ICPY473 Nuclear Physics
MUIC, Third Trimester 2020-21
U. Robkob, Physics-MUSC
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8 Nuclear Reactions

To make change of atomic nucleus by nuclear interaction, using collision process.

8.1 Reaction equation

Let T-target nucleus, P-projectile particle, R-residue nucleus from the reaction and x-emitted particle after reaction. The nuclear reaction equation reads

$$P + T \rightarrow R + x(s) \quad or \quad T(P, x)R \tag{8.1}$$

For example of ${}^{14}N(\alpha, p)^{17}O$, it was first done by E. Rutherford in 1910. The reaction energy Q is calculated from mass defect as

$$Q = (M_T + M_P - M_R - M_x)c^2 \tag{8.2}$$

For examples, see figure (8.1).

Reaction	Measured Q (MeV)	Reaction	Measured Q (MeV)
${}^{2}H(n,\gamma)^{3}H$	6.257 +/- 0.004	${}^{9}Be(p,\alpha)^{6}Li$	2.132 +/- 0.006
${}^{2}H(d,p)^{3}H$	4.032 +/- 0.004	${}^{10}B(n,\alpha)^{7}Li$	2.793 +/- 0.003
${}^{6}Li(p,\alpha)^{3}H$	4.016 +/- 0.005	${}^{10}B(p,\alpha)^{7}Be$	1.148 +/- 0.003
${}^{6}Li(d,p)^{7}Li$	5.020 +/- 0.006	${}^{12}C(n,\gamma)^{13}C$	4.948 +/- 0.004
${}^{7}Li(p,n)^{7}Be$	-1.645 +/- 0.001	${}^{13}C(p,n)^{13}N$	-3.003 +/- 0.002
${}^{7}Li(p,\alpha)^{4}He$	17.337 +/- 0.007	$*{}^{14}N(p,n)^{14}C$	-0.627 +/- 0.001
${}^{9}Be(n,\gamma)^{10}Be$	6.810 +/- 0.006	${}^{14}N(n,\gamma)^{15}N$	10.833 +/- 0.007
${}^{9}Be(\gamma,n)^{8}Be$	-1.666 +/- 0.002	${}^{18}O(p,n)^{18}F$	-2.453 +/- 0.002
${}^{9}Be(d,p)^{10}Be$	4.585 +/- 0.005	${}^{19}F(p,\alpha)^{16}O$	8.124 +/- 0.007

Figure 8.1: Nuclear reaction energy.

8.2 Reaction kinematics

In LAB-frame, fixed target, from energy conservation condition we have

$$M_P c^2 + K_P + M_T c^2 = M_R c^2 + K_R + M_x c^2 + K_x \tag{8.3}$$
$$Q = (M_P + M_T - M_R - M_x)c^2 = K_R + K_x - K_P \tag{8.4}$$

For $Q > 0$ it is called *exoergic reaction*, while for $Q < 0$ it is called *endoergic reaction*. From the reaction diagram below, see figure (8.2), the momentum conservation says that

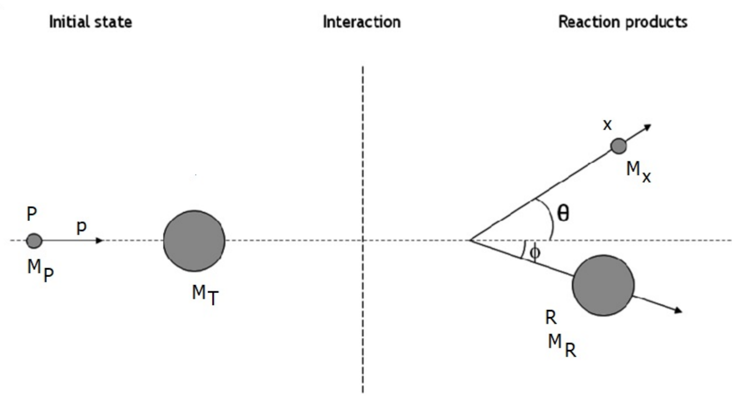

Figure 8.2: Nuclear reaction diagram.

$$M_p v_p = M_x v_x \cos\theta + M_R v_R \cos\phi \tag{8.5}$$
$$0 = -M_x v_x \sin\theta + M_R v_R \sin\phi \tag{8.6}$$

With $p = Mv = \sqrt{2MK}$, and using the fact that $\cos^2\phi + \sin^2\phi = 1$, we have

$$M_P K_P - 2(M_P K_P M_x K_x)^{1/2}\cos\theta + M_x K_x = M_R K_R \tag{8.7}$$

Replacing K_R in term of Q, we get

$$Q = K_x\left(1 + \frac{M_x}{M_R}\right) - K_P\left(1 - \frac{M_P}{M_R}\right) - \frac{2}{M_R}\sqrt{M_P K_P M_x K_x}\cos\theta \tag{8.8}$$

The prediction of Q from measured K_x in θ-direction. Conversely we have

$$\sqrt{K_x} = \sqrt{M_x M_P K_P}\cos\theta \pm \left\{M_x M_P K_P \cos^2\theta \right.$$
$$\left. +(M_R + M_x)[M_R Q + (M_R - M + P)K_P]\right\}^{1/2}/(M_x + M_R) \tag{8.9}$$

The prediction of K_x in θ-direction from the calculated Q. This shows the double-valued of K_x.

8.3 Threshold energy

In case of $Q < 0$ reaction, we need threshold energy of the projectile particle $K_P = K_{th}$ to initiate the reaction. Let us determine this in CM-frame

$$K_{CM} = \frac{M_P + M_T}{2} v_{CM}^2, \quad v_{CM} = \frac{M_P}{M_P + M_T} v_P \tag{8.10}$$

$$\rightarrow K_{CM} = \frac{1}{2} M_P v_P^2 \frac{M_P}{M_P + M_T} = K_{LAB} \frac{M_P}{M_P + M_T} \tag{8.11}$$

with $K_{LAB} = K_P$. Since the dissipate energy in the reaction is $E_{dis} = K_{LAB} - K_{CM}$, so that the energy available for the reaction is $E_{dis} + Q \geq 0$. At the threshold $E_{dis-th} + Q = 0$, then

$$K_{LAB} - K_{CM} = K_{LAB} \left(1 - \frac{M_P}{M_P + M_T}\right) = K_{LAB} \frac{M_T}{M_P + M_T} \tag{8.12}$$

$$\rightarrow E_{dis-th} = K_{LAB-th} \frac{M_T}{M_P + M_T} \rightarrow K_{th} = -Q \frac{M_T}{M_P + M_T} \tag{8.13}$$

For example of $^{14}N(\alpha, p)^{17})$, with $Q = -1.19MeV$, so that

$$K_{\alpha-th} = -(-1.19MeV) \frac{4 + 14}{14} = 1.53MeV$$

8.4 Reaction stages

According to V. Weisskopf

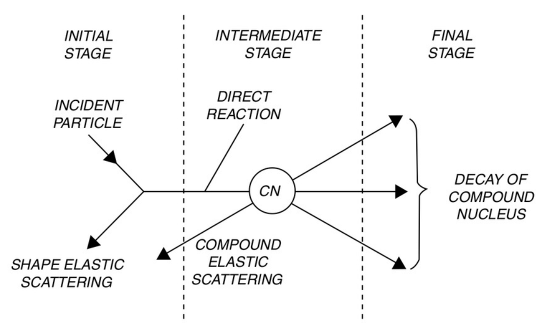

Figure 8.3: Nuclear reaction stages.

8.5 Reaction cross section