Astro 596/496 NPA
Lecture 3
Aug. 28, 2009

Announcements:

• PF 1 posted due Fri. Sept. 2, $\leq$12noon

Last time: abundances

Q: top 3 cosmic components?

Q: top solar system elements?

`www: solar system abundances`

clear patterns, features in solar system composition

want to understand how these patterns came about

we will see: these patterns represent
  a symphony of cosmic and stellar processes

Nuclear Physics

Nuclear Physics

atomic nuclei make of **nucleons** = protons and neutrons

nucleon	mass	spin	charge
proton	$m_p c^2 = 938$ MeV	$S_p = 1/2$	$Q_p = \|Q_e\| = e$
neutron	$m_n c^2 = m_p c^2 + 1.3$ MeV	$S_n = 1/2$	$Q_n = 0$

consider a nucleus with Z protons, N neutrons

mass number $A = Z + N$

Q: baryon number?

notation: $\boxed{{}^{A}_{N}\mathrm{X}^{Z}}$

but usually use shorthand, because:

chemical symbol X $\Rightarrow Z$, then can get $N = A - Z$

e.g., ${}^{3}_{1}\mathrm{He}^{2} \rightarrow {}^{3}\mathrm{He}$

"nuclide" $=$ a particular (Z, N) combination
(strictly, and a particular energy state)

`www: chart of the nuclides` – note axes

isobar: fixed A (e.g., ^{7}Li and ^{7}Be)
isotope: fixed Z (e.g., ^{6}Li and ^{7}Li)
isotone: fixed N (e.g., ^{14}N and ^{15}O)
Q: any Simpson's fans?

Q: isobar/tope/tone patterns on nuclide chart?

Nuclear Masses

to zeroth order:
mass of nucleus $= A \times$ "nucleon mass"

to make this idea precise, define
atomic mass unit (amu):

$$\begin{aligned} m_{\mathrm{u}} &= \frac{m(^{12}\mathrm{C})}{12} = \frac{1\ \mathrm{g}}{N_{\mathrm{A}}\mathrm{mol}} = 1.66 \times 10^{-24}\ \mathrm{g} \\ &= 931.5\ \mathrm{MeV}/c^2 \simeq 1\ \mathrm{GeV}/c^2 \\ &\simeq m_p \simeq m_n \end{aligned}$$

(neutral atom mass: includes $6 m_e c^2$)

now define: **mass excess** (or **mass defect**)

$$\Delta_i = (m_i - A_i m_u)c^2 \quad (1)$$

$\uparrow$ neutral atom mass (2)

e.g., $\Delta(^{12}\mathrm{C}) = 0$ *Q: why?*
$\Delta(^{16}\mathrm{O}) = -4.737$ MeV
$\Delta(^{1}\mathrm{H}) = 7.289$ MeV
`www: wallet card`

Q: why are mass defects $\neq 0$ for all but ^{12}C?

Nuclear Binding Energy

binding energy: for nuclide i

$$B_i = \text{parts} - \text{whole} \tag{3}$$

$$= \left(Z_i m_{\mathrm{H}} c^2 + N_i m_n c^2\right) - m_i c^2 \tag{4}$$

stability requires $B_i > 0$, i.e., whole $<$ sum of parts
(c.f., $m_{\mathrm{H}} = m_p + m_e - 13.6 \text{ eV}/c^2$)
Q: why?

`www: Chart of nuclides` – note valley of stability

note that larger nuclei have large B_i, but shared among more nucleons, so invent:
binding energy per nucleon B_i/A_i

`www: Great curve of nuclear binding energy`
Q: what strikes you?

Binding Energy: Trends and Consequences

Nuclear binding energy features:

- sharp rise in B_i/A_i at low A
- local max at ^{4}He
- no stable nuclei at $A = 5, 8$
- lowest B/A for D, LiBeB
- max B/A for middle masses: peak at ^{56}Fe

with this in mind, revisit solar abundances:

`www: SS abundances`

Q: significance?

The Nuclear Fingerprint in Solar Abundances

Many observed features in solar abundances
reflect observed features in nuclear binding energy curve

for example:

⋆ D, Li, Be, B are "fragile": weakly bound–low B/A
  but these also have very low abundances

⋆ binding has broad peak around ^{56}Fe
  ...where abundances show a broad peak

See nuclear BE effects in SS
(and stellar) abundances:

⇒ confirms: abundance pattern controlled by *nuclear physics*!

but atoms have their own binding too...

Q: why can't *abundance pattern be due to atomic binding?*

Nuclei vs Atoms

Useful to compare/contrast nuclear vs atomic interactions and structures

Q: controlling forces/interaction(s) in each?

Q: nuke/atomic similarities?

Q: nuke/atomic differences?

Properties of the Nuclear Force

EM force completely understood
via Maxwell's equations and QED
for static point charges: simple potential $V(r) = Q/r$
- central force
- always either attractive or repulsive

Nuclear force not fully understood, much more complicated
(see, e,g., Krane, *Nuclear Physics*)
- nuclear interaction and nucleons not fundamental
but manifestations of strong interactions among quarks
analogy: EM force vs molecular interactions
- nucleon-nucleon $(N - N)$ potential
not known from first principles: empirical

The Nuclear Force

- $N - N$ interaction *attractive* a "large" distances $\gtrsim 1$ fm,
  strongly *repulsive* at short distances $\lesssim 1$ fm
  $\rightarrow 0$ at ~ 1 fm

- $N - N$ interaction strongly *spin-dependent*
  e.g., $d = np$ exists only as $J = 1$ $(p \uparrow n \uparrow)$, *not* $J = 0$ $(p \uparrow n \downarrow)$
  $\Rightarrow$ have $\vec{s}_1 \cdot \vec{s}_2$ terms in $N - N$ potential

- $N - N$ potential has *non-central* "tensor" term
  anisotropic, angle average $= 0$

- $N - N$ force *charge symmetric*:
  $n - n$ interaction $= p - p$ aside from Coulomb effects

- $N - N$ nearly *charge independent*: $V_{nn} \simeq V_{pp} \simeq V_{np}$