Astro 596/496 NPA
Lecture 6
January 28, 2019

Announcements:

- Problem Set 1 posted on Compass
  uses solar system abundance data posted on course links

Last Time(s): odd/even effect in nuclear binding

`www: solar abundances for odd and even` $A$

magic numbers

*Q: role in nuclear stability?* `www: Chart of Nuclides`

*Q: role in solar system abundances?*

`www: solar abundances vs neutron number` $N$

decays *Q: basic types? typically* $\gamma$ *decay energy?*

`www: sample of nuclear level diagrams`

# Astrophysical Gamma Decays

famous example: $^{26}$Al decay chain

$$
\begin{aligned}
{}^{26}\mathrm{Al} &\rightarrow {}^{26}\mathrm{Mg}^{*} + e + \nu \\
& \quad {}^{26}\mathrm{Mg}^{*} \rightarrow {}^{26}\mathrm{Mg}^{\mathrm{g.s.}} + \gamma
\end{aligned}
\tag{1}
$$

where g.s. = ground state

`www:` $^{26}$Al `decay scheme`

$t_{1/2}(^{26}\mathrm{Al}) = 0.7$ Myr; $t_{1/2}(^{26}\mathrm{Mg}^{*}) = 0.5$ ps

*Q: decay modes? overall timescale?*

*Q: what required to see* $^{26}$Al *decays astrophysically?*

*Q: why might we hold out hope?*

# The Radioactive Sky: Aluminum-26

*to observe* $^{26}$Al *decay photons*

- em $^{26}$Al must exist in the cosmos today
- and *must decay where photons not absorbed*
- and *must be abundant enough* that $\gamma$ line flux detectable

hope: $^{26}$Al *long-lived*, might escape birth environment

experiment: search sky for 1.8 MeV decay $\gamma$ rays

`www: Galactic coordinates`

`www: COMPTEL 1.8 MeV sky`

**decay line seen!**

ω *Q: basic, model-independent implications?*

*Q:* $t_{1/2}$($^{26}$Al) *vs relevant astrophysical timescales–implications?*

# $^{26}$Al Gamma Lines: Smoking Gun of Nucleosynthesis

Most immediately (i.e., most model-independent):

⋆ *live radioactivity is present today in space*
in the form of "fresh" $^{26}$Al

But we can push further:

- radioactive decay is exponential in time:
  radionuclides lost after a few $t_{1/2}$
- we know $t_{1/2}(^{26}\text{Al}) = 0.7$ Myr
- age of Earth/Sun $\sim 5$ Gyr,
  age of Galaxy (i.e., Milky Way disk) $\sim 10$ Gyr

⇒ the $^{26}$Al we see was born "yesterday"
**nucleosynthesis is ongoing in the Galaxy today!**



*Q: implications of* $^{26}$Al *signal morphology (sky pattern)?*

# Implications of $^{26}$Al Gamma-Line Sky Morphology

- $^{26}$Al signal traces Galactic plane
  this is where star birth (and death) occur

⇒ **(at least some) nucleosynthesis is associated with stars**

- $^{26}$Al signal is *diffuse* – not collection of points
  (tricky to show because angular resolution bad)

⇒ $^{26}$Al is in the *interstellar medium* (ISM)
and since $^{26}$Al short-lived compared to stars

▷ **stars eject fresh nucleosynthesis products which mix into the ISM**

INTEGRAL can measure line shape, position well

`www:` $^{26}$Al `line shift vs Galactic longitude`

*Q: summarize result? implications? possible interpretation?*

# Other Astrophysical Radioactivities

**$^{60}$Fe** $t_{1/2} = 2.6$ Myr

- decay chain → gamma lines: similar to $^{26}$Al
- *diffuse line signal in Galactic* plane: similar to $^{26}$Al
- line ratio → $^{26}$Al/$^{60}$Fe ratio: probes SN nucleosynthesis!

**$^{56}$Ni** produced abundantly in supernovae

chain: $^{56}\mathrm{Ni} \xrightarrow{\text{6 days}} {}^{56}\mathrm{Co} \xrightarrow{\text{77 days}} {}^{56}\mathrm{Fe}$

decay energy trapped in remnant, *powers optical/IR luminosity*

*Q: if radioactively powered, SN brightness vs time?*

`www: SN light curves`

**$^{44}$Ti** produced modestly in supernovae

$t_{1/2} = 60.0$ yr *Q: implications? predictions?*

`www: Cas A, SN 1987A`

# Nuclear Reactions

interactions (collisions) can transform nuclei

example: two-body to two-body nuclear reaction

$$a + b \to c + d$$

initial state: *reactants* or parents
final state: *products* or daughters

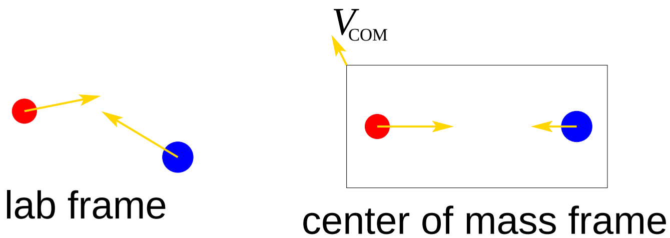
If one reactant is at rest: called a *target*
and bombarding particle is *projectile*

Notation

$a + b \to c + d$ written $a(b, c)d$
usually $a$ projectile, $b$ target, $c$ the faster daughter
e.g., $^{12}\text{C} + {}^{4}\text{He} \to {}^{16}\text{O} + \gamma$ is $^{12}\text{C}(\alpha, \gamma)^{16}\text{O}$

# Nuclear Reaction Kinematics

natural preferred frame: *center of mass*




$m_1\vec{v}_1 + m_2\vec{v}_1 = (m_1 + m_2)\vec{V}_{\text{CM}}$ (non-rel)

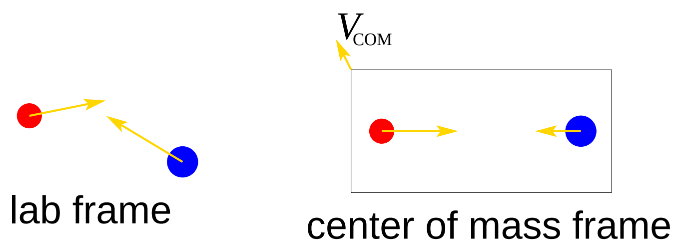
relative velocity: $\vec{v} = \vec{v}_1 - \vec{v}_1$

kinetic energy: two components

$$KE = \frac{1}{2}m_1 v^2 + \frac{1}{2}m_2 v^2$$
$$= \frac{1}{2}\mu v^2 + \frac{1}{2}(m_1 + m_2)V_{\text{CM}}^2 = (KE)_{\text{in CM}} + (KE)_{\text{of CM}}$$

where *reduced mass* $\mu = m_1 m_2/(m_1 + m_2)$

*Q: how much energy available for reaction?*




go to center of mass frame: $V_{\rm COM} = 0$

*energy available for reaction: kinetic energy in COM*

$$KE_{\rm COM} = \frac{1}{2}\mu v_{\rm rel}^2 \qquad (2)$$

consider nuclear reaction $a + b \rightarrow c + d$, i.e., $a(b,c)d$

*Q: how does energy conservation look?*

# Energy Conservation

for *reactions and decays* **total energy is conserved**

$$E_{\text{final}} = E_{\text{initial}} \tag{3}$$

but Einstein says: total energy includes rest mass energy!

example: "2 to 2" reaction $a + b \to c + d$:

$$(m_c + m_d)c^2 + (KE)_f = (m_a + m_b)c^2 + (KE)_i \tag{4}$$

where $KE$ is kinetic energy in center of mass

*change* in kinetic energy:

$$(KE)_f = (KE)_i + (m_a + m_b - m_c - m_d)c^2 \tag{5}$$

*Q: implications?*

# Nuclear Reaction Energy Release $Q$

reaction kinetic energy change

$$(KE)_f = (KE)_i + (m_a + m_b - m_c - m_d)c^2 = (KE)_i + Q \quad (6)$$

with reaction $Q$ value:

$$\begin{aligned} Q &= \text{initial masses - final masses} && (7) \\ &= [m_a + m_b - (m_c + m_d)]\, c^2 && (8) \\ &= \Delta_a + \Delta_b - \Delta_c - \Delta_c && (9) \end{aligned}$$

where last line uses mass defects & baryon conservation

**exothermic** reactions: $Q > 0$ (mass energy released)

can occur for any $(KE)_i$; "forward" reaction

**endothermic** reactions: $Q < 0$

need $(KE)_i > |Q|$ to go: " reverse" reaction

$\Rightarrow$ there is a "*threshold*" energy