PH501 · ADVANCED NUCLEAR PHYSICS

Lecture 1 — Why we do nuclear reactions

M.J. Kobra, Department of Physics, University of Rajshahi

1. Why reactions?

A nucleus is ~10^{-14} m across. No microscope reaches that, so we fire a probe at it and see what comes back. Reactions are our only direct test of shell-model and collective-model predictions. They also built every element heavier than helium inside stars. Rutherford's origin: Geiger and Marsden (1909) fired alphas at gold foil; ~1 in 8000 scattered past 90°, proving the charge sits in a tiny core.

2. Notation

$a + A \to b + B$, written compactly as $A(a, b)B$. Target first, then (projectile, ejectile), then residual. Example: $^{40}\mathrm{Ca}(d, p)^{41}\mathrm{Ca}$.

Type	Example	What it probes
Elastic	$A(a, a)A$	Potential, nuclear size
Inelastic	$A(a, a')A^*$	Collective structure, deformation
Stripping	$A(d, p)B$	Single-particle orbitals
Pickup	$A(p, d)B$	Hole states
Knockout	$A(p, 2p)B$	Deep-hole states, occupancies
Capture	$A(n, \gamma)B$	Stellar reactions
Compound	$a + A \to C^* \to \dots$	Level densities, statistics

3. Conservation laws

Quantity	Holds	Comment
Energy	always	Q-value follows from this
Momentum	always	Defines the CM frame (Lecture 2)
Charge Z	always	Proton numbers balance
Baryon number A	always	Mass numbers balance
J	always	Selection rules (Lecture 8)
Parity π	strong, EM	Weak breaks it; irrelevant here
Isospin T	strong	Coulomb breaks it slightly

4. The Q-value

$$Q = (m_a + m_A - m_b - m_B)\,c^2 = (T_b + T_B) - T_a$$

$Q > 0$: exothermic, runs at any energy (e.g. ^{6}Li(n, α)^{3}H, $Q = +4.78$ MeV). $Q < 0$: endothermic, has a threshold (e.g. ^{14}N(α, p)^{17}O, $Q = -1.19$ MeV). Lecture 2 derives the threshold formula.

Worked example: ^{40}Ca(d, p)^{41}Ca.

$$\Delta m = (2.014102 + 39.962591) - (1.007825 + 40.962278) = +0.006590 \text{ u}$$

$$Q = 0.006590 \times 931.494 \approx +6.14 \text{ MeV}$$

Exothermic. The neutron is more tightly bound in ^{41}Ca than in the deuteron; the proton carries most of the released energy.

5. Direct vs compound

A nucleon crosses a nucleus in ~10^{-22} s. *Direct*: the projectile interacts with one or a few nucleons and leaves before the energy spreads (fast, one-step, surface, remembers the entrance). *Compound*: the projectile is absorbed, energy equilibrates over ~10^{-16} s, one nucleon eventually escapes (Bohr independence: forgets how it formed).

	Direct	**Compound**
Time	~10^{-22} s	~10^{-16} s
Mechanism	surface, one-step	volume, many-step
Spectrum	discrete peaks, high E	smooth Maxwellian, low E
Angular dist.	forward-peaked, oscillatory	≈ symmetric about 90°
Memory	yes	no
Selectivity	strong	weak

Either the energy spectrum or the angular distribution on its own usually identifies the mechanism.

Direct reactions are selective: each type reads out a specific piece of structure. Elastic → potential and size (dσ/dΩ diffraction). Inelastic → deformation (collective 2^+ strength). (d, p) → ℓ from the angular-distribution shape, S from its magnitude. Knockout → deep-hole occupancies. That ℓ-and-S measurement is how reactions connect to the shell model (Lectures 6, 8).

6. The four families

Family	**Reaction**	**What happens**	**Example**
Stripping	(d, p)	nucleon transferred projectile → target	^{40}Ca(d, p)^{41}Ca
Pickup	(p, d)	nucleon transferred target → projectile	^{41}Ca(p, d)^{40}Ca
Break-up	(d, np)	loosely-bound projectile splits	^{9}Be(d, np)^{9}Be

Family	Reaction	What happens	Example
Knock-out	$(p, 2p)$	target nucleon ejected; both emerge	$^{16}O(p, 2p)^{15}N$

Next: Lecture 2

We can now classify reactions and compute Q. What we need next: where do the products go? Lecture 2 gives the LAB ↔ CM transformations, the Q-value equation, and the threshold formula.

References

- Satchler, *Introduction to Nuclear Reactions*, 2nd ed. (1990): §1.3, §2.1, §2.3–2.5, §2.18.
- Bertulani, *Nuclear Physics in a Nutshell* (2007): ch. 10.
- Krane, *Introductory Nuclear Physics* (1988): ch. 11.