Lesson 12

Nuclear Reactions -- Part 2
Compound Nuclear Reactions

- The compound nucleus is a long-lived reaction intermediate that is formed by a complex set of interactions between the projectile and the target.
- The projectile and target nuclei fuse and the energy of the projectile is shared among all the nucleons of the composite system.
- The lifetime of the CN is $\sim 10^{-18} - 10^{-16}$ s. This lifetime is directly measurable by crystal-blocking techniques.
Independence Hypothesis or “Amnesia Assumption”

- The mode of decay of the CN is independent of its mode of formation.
- Caveat: Conservation laws apply.
- Experimental evidence: the Ghoshal expt.
- Angular distributions symmetric about 90° in CN frame.
The Ghoshal Experiment

$^{62}\text{Cu} > ^{63}\text{Zn} > ^{62}\text{Ni}$

ang. mom effects
Cross Sections--General

\[ \sigma = \pi \hbar^2 \sum_{\ell = 0}^{\infty} (2\ell + 1)T_{\ell} \]

probability = \[ \frac{T_{\ell}^\beta (E_\beta)}{\sum_{\ell, E_\gamma} T_{\ell}^\gamma (E_\gamma)} \]
Cross Sections--Energy Dependence

Γ/D >> 1

Γ/D << 1
\[ \frac{\Gamma}{D} \ll 1 \]

For reaction \( a + A \rightarrow C \rightarrow b + B \)

\[
\sigma = \pi \hat{\lambda}^2 \frac{\left( 2J_C + 1 \right)}{(2J_A + 1)(2J_a + 1)} \frac{\Gamma_{aA} \Gamma_{bB}}{\left( \epsilon - \epsilon_0 \right)^2 + \left( \frac{\Gamma}{2} \right)^2}
\]

Applying this to \((n,\gamma)\) reactions

\[
\sigma_{n,\gamma} = \pi \hat{\lambda}^2 \frac{\left( 2J_C + 1 \right)}{(2J_A + 1)(2)} \frac{\Gamma_n \Gamma_{\gamma}}{\left( \epsilon - \epsilon_0 \right)^2 + \left( \frac{\Gamma}{2} \right)^2}
\]
Γ/D >> 1

For reaction $a + A \rightarrow C \rightarrow b + B$

$$\sigma_{ab} = \sigma_C P_C(b)$$
Γ/D >> 1

- Assumption is that of statistical equilibrium
- For reaction $a + A \rightarrow C \rightarrow b + B$
  \[ \sigma_{ab} = \sigma_{C} \cdot P_{C}(b) \]
- So the problem is to calculate the probability that $C$ will decay to $B + b$.

\[
\sigma(a,b) = \pi R_{aA}^2 \left(1 - \frac{B_{aA}}{\epsilon_{aA}}\right) \int_{x}^{U_{C} - S_{B}} \frac{I(\epsilon_{Bb}) \, d\epsilon_{Bb}}{\sum_{j} \int_{0}^{U_{C} - S_{B}} I(\epsilon_{j}) \, d\epsilon_{j}},
\]

\[
I(\epsilon_{Bb}) \, d\epsilon_{Bb} = \frac{8 \mu_{Bb} \sigma_{Bb} \cdot \epsilon_{Bb} \cdot \rho_{B}(U_{C} - S_{b} - \epsilon_{Bb})}{\hbar^{3} \rho_{C}(U_{C})} \, d\epsilon_{Bb},
\]
Level densities

\[ \rho(E^*) = C \exp[2(aE^*)^{1/2}] \]

\[ a = \frac{A}{12} \text{ to } \frac{A}{8} \]

\[ E^* = aT^2 - T \]
If emitted particles are neutrons

\[ N(\varepsilon) d\varepsilon = \frac{\varepsilon}{T^2} \exp\left(-\frac{\varepsilon}{T}\right) d\varepsilon \]
If emitted particles are charged particles

\[ N(\varepsilon) d\varepsilon = \frac{\varepsilon - \varepsilon_s}{T^2} \exp\left(-\frac{\varepsilon - \varepsilon_s}{T}\right) d\varepsilon \]
Excitation functions
Photonuclear Reactions
Photonuclear Reactions

- GDR— a giant oscillation of the nuclear protons vs the nuclear neutrons
- dipole sum rule

\[ \int_{0}^{\infty} \sigma_{abs}(E_\gamma) \, dE_\gamma \propto \frac{NZ}{A} \approx 0.058 \frac{NZ}{A} MeV - barns \]
Heavy Ion Reactions

• Classical motion
• Dominated by high angular momentum
• $A_{\text{proj}} > 4$
Mechanisms

- Peripheral collisions
- Grazing collisions
- Distant collisions

Elastic scattering direct reactions
Incomplete fusion and deep inelastic collisions
Elastic (Rutherford) scattering Coulomb excitations
Mechanisms
Elastic scattering
BOMBARDING ENERGY

A
ENERGY NEEDED TO MAKE CONTACT

B
ENERGY TO OVERCOME CONDITIONAL SADDLE

C
ENERGY TO OVERCOME UNCONDITIONAL SADDLE

COMPOUND NUCLEUS
REACTIONS

MONONUCLEUS (FUSION-FISSION LIKE)
REACTIONS

DINUCLEUS (DAMPED OR DEEP-INELASTIC)
REACTIONS

BINARY (ELASTIC AND QUASI-ELASTIC)
REACTIONS

EXTRA PUSH
\[ \sigma_R = \pi R_{\text{int}}^2 \left[ 1 - \frac{V(R_{\text{int}})}{E_{\text{cm}}} \right] \]

\[ R_{\text{int}} = R_1 + R_2 + 3.2 \text{ fm} \]

\[ R_I = 1.12 A_i^{1/3} - 0.94 A_I^{-1/3} \text{ fm} \]

\[ V(R_{\text{int}}) = 1.44 \frac{Z_1 Z_2}{R_{\text{int}}} - b \frac{R_I R_2}{R_1 + R_2} \]
Fusion of $^{16}$O + $^{A}$Sm

$^{148}$Sm: $\beta_2 = 0$

$^{154}$Sm: $\beta_2 = 0.3$

$E_{\text{Lab}}$ (MeV) vs. $\sigma_{\text{int}}$ (mb)
$^{40}\text{Ar}(^{124}\text{Sn},xn)^{164-x}\text{Er}$

$E_{\text{Beam}} = 161$ MeV

$E^* = 53.8$ MeV
Deep Inelastic Scattering
High Energy Reactions

- Low energy (< 10 MeV/A)
- Intermediate Energy (20-250 MeV/A)
- High Energy (>250 MeV/A)
Spallation
New high energy mechanisms

- Spallation
- IMF formation
- Cascade processes
- Participant-Spectator Picture
Cascades

nucleon-nucleon collisions
Participant-Spectator Physics

(a) ABRASION

"DIRTY CUT"

ABLASION

(b)
Multifragmentation

- “Multifragmentation” refers to central collisions where several IMFs are emitted.
- Caloric curve