Quick notes on
s-process

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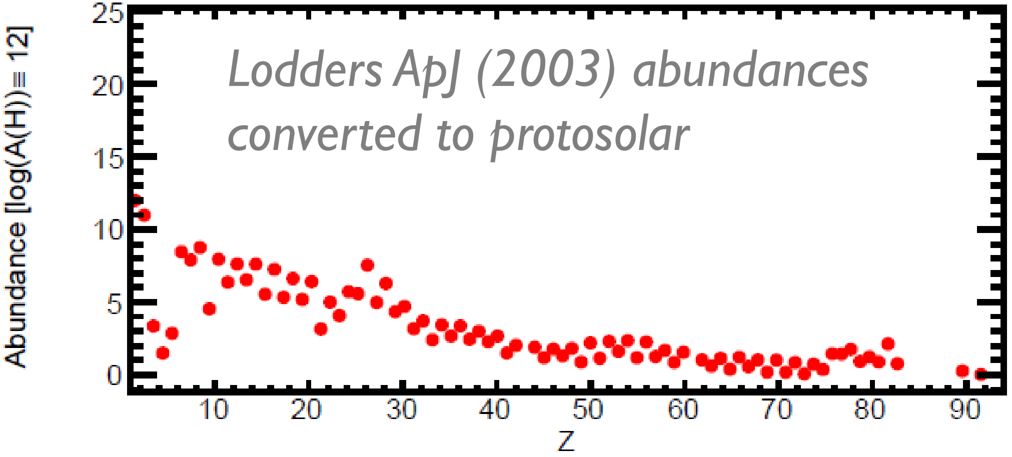
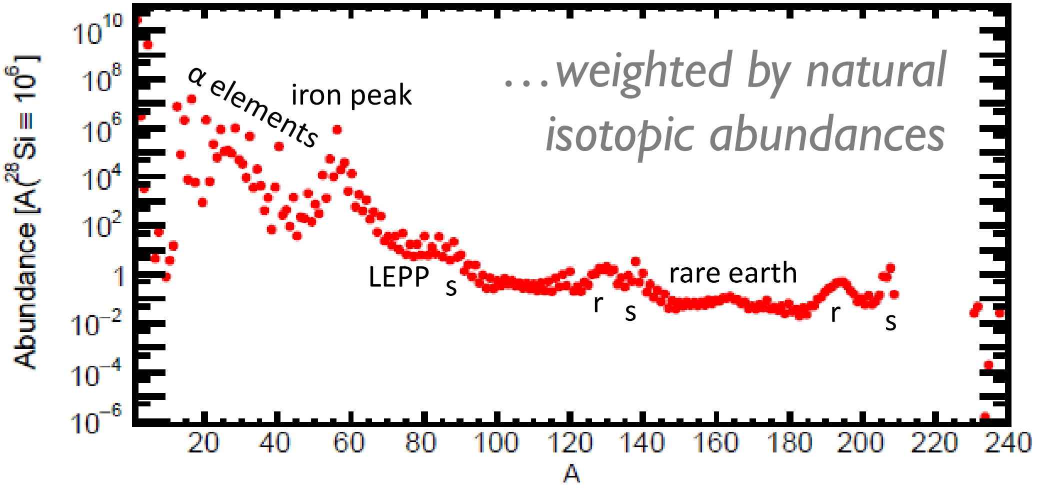
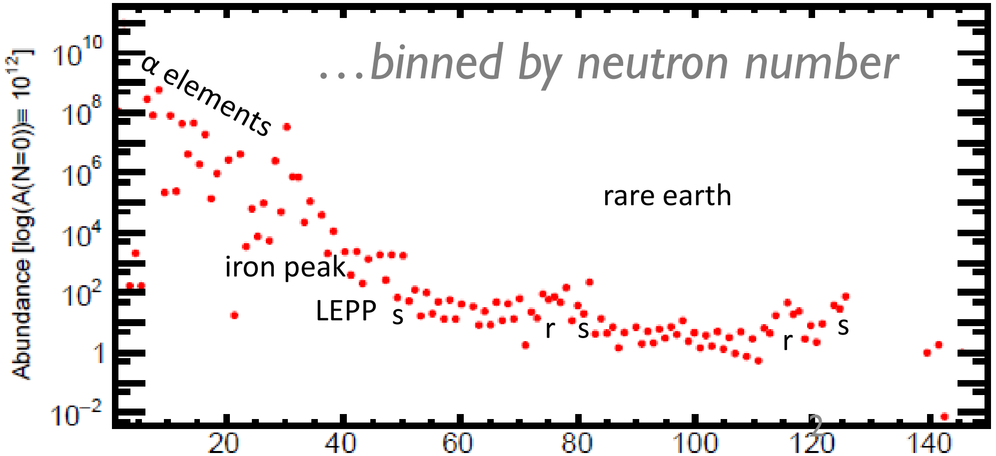
The case for neutron-capture processes

- Looking at the solar system abundances in terms of A, we see some pretty interesting patterns
- The α elements and iron peak are consistent with our picture for massive star evolution, but we see several other features beyond iron
- Focusing on the peaks labeled *s* and *r*, we see that the *s* peaks are located at neutron magic numbers 50, 82, 126, with the *r* peaks located just below (at least for 82 & 126)
- Logically, it follows that the processes making the *s* and *r* processes somehow involve sequences of neutron capture reactions that pass through these magic numbers on the nuclear chart. This is because one feature of magic N nuclei is low neutron-capture cross sections relative to neighboring nuclei

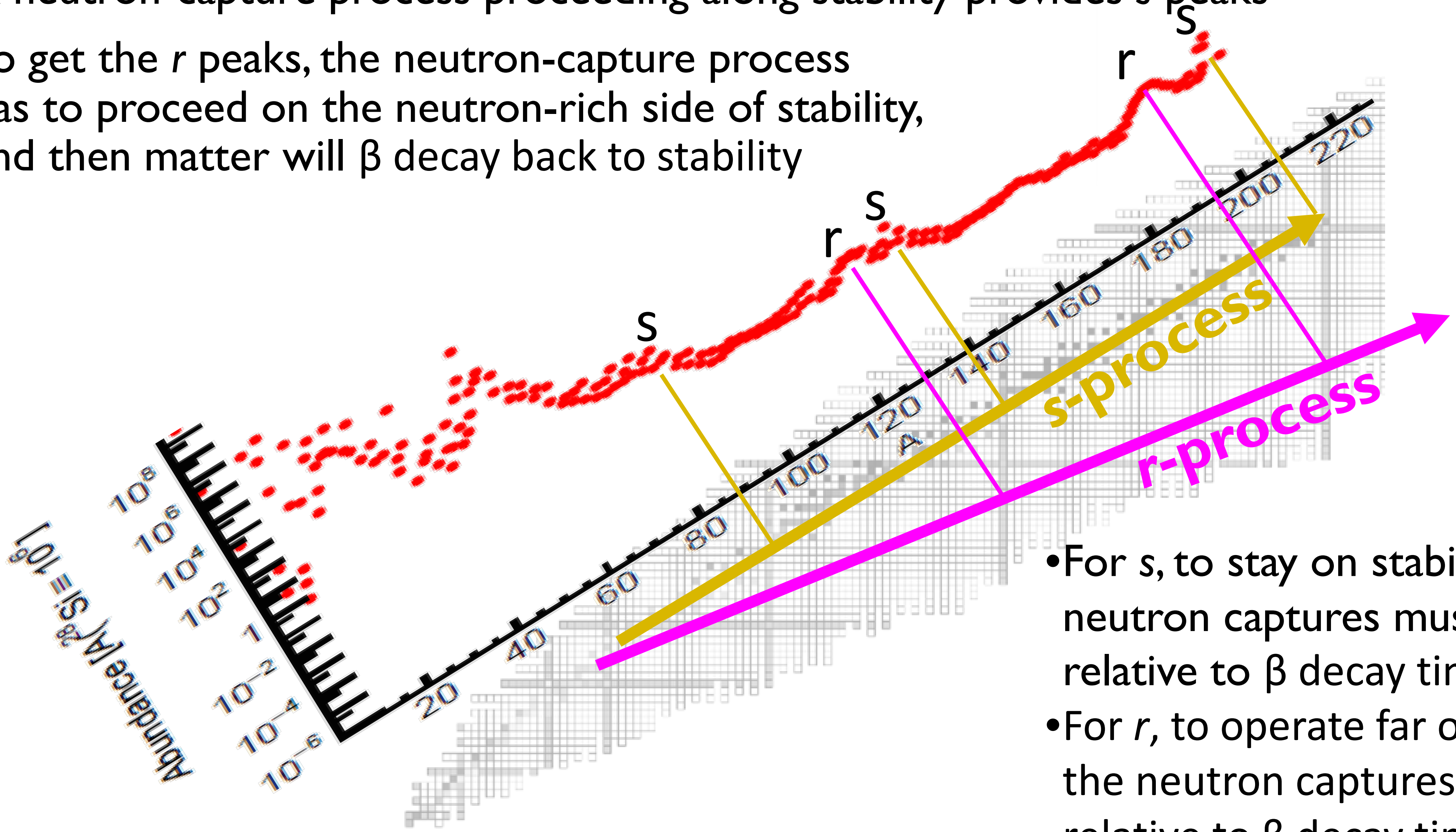

Lodders ApJ (2003) abundances converted to protosolar


…weighted by natural isotopic abundances


…binned by neutron number

We can see where on the nuclear chart the *s* & *r* processes must have occurred by considering where in terms of *Z* pile-up at a magic *N* must have occurred to give the observed peak in *A*

- A neutron-capture process proceeding along stability provides *s* peaks
- To get the *r* peaks, the neutron-capture process has to proceed on the neutron-rich side of stability, and then matter will β decay back to stability



- For *s*, to stay on stability, the neutron captures must be **s**low relative to β decay timescales
- For *r*, to operate far off stability, the neutron captures must be ***r***apid relative to β decay timescales

Neutron-capture time-scale: ‘s’-process

Time-scale for ‘slow’ neutron capture

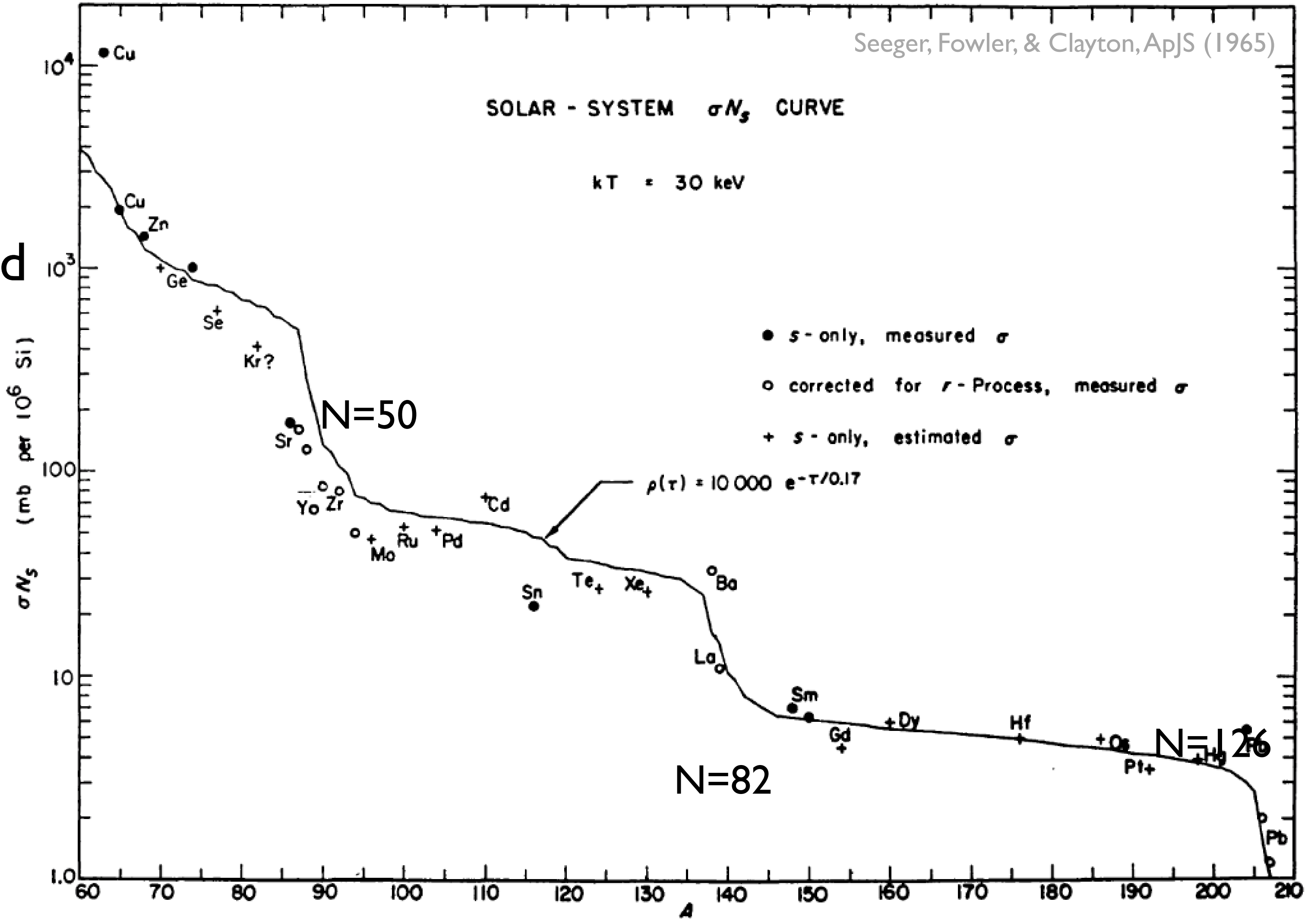
1. ~10^8 neutrons in a box of 1cm^3, each moving from thermal velocity
2. ~1/6 leave a single box side with a velocity given by:
   - E~kT ~mv^2 → $v=\sqrt{\frac{kT}{m}} \approx \sqrt{\frac{25keV}{10^{-27}kg}} \approx 10^9$cm/sec
3. 1/6 of the neutrons leave from a cube face, with 1cm^2 area every 10^{-9} seconds
   - → neutron flux ~10^{17} neutrons/cm^2/sec
4. neutron-capture cross-section (at ~25keV): ~100mb = $10^{-25}cm^2$
5. neutron-capture rate = (flux)x(cross-section)
   ≈ 10^{17} neutrons/cm^2/sec x 10^{-25} cm^2 = 10^{-8}/sec
6. neutron-capture time = 1/Rate ≈10^8seconds ~ 1 decade

s-process nucleosynthesis

- For the *s*-process, we need an environment where nuclei can bathe for a long time in a moderate neutron density ($n_n \sim 10^{7-10}\mathrm{cm}^{-3}$). Let's consider the reaction flow for this case.
- For isotope (Z,A), the abundance change is the sum of production & destruction mechanisms, $\frac{dN_{Z,A}}{dt}(t) = n_n(t) n_{Z,A-1}(t)\langle\sigma v\rangle_{Z,A-1} - n_n(t) n_{Z,A}(t)\langle\sigma v\rangle_{Z,A} - \lambda_{\beta:Z,A} n_{Z,A}(t)$
- We'll ignore species with fast β-decays, since they'll just form the more stable isobar more or less instantly, so we can set the last term to zero
- Note that $\langle\sigma v\rangle_{n\ cap} \sim constant$, and anyhow we'll assume a constant temperature, so $\langle\sigma v\rangle_i \rightarrow \sigma_i v_T$, where v_T is the thermal velocity for the environment temperature
- As such, our abundance change equation is now $\frac{dN_{Z,A}}{dt}(t) = n_n(t) v_T\left(\sigma_{Z,A-1} n_{Z,A-1} - \sigma_{Z,A} n_{Z,A}\right)$
- Note that $n_n(t) v_T$ is the neutron flux. Integrating this over time gives the neutron irradiation $\tau = \int_0^t n_n(t) v_T\, dt = v_T \int_0^t n_n(t)\, dt$, which is referred to as the neutron exposure
- Re-casting our abundance change in terms of τ, $\frac{dN_{Z,A}}{d\tau} = \sigma_{Z,A-1} n_{Z,A-1} - \sigma_{Z,A} n_{Z,A}$
- In equilibrium, $\frac{dN_{Z,A}}{d\tau} = 0$, so $\sigma_{Z,A-1} n_{Z,A-1} = \sigma_{Z,A} n_{Z,A} = constant$
- So, we can get *s*-process relative abundances based solely on neutron-capture cross sections!

The steady flow approximation

- The steady-flow approximation holds roughly in between magic *N*
- Tests can be performed for elements with multiple isotopes that are shielded from the *r*-process and have measured neutron-capture cross sections, e.g. ^{122,123,124}Te


Seeger, Fowler, & Clayton, ApJS (1965)

Reactions of special interest are those with half-lives similar to the neutron-capture time. They're called branch-points. They not only alter the abundance pattern, but can be used as s-process thermometers and neutron-density probes, since <σv> isn't exactly constant.

Where do the s neutrons come from?

- More careful analyses (e.g. checks with the Te isotopes and branch-points) demonstrate the need for different neutron fluxes for different durations.
  These are the
  - **Weak**: 60<A<90, near He/C shells in massive stars
  - **Main**: Sr-Pb, thermal pluses in AGB stars
  - **Strong**: Pb enhancement for low-metal AGB stars

  components. For each kT~30keV or thereabouts.
- No matter, the neutron sources turn-out to be $^{13}C(\alpha,n)$ and $^{22}Ne(\alpha,n)$, where the former only operates for the AGB cases and the latter only operates during brief flashes for the AGB cases

Herwig, Ann. Rev. Astron. Astro. 2005