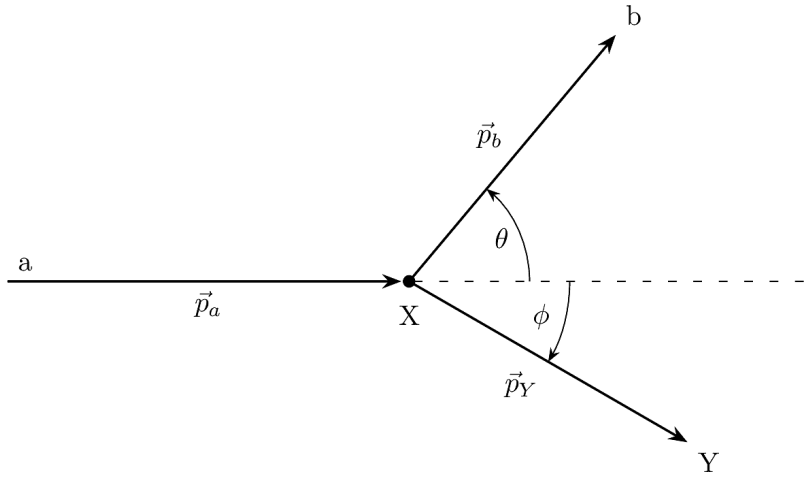
Supplementary Worksheet #11
Nuclear Reactions

1 Basics



Atom or particle	Atomic mass (u)
n	1.00866491595
$^{1}\mathrm{H}$	1.00782503223
$^{4}\mathrm{He}$	4.00260325413
$^{13}\mathrm{C}$	13.00335483507
$^{16}\mathrm{O}$	15.99491461957
$^{58}\mathrm{Ni}$	57.93534241
$^{61}\mathrm{Cu}$	60.9334578

1.1 Relationships

Consider the nuclear reaction $X(a,b)Y$, in which projectile a strikes a stationary target X, producing particle b and residual nucleus Y. The figure shows the reaction geometry in the laboratory frame.

1. Write the reaction Q value in terms of the nuclear masses of X, a, b, and Y.
2. Explain why atomic masses may be used instead of nuclear masses for this reaction.
3. Express Q in terms of the kinetic energies T_a, T_b, and T_Y.
4. Write the kinematic relation connecting Q, T_a, T_b, and the laboratory emission angle θ of particle b. Identify the term that contains the angular dependence.
5. For an endothermic reaction ($Q < 0$), write the expression for the threshold projectile energy in the laboratory frame.

1.2 Think about the physics.

6. Why does the kinetic energy of the outgoing particle depend on its emission angle?
7. Why is the threshold energy of an endothermic reaction greater than $|Q|$?
   Why isn't it simply $(m_a + m_X) - (m_b + m_Y)$?
8. At threshold, are the outgoing particles necessarily at rest? Explain your answer.

2 Nuclear Reaction $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}^*$

It is desired to study the first excited state of $^{16}\mathrm{O}$, which lies at an energy of $6.049\ \mathrm{MeV}$ above the nuclear ground state. This state can be populated using the (α, n) reaction on a $^{13}\mathrm{C}$ target: $^{13}\mathrm{C}(\alpha, n)^{16}\mathrm{O}^*$ where $^{16}\mathrm{O}^*$ denotes the excited nucleus.

9. Write the expression for the Q **value** using nuclear masses, including the excitation energy of $^{16}\mathrm{O}$.

10. Calculate Q and state whether the reaction is exothermic or endothermic [Ans: $-3.833\ \mathrm{MeV}$; endothermic].

11. Using the result from part **9.**, calculate the **threshold energy** of the incident α particle [Ans: $5.013\ \mathrm{MeV}$].

12. At threshold, at what laboratory angle is the neutron emitted? [Ans: $0°$]

13. How does the emitted neutron's energy depend on its laboratory angle relative to the incident beam?

14. Determine the **minimum** α**-particle energy** required for neutron emission at $90°$ [Ans: $5.113\ \mathrm{MeV}$].

3 Nuclear Reaction $^{58}_{28}\mathrm{Ni}(\alpha, p)^{61}_{29}\mathrm{Cu}$

15. Determine the Q **value** for the nuclear reaction $^{58}_{28}\mathrm{Ni}(\alpha, p)^{61}_{29}\mathrm{Cu}$ using the Q-value Calculator (QCalc) available at the National Nuclear Data Center website: `nndc.bnl.gov/qcalc/`.

16. Shown below are two spectra of protons obtained from this reaction using an α-particle beam with an energy of $12.5\ \mathrm{MeV}$.

The highest-energy proton group corresponds to population of the ground state of $^{61}\mathrm{Cu}$ (labelled 0), while the remaining groups correspond to excited states labelled $1, 2, 3, \ldots$.

The spectra were recorded at laboratory angles of $90°$ and $154°$.

a) What do the axes of the spectra represent?

b) Explain why multiple proton energies are observed at a fixed detector angle.

c) Identify which spectrum corresponds to $90°$ and which corresponds to $154°$.

d) The peaks corresponding to the same excited states have different heights in the two spectra. Explain why the peak intensities are not the same.

