NEUTRON-INDUCED NUCLEOSYNTHESIS
IN THE R-PROCESS

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For a long time, men tried to understand the world surrounding him. One way is to dissect complex structures and search for simpler, basic constituents.

Already in the 5. century B.C., Empedokles of Agrigent said that all material things are composed of only four basic constituents, the elements earth, water, air and fire.

The alchemists (and astrologers) thought that elements can be transmuted, but, apart from cosmogonies as in Genesis, there was no theory of the origin of elements.
Composition of extraterrestrial matter
Old and new observables

Optical spectroscopy: Bunsen/Kirchhoff
Birth of astrophysics 1863: 9 elements detected in Aldebaran and Betelgeuse

- Spectroscopy of ultra-metal-poor Halo stars
  Interstellar matter (ISM) 13 Gy ago

- Elemental and isotopic composition of meteorites
  Interstellar Medium 4.6 Gy ago

- Pre-solar grains in meteorites and high atmosphere
  ISM prior to formation of Solar system

- Ultra-heavy component of cosmic rays
  Recent nucleosynthesis events

- STARDUST at comet 81P/Wild 2 (Jan. 2004)
Hot Big-Bang Nucleosynthesis

Following the discovery of the expansion of the Universe, Lemaitre proposed, that the Universe at the beginning must have been extremely dense and hot.

In the late 40's, Gamow, Bethe et al. developed a first theory of nucleosynthesis in the first hour after the Big Bang. But, the neutron captures proposed, cannot overcome mass 8.

FIG. 1.
Log of relative abundance
Atomic weight
Solar System Abundances and Nuclear Structure

Already in 1917, Harkins connected elemental abundances and nuclear structure. Up to the mid-50’s, elemental and isotopic solar abundances were determined with high precision by several groups (as the Noddacks, Goldschmidt).

Harkins noted an odd-even effect.

Increased abundances for magic numbers were observed by W. Elsasser already around 1933.

Suess and Urey
„Abundances of the Elements“
(Rev. Mod. Phys. 28 (1956) 53)
In the early 50's, the development of the nuclear shell-model (Göppert-Mayer and Jensen, Haxel, Suess) was the basis for the understanding of nucleosynthesis.

Several groups worked out a detailed picture, as
- Suess and Urey
- A.G.W. Cameron
- C.D. Coryell
- B²FH

Remark: Hoyle wanted to explain nucleosynthesis without a „Big Bang“

Review of Modern Physics

Synthesis of the Elements in Stars

E. Margaret Burbidge, G. R. Burbidge, William A. Fowler, and F. Hoyle

„It is the stars, The stars above us, govern our conditions”;
(King Lear, Act IV, Scene 3)

but perhaps

„The fault, dear Brutus, is not in our stars, But in ourselves,“
(Julius Caesar, Act I, Scene 2)

B²FH, the „Bible“ of Nuclear Astrophysics
B²FH predicted correctly even the detailed behaviour at N=50, 82 and 126. The „climb up the staircases“, the major waiting-point nuclei involved, as well as the „break-through pairs“, and their „association with the rising sides of major peaks in the abundance curve for the r-process“ are still today important properties to be studied experimentally and theoretically.
B²FH concluded that a
"reasonable but not exact agreement with observed abundances is obtained".

Fig. VII.3 of B²FH: Classical static r-process calculation compared to observed abundances of Suess and Urey.
R-process cannot be described with one single parameter set. With fixed temperature at least four sets of neutron densities and time durations are necessary:

- three corresponding to the abundance maxima at neutron magic numbers 50, 82 and 126
- one for the actinide region
Shell Quenching?

Deficiencies prior to the main peaks were attributed by our group to nuclear structure effects: too strong shell strength for neutron-rich magic nuclei far from stability.

Question:
Can one learn neutron-dripline physics from astrophysical observables?
Nuclear physics input data

Data for extremely neutron-rich nuclei, mostly out of reach of actual experimental techniques:
- nuclear masses
- $\beta$-decay properties: $T_{1/2}$, $P_n$, $\beta$-delayed fission
- $(n,\gamma)$, $(\gamma,n)$, n-induced fission

Approximation to full network calculations already give insights in decisive data:
- "canonical" $r$-process
  - $(n,\gamma)\leftrightarrow(\gamma,n)$ equilibrium ("waiting-point")
  - $\beta$-flow equilibrium
  - Fe seed nuclei
  - $Y(Z)\lambda_\beta = \text{const.}$
  - In the simplest case, $S_n$ and $T_{1/2}$ (by given neutron number and temperature) are sufficient
Importance of **experimental** data

- The r-process abundances of the actinides depend also on nuclear-structure data at the **magic neutron-numbers**, nuclei which act as **bottle-necks** for the matter flow.
- Up to present, only neutron-rich nuclei with N=50 and 82 could be observed.
- Future RIB-facilities hopefully will make N=126 accessible for experiments.
Importance of **selectivity** in production and detection

Low production yields demand imperatively **high-selectivity** in separation and detection:

- Z-selective resonance-ionization laser ion-sources
- isobar separation
- „neutron-converter“ to suppress proton-rich isobars
- multifold-coincidence methods at multi-detector arrays
- projectile-fragmentation, TOF techniques

Laser excitation scheme for Cd

Laser ion-source + converter
Additional selectivity from hyperfine splitting

• Solid line:
  - HF-splitting of the $\pi g_{9/2}$ configuration
• Dashed line:
  - $\pi p_{1/2}$ component

Laser ion source
• Laser set to off-center frequency $g_{9/2}$ ground-state decay
• Laser on central frequency
  Indication of isomeric decay
R-process „waiting-point“ nucleus $^{130}$Cd: N=82 shell-quenching

Nuclear-physics „surprises“
- high excitation energy of $1^+$ level
- high $Q_\beta$-value of 8.34 MeV

Comparison with mass models

• The weakening (quenching) of the shell gaps can be simulated by reducing the $l^2$-term in the Nilsson potential
• The trough in the abundances prior to $N=82$ vanishes
First experimental hints at „shell quenching“ at N=82?

**FIG. 3: Comparison of normalized mass deviations of 92Sn and 112Cd isotopes from model predictions with „shell quenching“ [27, 28, 30], experimental values and very recent short-range extrapolations for 110Sn and 112Cd [21, 22] relative to the „unquenched“ FRDM [24]. The deviation to our experimental value of 112Cd corresponds to a mass difference of 1.27 MeV.**
Fit to solar r-process isotopic abundances obtained as superposition of 16 $n_n$-components. There is also a good fit to the r-process Pb and Bi contributions after summing up the $\alpha$-decay chains of heavier nuclei.

Observed neutron-capture elemental abundances in an ultra-metal-poor halo-star (squares) compared to scaled solar values (dots) and our calculated r-abundances (full line).
Progenitors of the Actinides

After freeze-out, the extremely neutron-rich nuclei undergo $\beta$, $\beta$-del. n-, $\beta$-del. fission-, sp. fission decay
- New attempt to include $\beta$-del. fission decay by Schatz et al.
- Extended studies underway

Progress in mass modeling required:
- Production ratios even of close-lying nuclides as $^{232}$Th and $^{238}$U differ considerably when applying different mass models.
Ultra-metal-poor Halo stars
Th-U cosmochronometer

• Th-U chronometer ideal for dating of solar system.
• Lower limit for age of the Universe requires models of Galactic chemical evolution.

• High-resolution optical spectroscopy of ultra-metal-poor, very old Halo red giant stars opens new perspectives:
  • One (or few) nucleosynthesis events seeded ISM.
  • Scaled solar system r-process abundances for $56 \leq Z \leq 79$.
  • Radioactive dating requires „production ratios“.
  • Th/U ratio (hopefully) less effected by extrapolations of nuclear structure
Fission Recycling
The termination of the r-process by fission was already discussed by B²FH

Attempt to calculate the light curve
Site of the r-process?

In the supernova scenarios, the neutron flux is not sufficient to drive the path deep into the fission region: about 1 - 2 % fissions.

Contrary, in the neutron-star merger scenario, high neutron fluxes lead to the fission of substantial parts of the nuclei, which then act as new seed nuclei: fission recycling.
Influence of fission

Attempt to include spontaneous and $\beta$-delayed fission modes
- very old data set
- no mass distribution of fission fragments
- no fission recycling
Recently, new interest in termination of r-process by fission

- New scenarios as jets from SNe
Future developments

r-process calculations
- inclusion of termination of r-process by fission
- fission barriers, rates, mass distributions
- dynamical network calculations

The latest results will be presented by the following speakers!

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