Nuclei in the Cosmos School
2025

EXPERIMENTAL NUCLEAR PHYSICS

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North Carolina State U, USA

NASA/Space Telescope Science Institute

Outline

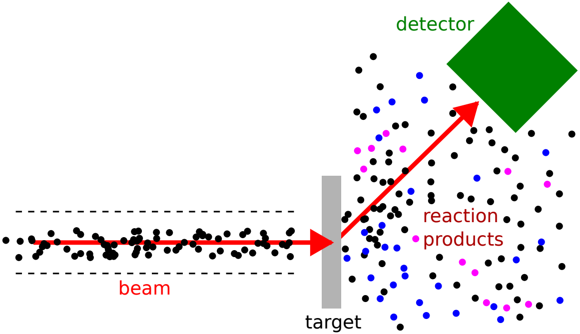
1. Experimental Yields
   - Count rates
2. Resonant reactions
   - Recap
   - Brief discussion of resonance theory
3. Indirect measurements
   - Transfer measurements
4. Peculiarities and details
   - Absolute cross sections
   - Target effects in transfer measurements
   - Astrophysical S Factor

Outline

Experimental yield

$$Y = \frac{N_R}{N_b}$$

- Detector doesn't measure all reaction products
- Reaction products aren't always emitted isotropically



Experimental yield

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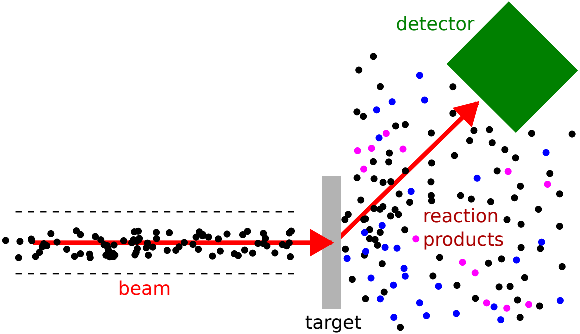
- Yield

$$Y = \frac{I}{N_b B \eta W}$$



- I: intensity of measured reaction product
- B: branching ratio if reaction product only carries part of strength
- η: detector efficiency
- W: Angular distribution correction

Count rates (for narrow resonance)

- Recall our two expressions for yield: experimental and theoretical

$$Y = \frac{I}{N_b B \eta W} \qquad \text{and} \qquad Y_{\mathrm{max}} = \frac{\lambda_r^2}{2} \frac{\omega\gamma}{\epsilon_r}$$

- Combine and find an expression for intensity of reaction products at top of yield curve

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- Combine and find an expression for intensity of reaction products at top of yield curve

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

- For convenience, convert N_b to $I_b/q_b t$
  - I_b is beam current
  - q_b is beam charge in Coulombs
  - Δ t is length of experiment

$$\frac{I}{t} = \frac{\lambda_r^2}{2}\frac{\omega\gamma}{\epsilon_r}\frac{I_b}{q_b} B \eta W$$

Example: ^{22}Ne(p,γ)^{23}Na

$$\frac{I}{t} = \frac{\lambda_r^2}{2} \frac{\omega\gamma}{\epsilon_r} \frac{I_b}{q_b} B \eta W$$

Narrow resonance at 35 keV dominates rate at low T

- $\omega\gamma \sim 2 \times 10^{-15}$ eV
- Beam current: 2 mA
- Target effective stopping power: $\epsilon_r = 1.9 \times 10^{-14}$ eV cm^2/atom
- Detector efficiency: η = 100%
- Isotropic γ-ray emission: W=1

Count rate: I/t = 1 × 10^{-10} counts per hour!

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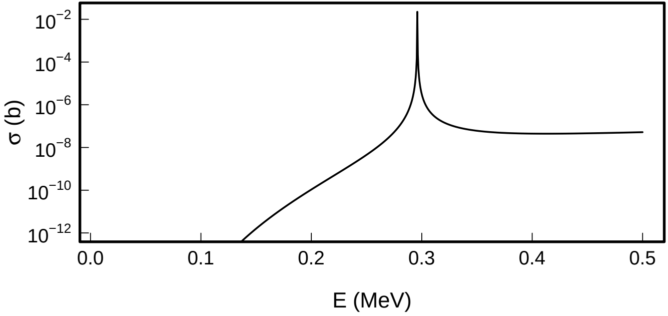
Resonant reaction cross section



Either

$$\sigma(E) = \omega \frac{\Gamma_a \Gamma_b}{(E - E_r)^2 + \Gamma^2/4}$$

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

Or

$$\omega\gamma = \frac{\Gamma_a \Gamma_b}{\Gamma}$$

$$N_A\langle\sigma v\rangle_{01} = N_A \left(\frac{2\pi}{\mu_{01} kT}\right)^{3/2} \hbar^2 \omega\gamma e^{-E_r/kT}$$

Definitions

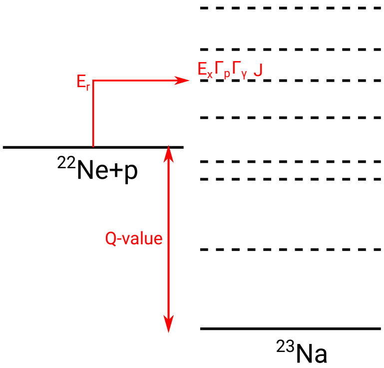
$$\sigma(E) = \omega \frac{\Gamma_a \Gamma_b}{(E - E_r)^2 + \Gamma^2/4}$$

- Widths
  - Total width (FWHM):
    $\Gamma = \Gamma_a + \Gamma_b + \ldots$
  - Partial width:
    Γ_a. Corresponds to *probability of a level decaying through channel a*
- Branching ratio:

$$B_a = \frac{\Gamma_a}{\Gamma}$$

- ω:

$$\omega = \frac{2J + 1}{(2J_0 + 1)(2J_1 + 1)}$$



- Resonance energy: E_r
- Q-value: Energy released in a reaction

Land and Thomas

REVIEWS OF
MODERN PHYSICS
VOLUME 30, NUMBER 2, Part I — APRIL, 1958

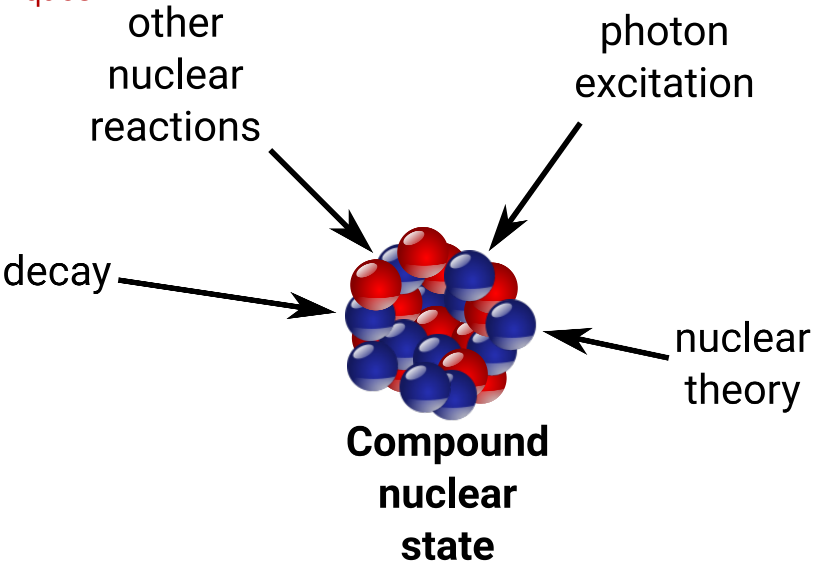
R-Matrix Theory of Nuclear Reactions

A. M. LANE, *Atomic Energy Research Establishment, Harwell, Berkshire, England*

AND

R. G. THOMAS,* *Los Alamos Scientific Laboratory, Los Alamos, New Mexico*

Indirect techniques



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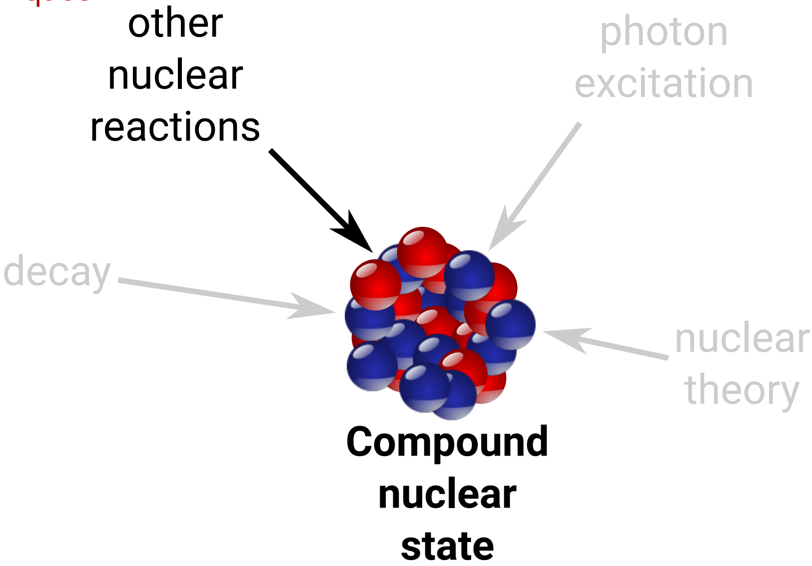

Outline

Determining proton partial widths

$$\sigma(E) = \omega \frac{\Gamma_p \Gamma_\gamma}{(E - E_r)^2 + \Gamma^2/4}$$

- Partial width calculated by

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

- Dimensionless Single-Particle Reduced Width

$$\theta_p^2 = \frac{R}{2} |u_p(R)|^2$$

  - $u_p(R)$ is the radial wavefunction of a single particle at the channel radius

- R is the channel radius: $R = R_0(A_t^{1/3} + A_p^{1/3})$
- P_c is Penetration factor
- C^2 is isospin Clebsch-Gordon Coefficient
- S is the Spectroscopic Factor
  - Note: $C^2 S$ is colloquially the "Spectroscopic Factor"
  - How "single particley" the state is
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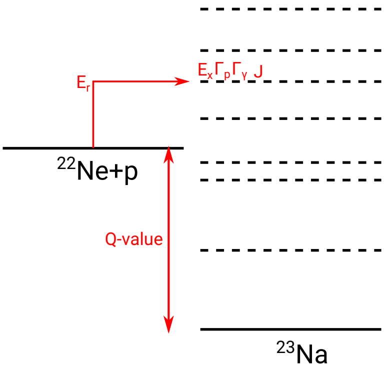

- ^{3}He is a deuteron+proton
- Transfer proton from ^{3}He to ^{22}Ne - proton stripping
- Extra degree of freedom in deuteron
  - Allows higher beam energy
  - Higher cross section
- Can measure
  - Energy of deuteron $\rightarrow E_r$
  - Angular distribution of deuteron $\rightarrow$ J
  - Cross section $\rightarrow \Gamma_p$
- Requires some theory…

See Hammache and de Séréville, Front. in Phys. 8 (2021) 602920

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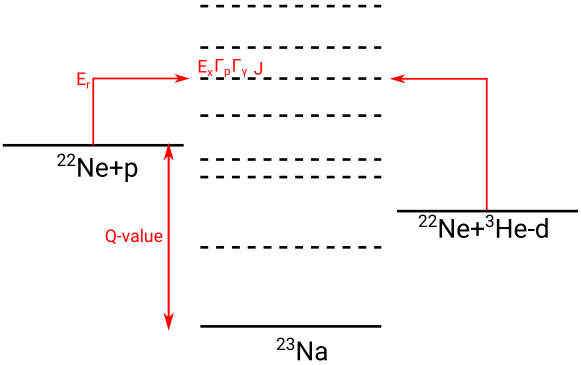

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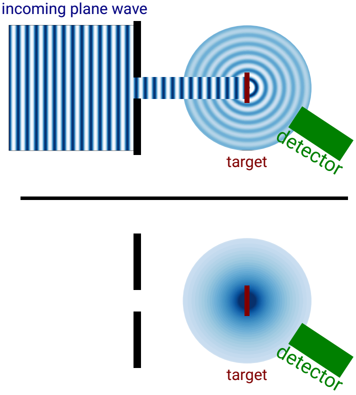
Elastic scattering



Case for $\ell = 0$

- Total wave function far from the target

$$\Psi(\vec{r}) = N\left[e^{i\vec{k}\cdot\vec{r}} + f(\theta)\frac{e^{ikr}}{r}\right]$$

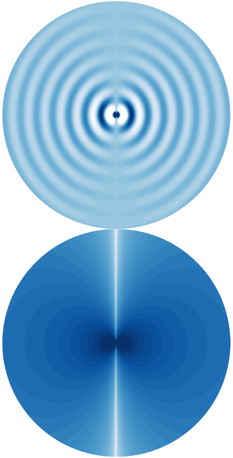
- To combine the coordinate systems, we expand the incoming wave in terms of partial waves:

$$e^{ikz} = \sum_{\ell=0}^{\infty}(2\ell+1)i^{\ell}j_{\ell}(kr)P_{\ell}(\cos\theta)$$

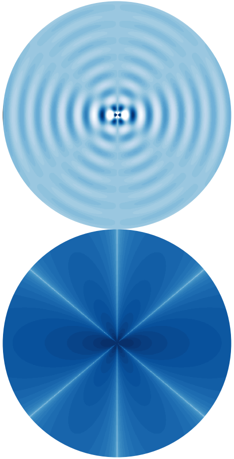
- The scattering amplitude becomes:

$$f(\theta) = \frac{1}{k}\sum_{\ell=0}^{\infty}(2\ell+1)e^{i\delta_{\ell}}\sin\delta_{\ell}P_{\ell}(\cos\theta)$$

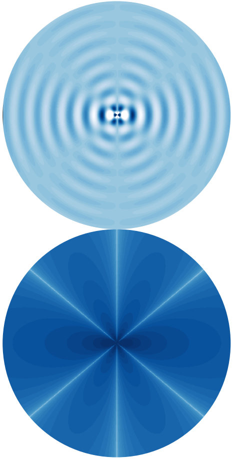
Elastic scattering



Case for ℓ=1

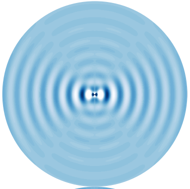


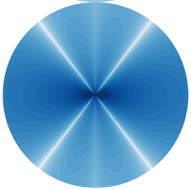
Case for ℓ=2

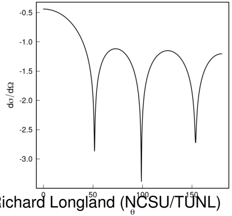


Case for ℓ=3

Elastic scattering







- The scattering amplitude is:

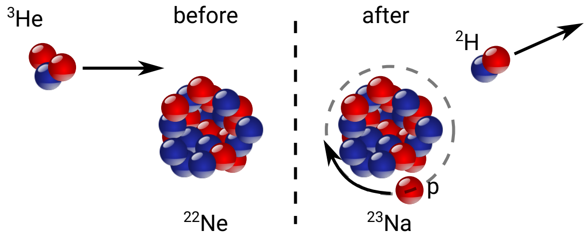
$$f(\theta) = \frac{1}{k}\sum_{\ell=0}^{\infty}(2\ell+1)e^{i\delta_\ell}\sin\delta_\ell P_\ell(\cos\theta)$$

- Cross section measured by detector:

$$\frac{d\sigma}{d\Omega} = f^*(\theta)f(\theta)$$

- Traditionally, use cross section to find δ_ℓ, which derive from the shape of the nuclear potential

Transfer reactions

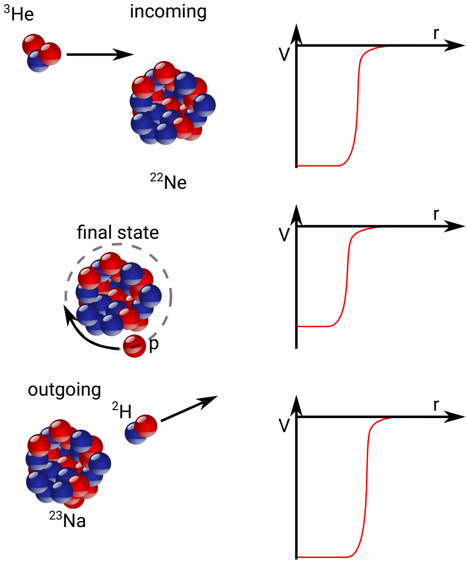


- Elastic scattering on previous slides is dominant
- Small perturbation causes direct transfer from initial state to final state
- Cross section:

$$d\sigma/d\Omega \propto |\langle\Psi_f^*|V|\Psi_i\rangle|^2$$

- Use partial wave expansion again, but now there are often only a few contributing terms $\rightarrow$ $d\sigma/d\Omega$ tells us ℓ!
- Final state is described by core (^{22}Ne) plus transferred nucleons
  - Projectile in optical potential of target
  - Perturbing nuclear potential (including transfer of nucleons)
  - Outgoing particle in potential of residual

Transfer reactions



Transfer reactions

$$\frac{d\sigma}{d\Omega}_{exp} = C^2 S_{\mathrm{proj}} C^2 S_{\mathrm{targ}} \frac{d\sigma}{d\Omega}_{th} \qquad \Gamma_p = 2\frac{\hbar^2}{\mu R^2} P_c\, C^2 S\, \theta_p^2$$

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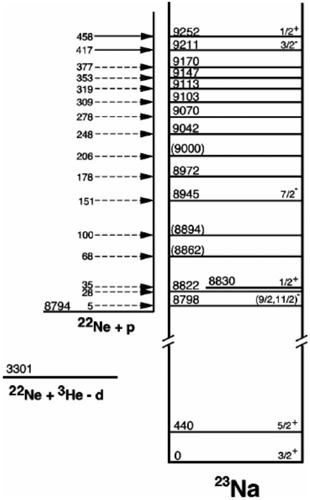
- Experimental needs
  - Accelerated beam of intermediate-energy light particles
  - Target of interest
  - Measure outgoing particles (elastic scattering and reaction products)
  - Measure scattering at different angles
  - Particle energy resolution compatible with level density (transfer to different final states)
    - ★ $\sim$ 20 keV in this case of ^{22}Ne(p,γ)^{23}Na

Transfer reactions - $^{22}Ne(p,\gamma)^{23}Na$ using $(^3He,d)$

Hale *et al., Physical Review C 65 (2001) 015801*



- Implanted ^{22}Ne ions into 40 μg/cm^2 carbon foils
  - Using conversions from yesterday, how thick is this?
- 20 MeV $^3He^{++}$ beam, 100 – 150 pnA
- TUNL Enge split-pole spectrograph with 2 msr aperture
- Data collected from 5° to 35°

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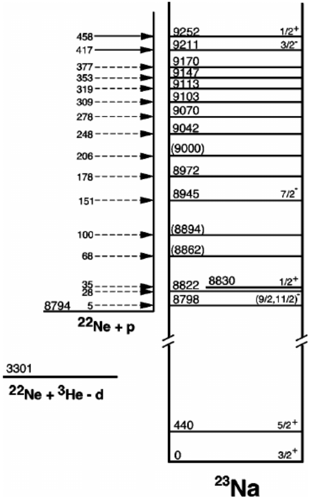

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- Some questions:
  1. How do we create a target?
  2. How do we know how much neon is in there?
  3. What if the neon leaches out during our experiment?
  4. What yield $\rightarrow \sigma$ regime are we in?

Transfer reactions - ^{22}Ne(p,γ)^{23}Na using (^{3}He,d)

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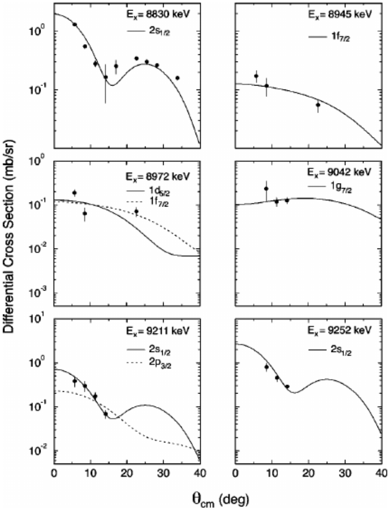
Hale et al., Physical Review C 70 (2004) 045802



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- 8830 keV: ℓ=0, C^2S = 0.039

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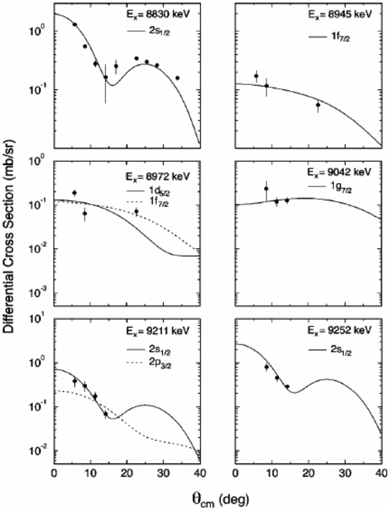

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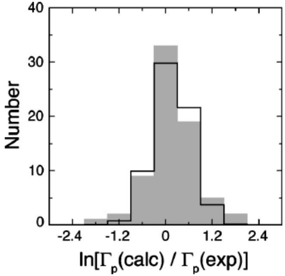
- Uncertainties on these values? A factor of 1.6



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Resonance strength measurement

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

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

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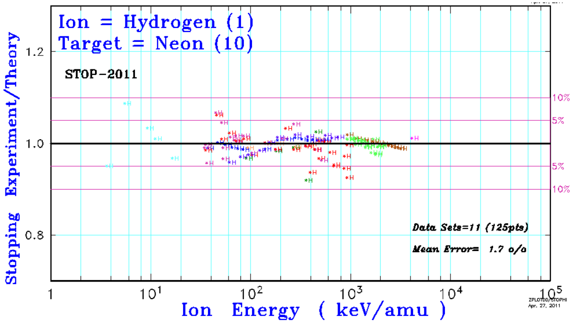
  - stopping powers
  - assumptions about target composition
  - target stability
- Stopping powers
  - SRIM.org
  - Be careful to check where measurements are available



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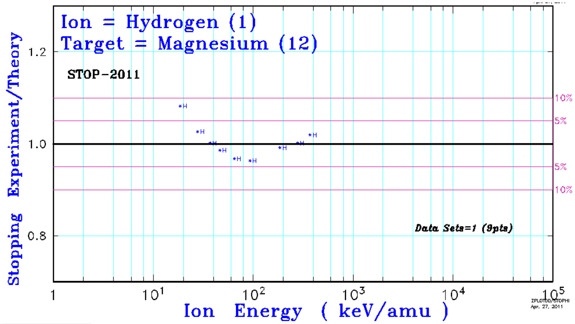

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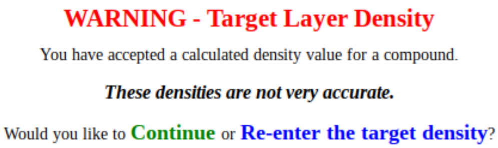
- e.g. what is the molecular model you're using?


WARNING - Target Layer Density

You have accepted a calculated density value for a compound.

These densities are not very accurate.

Would you like to **Continue** or **Re-enter the target density**?

Beam current

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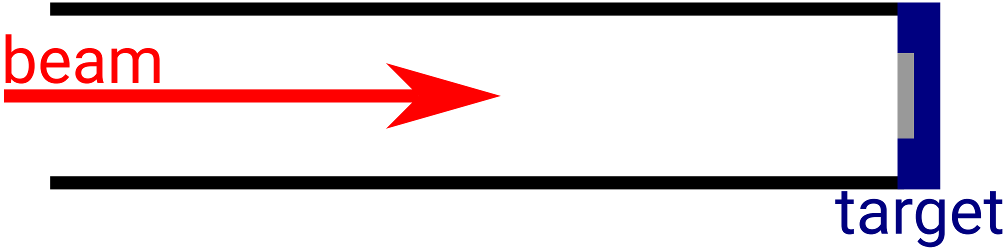

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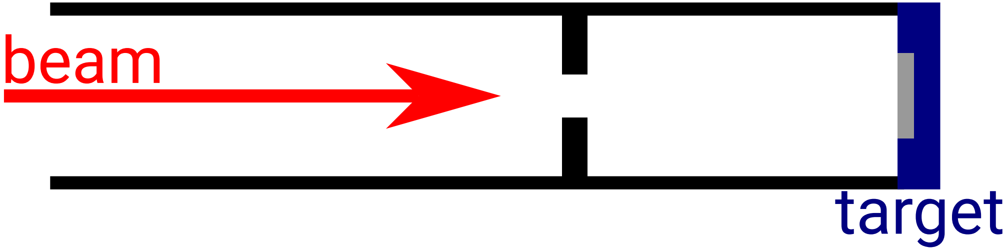

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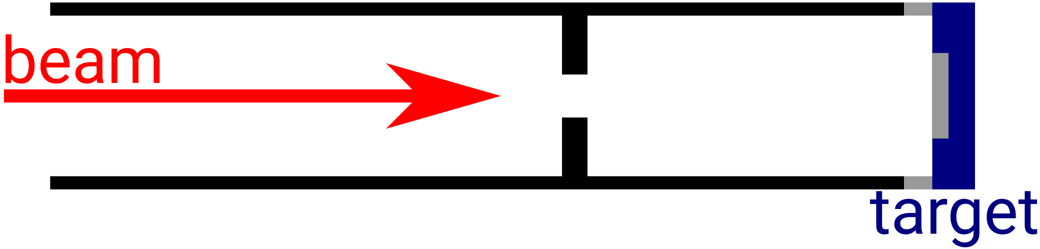

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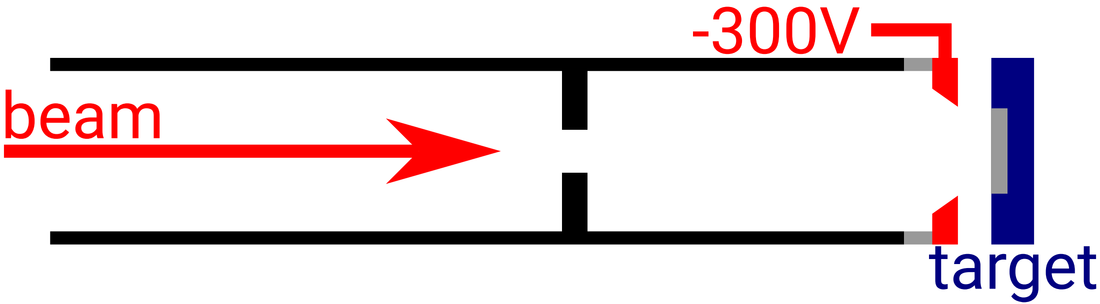
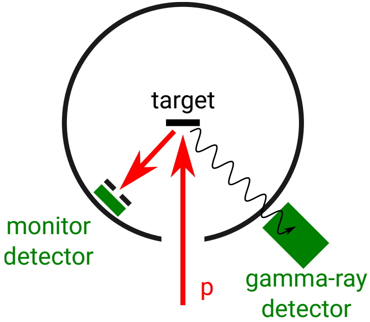


Performing measurements relative to Rutherford scattering

- Low-energy: beam scatters according to Rutherford



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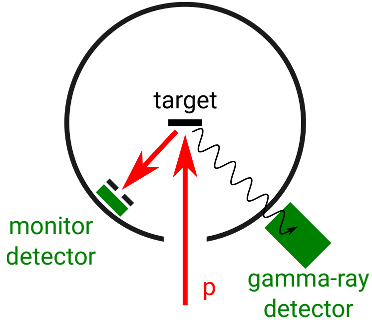

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- Yield from Rutherford scattering

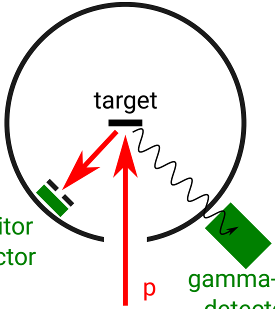
$$Y_{\text{Ruth}} = \frac{N_{p'}}{N_p \Omega_{\text{mon}}} = \int_{E_0-\Delta E}^{E_0} \frac{\sigma(E)}{\epsilon(E)} dE \approx \sigma n_t$$

- Yield from reaction

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

Performing measurements relative to Rutherford scattering

- Low-energy: beam scatters according to Rutherford



- Resonance strength from integrated yield

$$\omega\gamma = \frac{2}{\lambda_r^2}\frac{A}{n_t}$$

- 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

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

- Combining everything above

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

Performing measurements relative to Rutherford scattering

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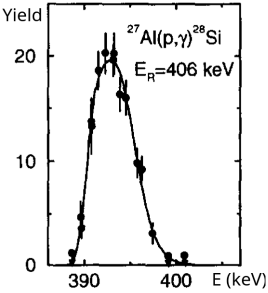
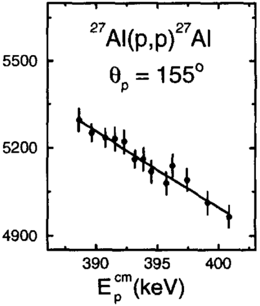
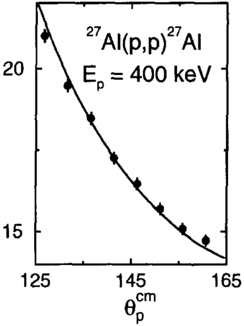
Powell et al., Nucl. Phys. A 644 (1998) 263







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

Target effects in transfer measurements

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

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

- Elastic scattering

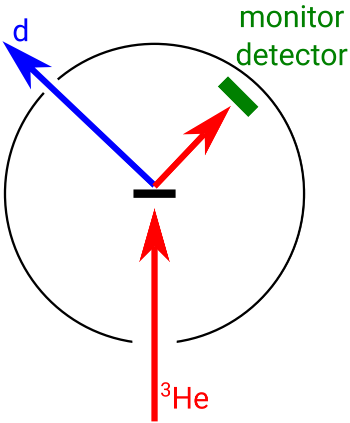
$$\frac{d\sigma}{d\Omega}_e = \frac{dY}{d\Omega}_e A$$

- 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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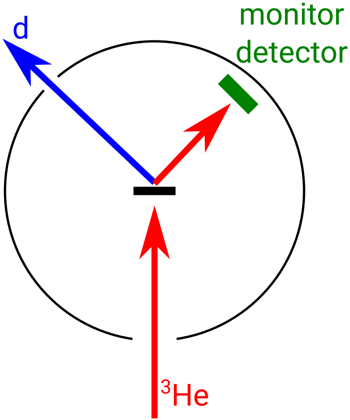

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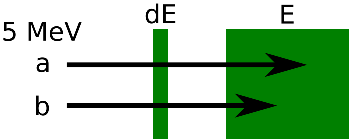
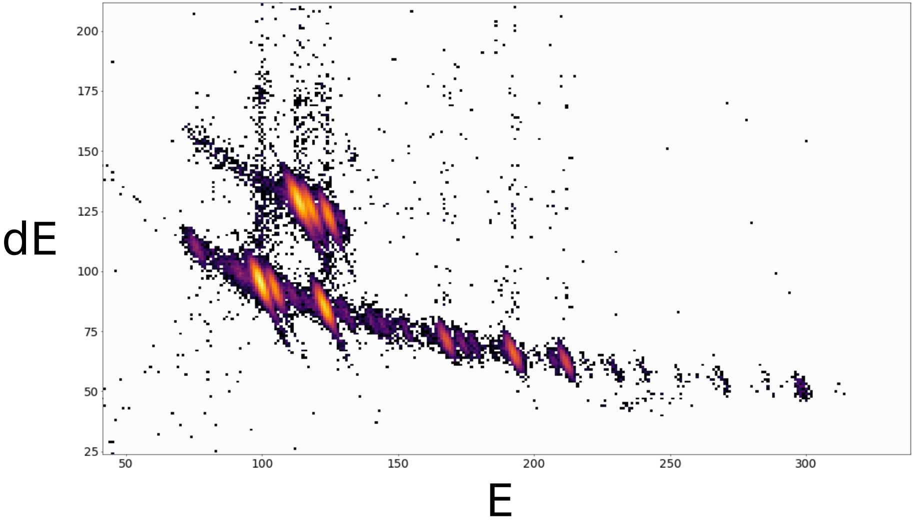
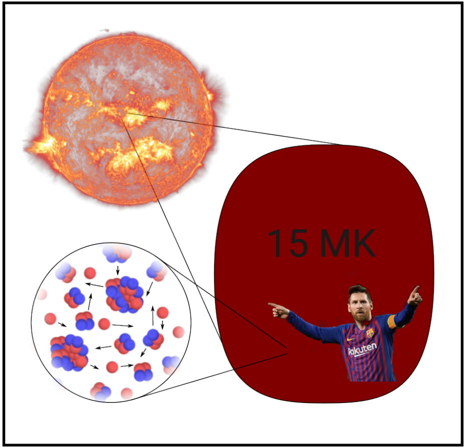


Silicon telescope spectrum



Astrophysical S Factors

Reaction rates and cross sections



- Particle velocities distributed according to a Maxwell-Boltzmann distribution

$$N_A\langle\sigma v\rangle_{01} = \left(\frac{8}{\pi\mu_{01}}\right)\frac{N_A}{(kT)^{3/2}}\times \int_0^\infty E\,\sigma(E)\,e^{-E/kT}\,dE$$

(cm^3 mol^{-1} s^{-1})

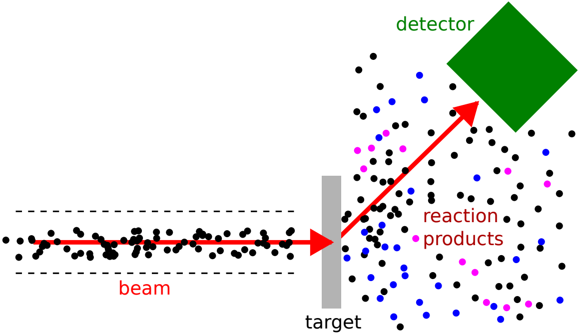
- For a known temperature, we only need to know $\sigma(E)$ to calculate reaction rate
- For the rest of my lectures, we will concern ourselves with *how*, exactly, to measure σ(E)

What, exactly, is σ(E)

Cross section

$$\sigma(E) \equiv \frac{\text{number of reactions per time}}{(\text{number of incident particles per area per time})(\text{number of target nuclei in the beam})}$$

- Number of reactions
  - We need a detector that can count outgoing radiation from our experiment (Faïrouz Hammache will cover details)
- Number of incident particles
  - Need a beam of particles (Faïrouz again!)
- Number of target nuclei
  - Need to create a target (yes, Faïrouz will cover this too!)

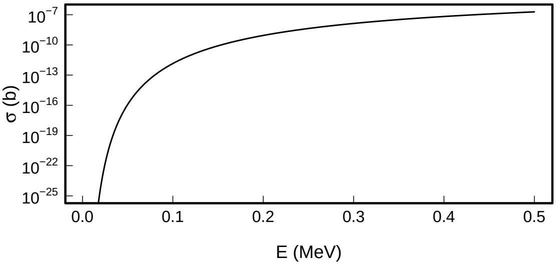


Astrophysical S factor

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

- Back to ^{16}O(p,γ)^{17}F reaction

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



- 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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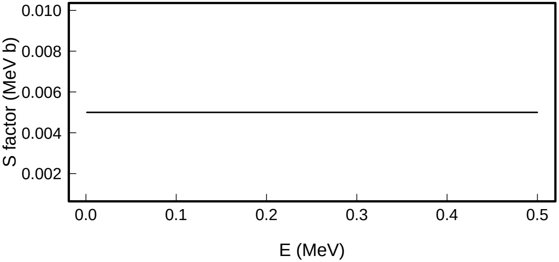

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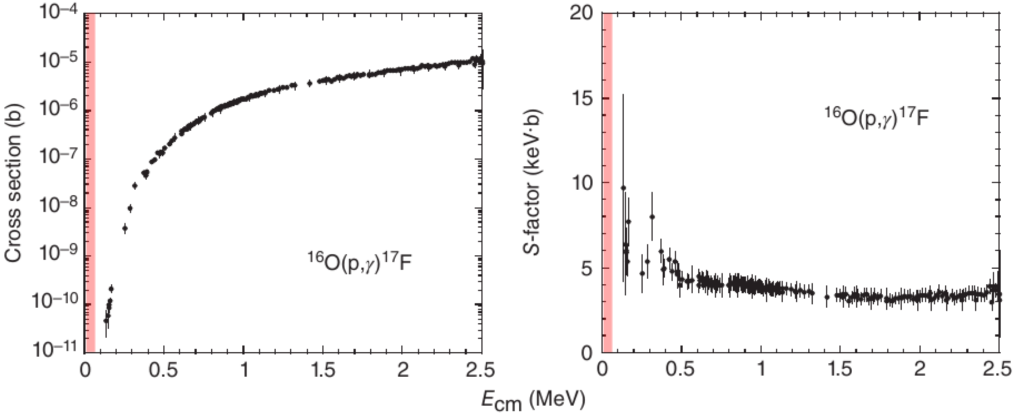
- *S* is Astrophysical S Factor

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

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

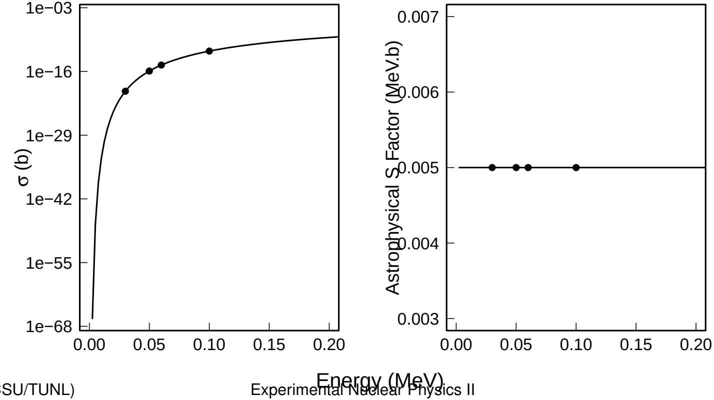


Iliadis, Nuclear Physics of Stars (2nd ed) 2015

Astrophysical S Factor

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

$$S(E) \equiv E e^{2\pi\eta}\sigma(E), \qquad 2\pi\eta = \frac{2\pi}{\hbar}\sqrt{\frac{\mu}{2E}} Z_0 Z_1 e^2$$



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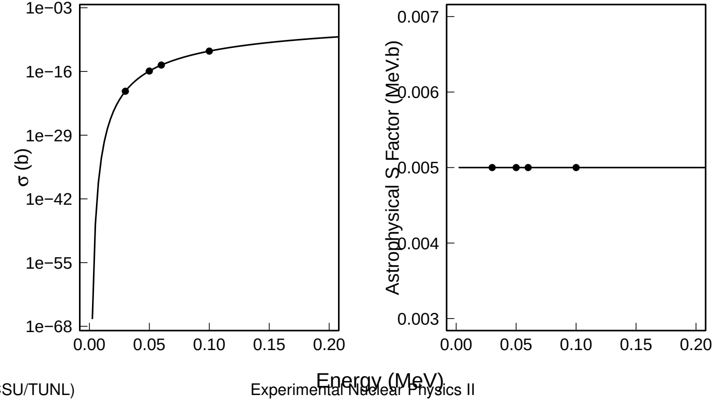

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