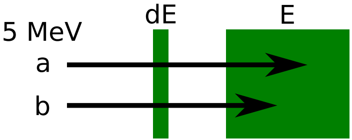
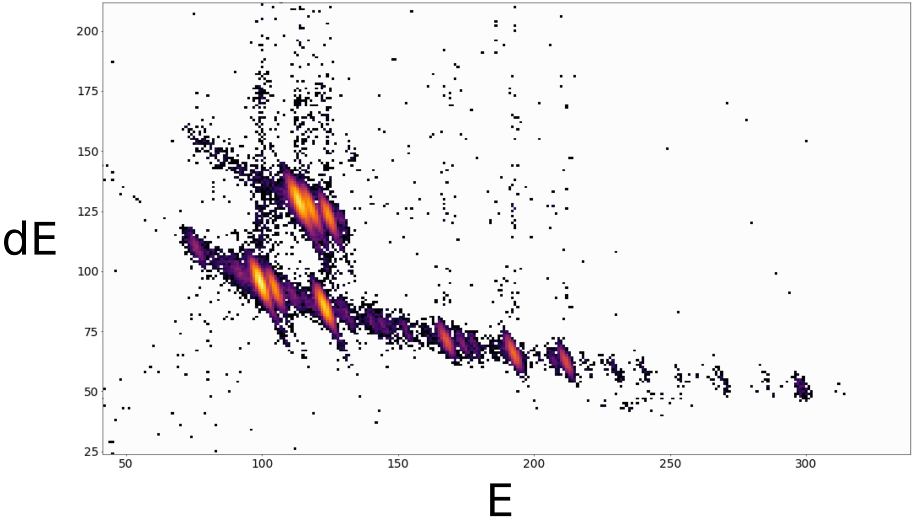
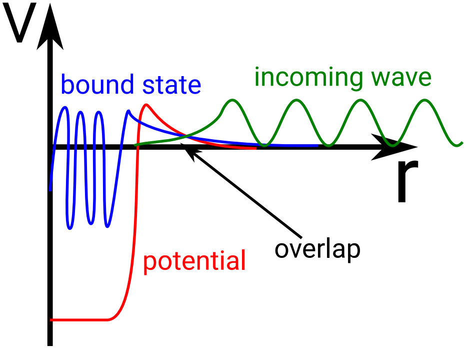


Silicon telescope spectrum



Asymptotic Normalization Coefficients

- Low-energy, peripheral reactions take place outside the nuclear radius
- Cross section is proportional to overlap integral

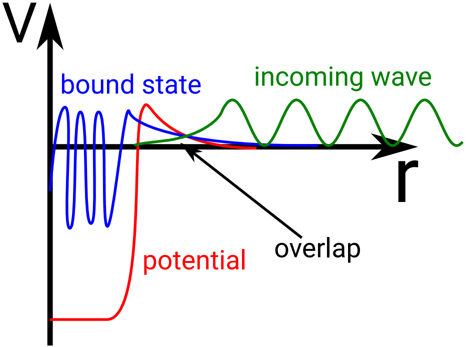


Asymptotic Normalization Coefficients

- Low-energy, peripheral reactions take place outside the nuclear radius
- Cross section is proportional to overlap integral
- Far away from the nucleus, radial bound-state wavefunctions can be approximated by

$$u(r) \approx b_{\ell_f} W_{-\eta, l_f+1/2}(2kr)$$

  - ℓ_f: Orbital angular momentum of bound particle
  - k: bound state wavenumber
  - η: Sommerfeld parameter
  - b_ℓ: single-particle ANC
  - W: Whittaker function



Asymptotic Normalization Coefficients

- Radial wavefunction for single particle far from nucleus

$$u(r) \approx b_{\ell_f} W_{-\eta, l_f+1/2}(2kr) \qquad (1)$$

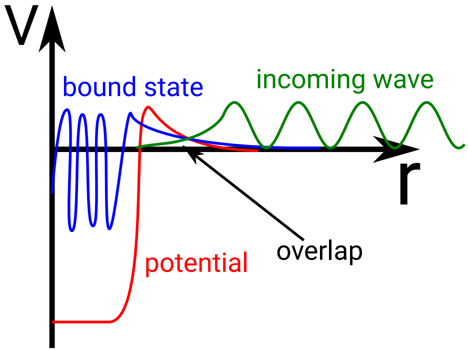
- For a reaction, the overlap integral in the single-particle model

$$I(r) \approx \sqrt{C^2 S_{\ell_f}} u(r)$$

- If this is mostly peripheral

$$I(r) \to C_{\ell_f} u(r)$$

where C_{ℓ_f} is the ANC



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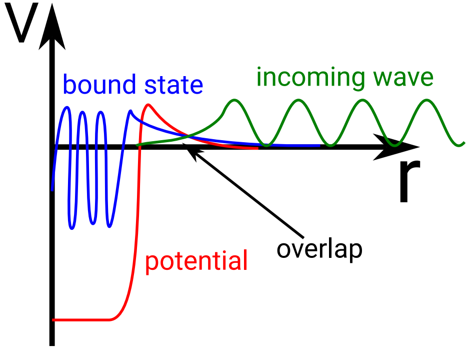

- Putting together:

$$C^2 S = \frac{C^2_{\ell_f}}{b^2_{\ell_f}}$$

Asymptotic Normalization Coefficients

$$C^2 S = \frac{C_{\ell_f}^2}{b_{\ell_f}^2}$$

$$\Gamma_p = 2\frac{\hbar^2}{\mu R^2} P_c \, C^2 S \, \theta_p^2$$

- Why is this useful?
- $C^2 S_f$ and b_{ℓ_f} are both model dependent, but C_{ℓ_f} isn't

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- Anne performs a transfer experiment
  - Uses $R_0 = 1.25$ fm
  - Calculates $C^2 S$
  - Carlos takes Anne's $C^2 S$ value
  - Calculates σ using $R_0 = 1.1$ fm
  - WRONG!

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  - WRONG!

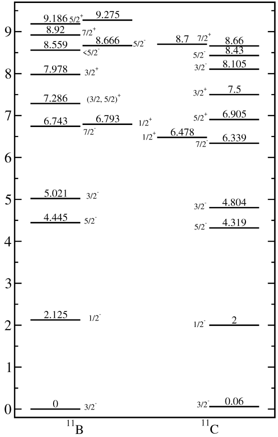
- Bri performs a transfer measurement
  - Uses $R_0 = 1.25$ fm
  - Calculates $C^2 S$, b_{ℓ_f}, and ANC, C_{ℓ_f}
  - Carlos takes Anne's C_{ℓ_f} value
  - Calculates σ using $R_0 = 1.1$ fm and his own b_{ℓ_f}
  - Correct!

Outline

Mirror states

$$\Gamma_p = 2\frac{\hbar^2}{\mu R^2} P_c\, C^2 S\, \theta_p^2$$

- Nuclear force is approximately charge symmetric



Sheikh et al., Symmetry 16 (2024) 6

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- Can try to use C^2S from mirror nucleus

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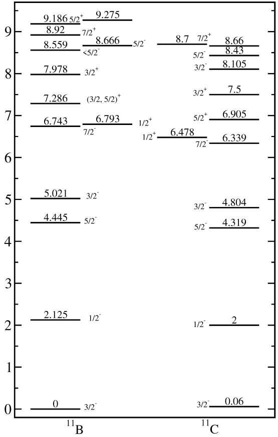


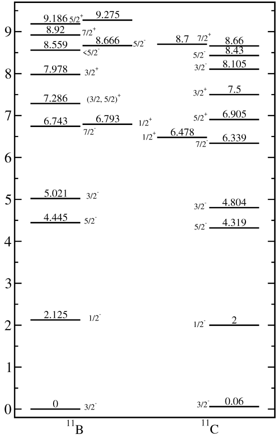
Sheikh et al., Symmetry 16 (2024) 6

- Spectroscopic factor, C^2S, contains all of the nuclear physics
- Can try to use C^2S from mirror nucleus
- e.g., ^{17}F(p,γ)^{18}Ne
  - ^{18}Ne has 10 protons and 8 neutrons
  - ^{18}O has 8 protons and 10 neutrons

Mirror states

$$\Gamma_p = 2\frac{\hbar^2}{\mu R^2} P_c\, C^2 S\, \theta_p^2$$

- Nuclear force is approximately charge symmetric



Sheikh et al., Symmetry 16 (2024) 6

- Spectroscopic factor, C^2S, contains all of the nuclear physics
- Can try to use C^2S from mirror nucleus
- e.g., ^{17}F(p,γ)^{18}Ne
  - ^{18}Ne has 10 protons and 8 neutrons
  - ^{18}O has 8 protons and 10 neutrons
  - ^{17}O(d,p)^{18}O "neutron stripping" transfers neutron onto ^{17}O core
  - $\rightarrow$ neutron C^2S in ^{18}O

Mirror states

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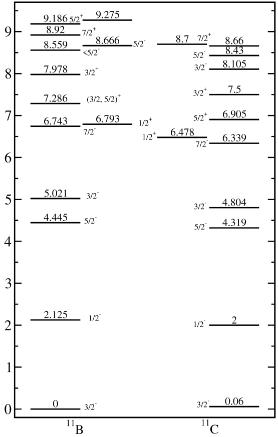

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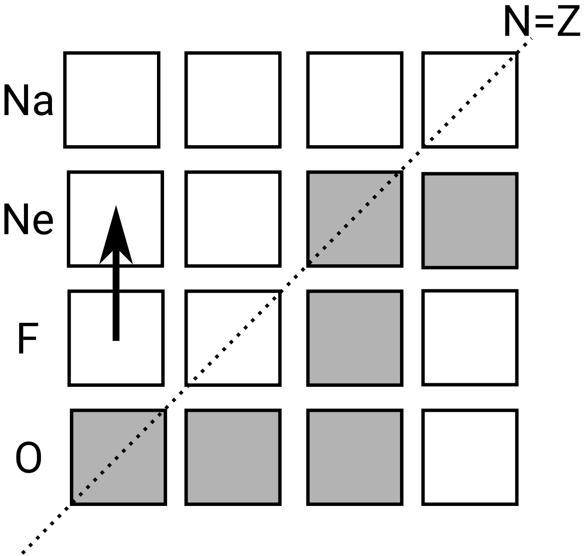
  - $\rightarrow$ proton C^2S in ^{18}Ne

Mirror states

- From previous slide, can use $^{17}O(d,p)^{18}O$ to understand $^{17}F(p,\gamma)^{18}Ne$



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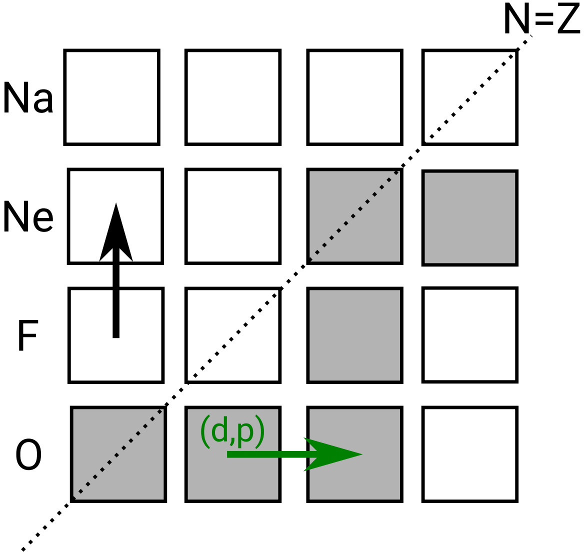
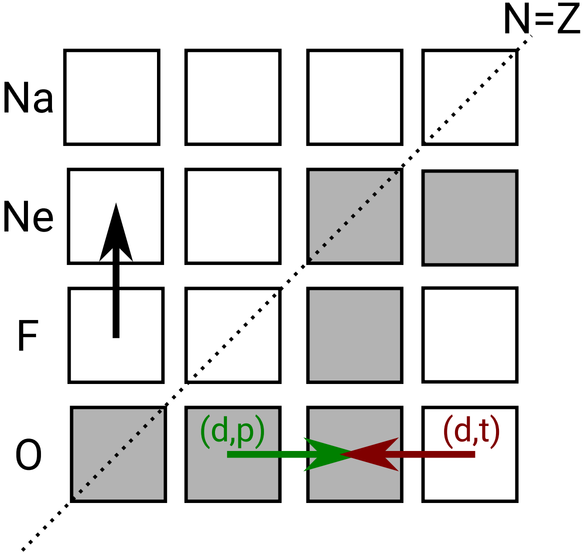


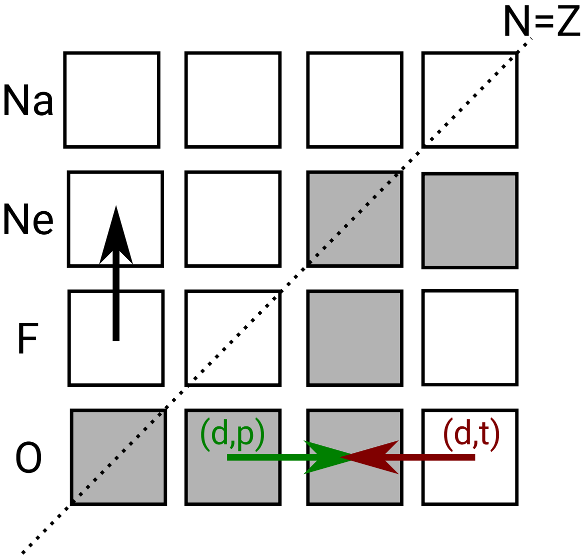
Mirror states

- From previous slide, can use ^{17}O(d,p)^{18}O to understand ^{17}F(p,γ)^{18}Ne
- We cannot use neutron pick-up ^{19}O(d,t)^{18}O



Mirror states

- From previous slide, can use ^{17}O(d,p)^{18}O to understand ^{17}F(p,γ)^{18}Ne
- We cannot use neutron pick-up ^{19}O(d,t)^{18}O
- What reaction would we use to understand ^{18}Ne(n,γ)^{19}Ne?



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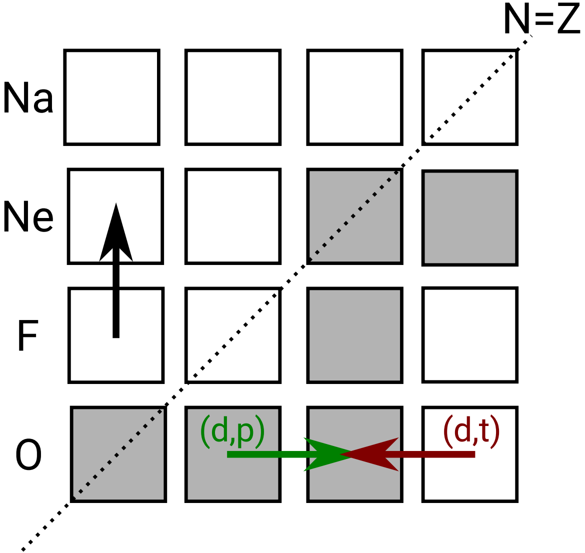

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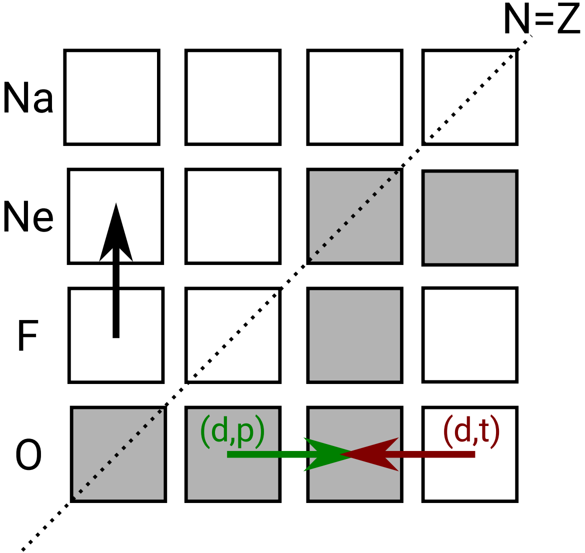
- How about ^{19}F(p,γ)^{20}Ne?



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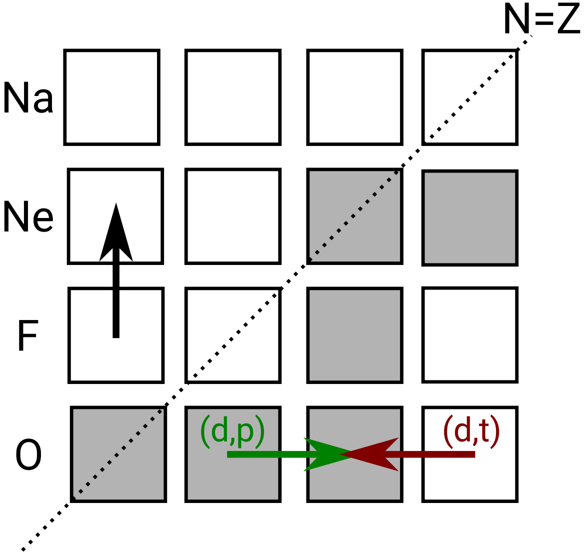
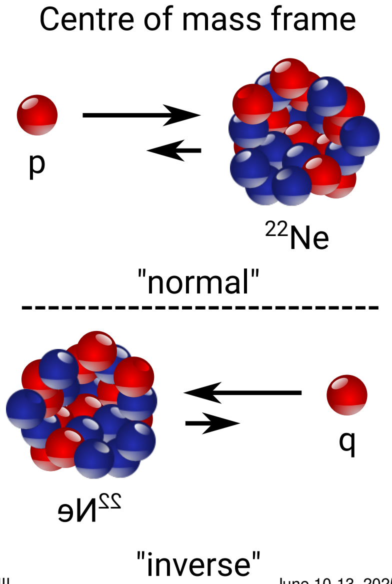
  - ^{18}O(p,γ)^{19}F
- How about ^{19}F(p,γ)^{20}Ne?
  - ^{20}Ne has no mirror



Outline

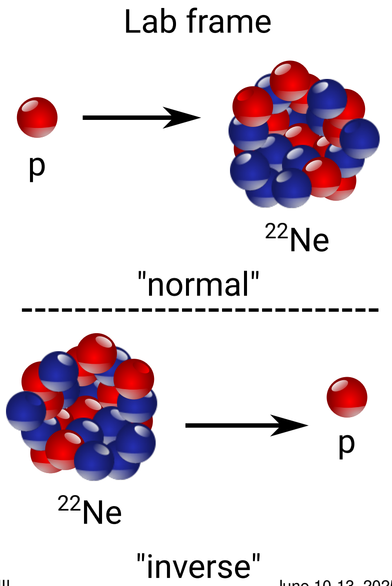
Inverse kinematics experiments

- In the center of mass, these are *exactly* the same as everything I've spoken about up to now



Inverse kinematics experiments

- In the center of mass, these are *exactly* the same as everything I've spoken about up to now
- In the laboratory, they're very different
  - Scattered particles move forward
  - Light reaction products go everywhere
    - ★ Doppler effects are large
    - ★ Angular resolution is critical



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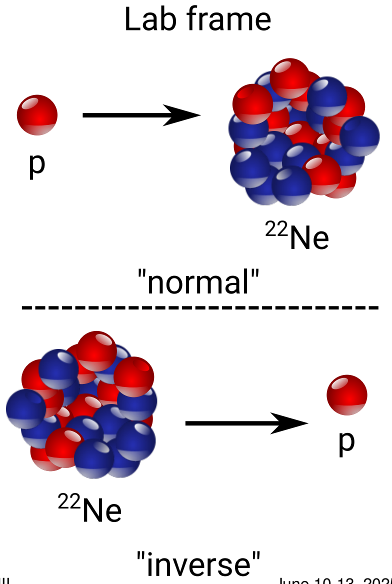
C.M. Conversions

$$E_{\text{c.m.}} = E_{b,\text{lab}} \frac{m_t}{m_b + m_t}$$



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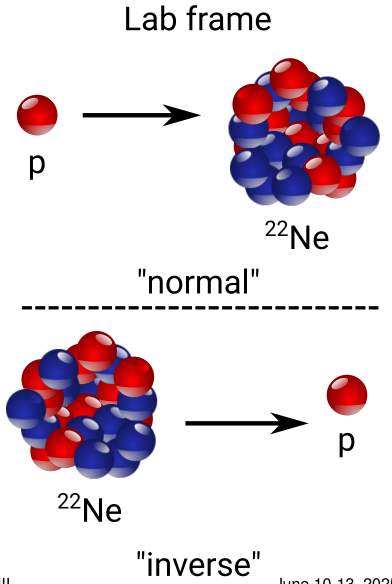
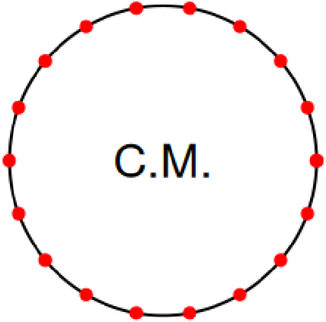


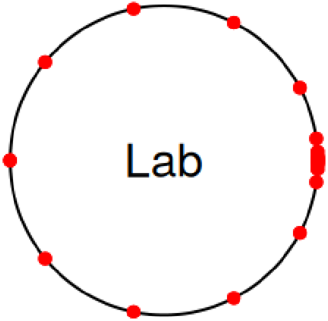
C.M. Conversions

$$E_{\text{c.m.}} = E_{b,\text{lab}} \frac{m_t}{m_b + m_t}$$

- Which is why inverse kinematics folks quote energy in MeV/u

Kinematics for (p,γ)



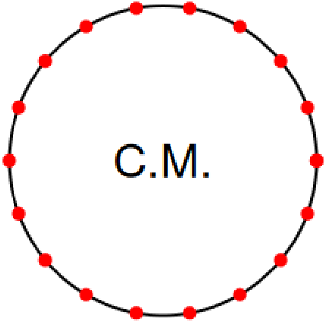


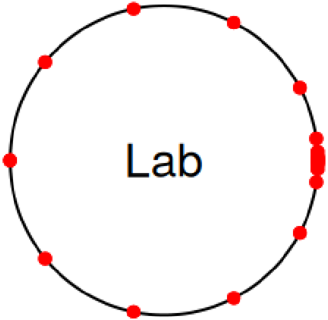
Disadvantages

- Outgoing particles all going forward
  - Doppler corrections needed for γ rays
  - Unreacted beam and reactions go same direction!
- Low beam intensities

Advantages

Kinematics for (p,γ)





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  - Unreacted beam and reactions go same direction!
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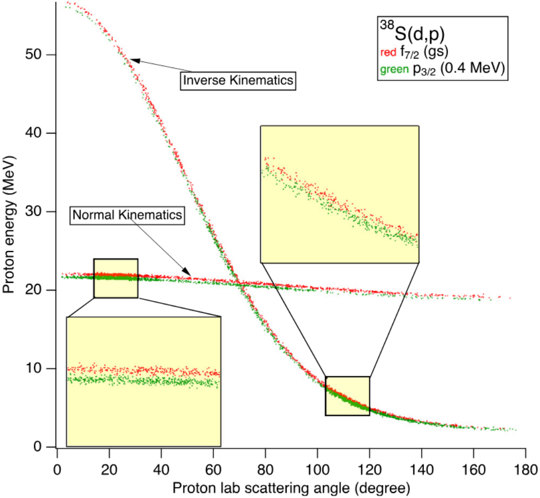
Advantages

- Can study (p,γ) reactions on unstable nuclei
- Can collect (almost) everything
- Very low contaminants

Kinematics for particle transfer



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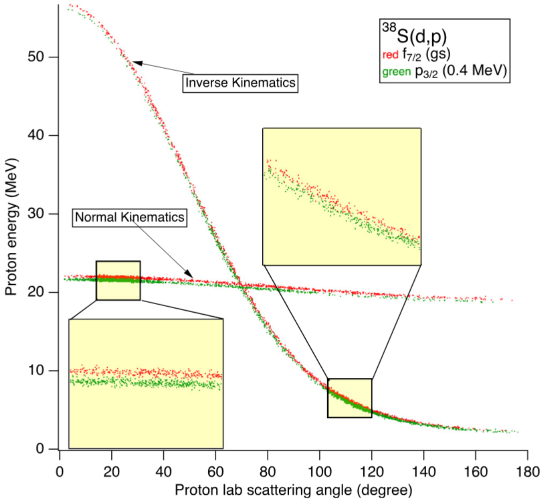
  - Depends on kinematic details, Q-values, etc.

Kinematics for particle transfer



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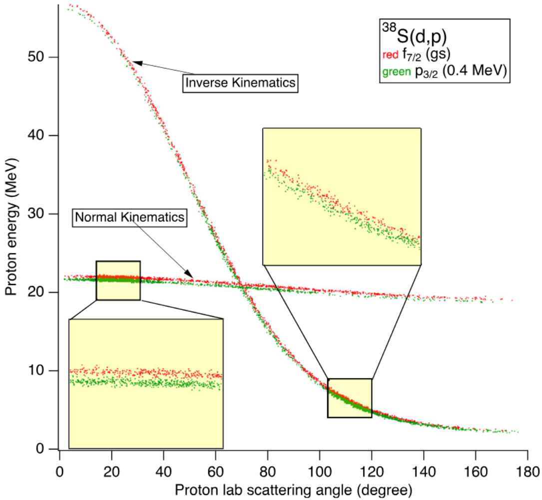
Kinematics for particle transfer



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- See Faïrouz's talk about HELIOS, active targets, etc.

Fin!