Formation of Super-Heavy Elements in Astrophysical Nucleosynthesis

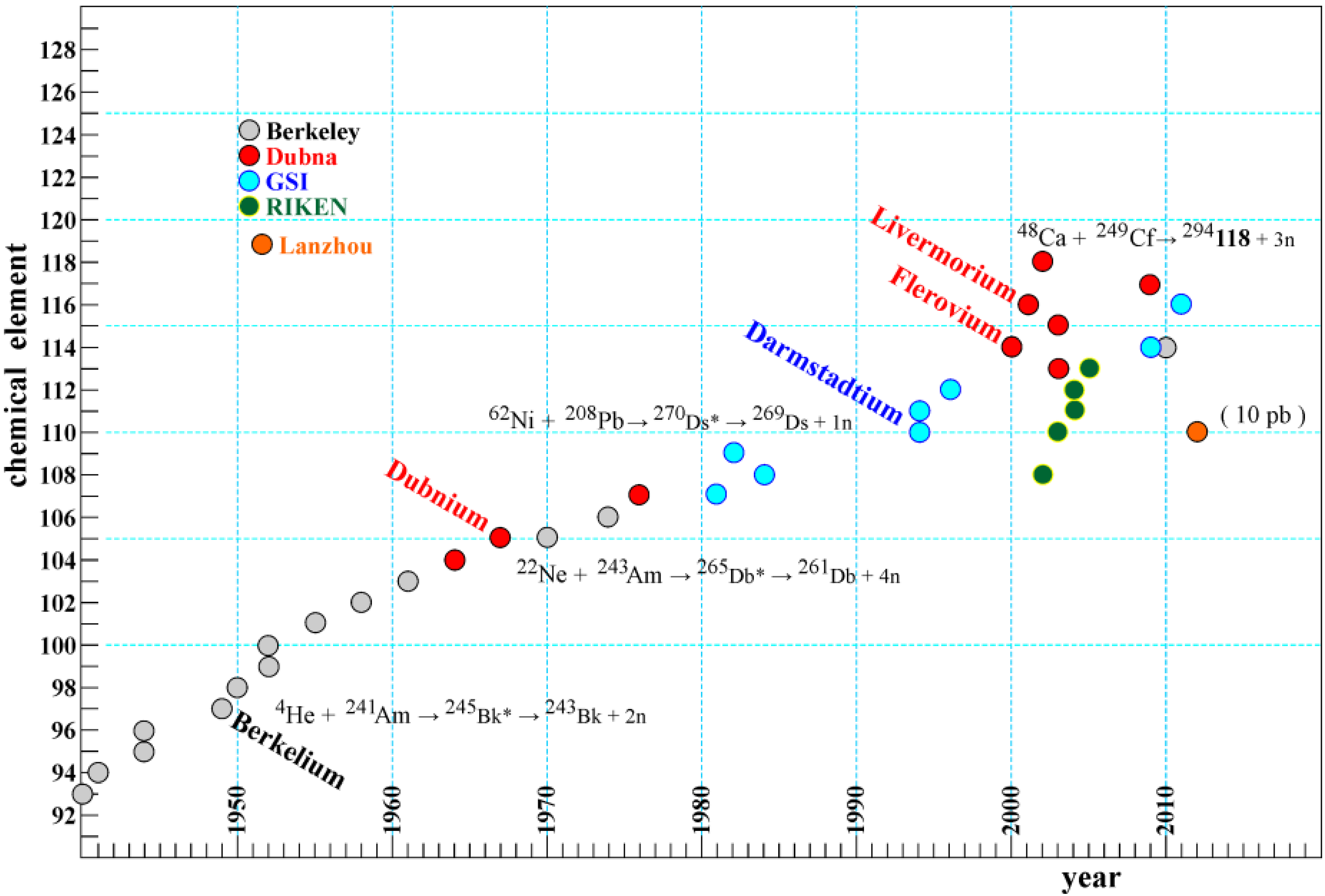
- **SHE: state of the art**
- **Search of SHE in nature (short historical sketch)**
- **Neutron capture process:**
  - **Equations of nucleosynthesis**
  - **Multiple nuclear explosions**
  - **Pulsed nuclear reactors**
  - **Synthesis of SH nuclei in astrophysical *r* process**
- **Summary**

Valeriy Zagrebaev

Flerov Laboratory of Nuclear Reactions, JINR, Dubna

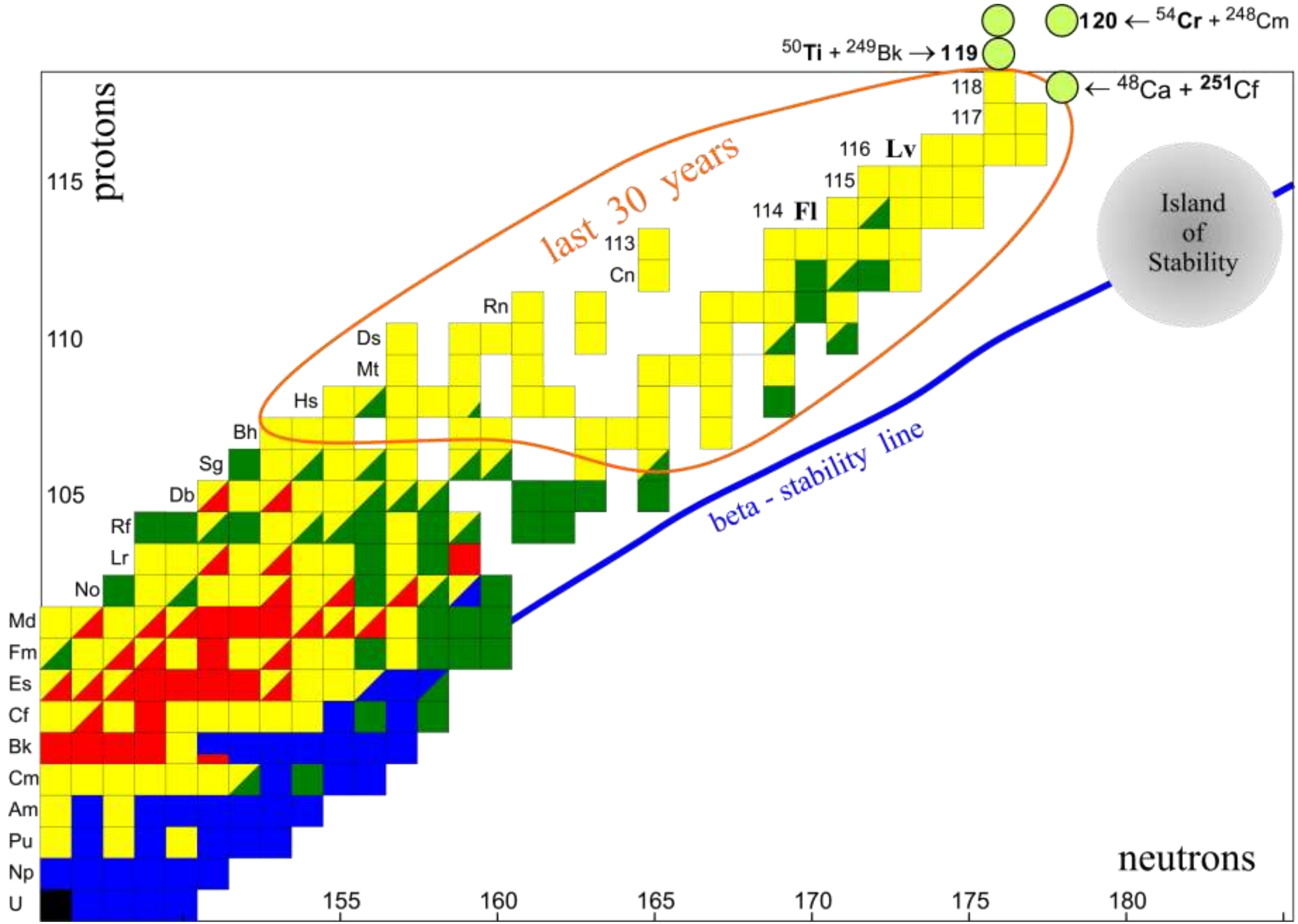
for "NSD-II", July 10, 2012, Opatija, Croatia

Hand-made elements (history)



2011: a new player has gone in the field

We are still far from the Island of Stability



How can we synthesize superheavy nuclei ?

1. Fusion reactions: beams of stable nuclei,
radioactive ion beams (no chances in near future)

2. Multi-nucleon transfer reactions (have been tested 30 years ago)

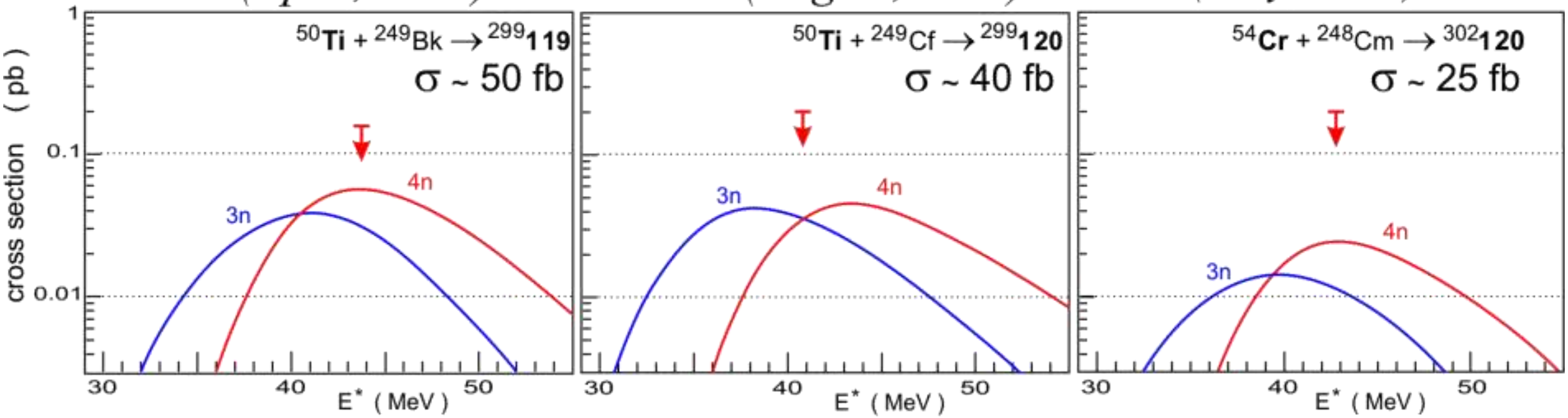
3. Neutron capture [+ subsequent beta(-) decay] **processes:**

nuclear explosions,
nuclear reactors,
supernova

New elements 119 and 120 are coming !

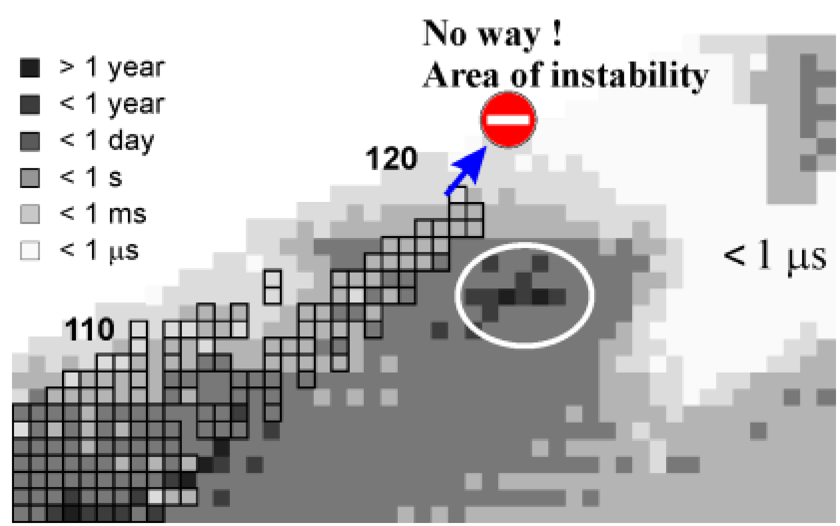
Ti beam: *TASCA (April, 2012)* *TASCA (August, 2011)*

Cr beam: *SHIP (May, 2011)*



predictions: Zagrebaev & Greiner, PRC 2008

factor $\frac{1}{20}$ as compared to ^{48}Ca



Probably, these elements are the last ones which will be synthesized in the nearest future

Search for SHE in cosmic rays

1971, Dubna, P. Fowler: Tracks of SHE!?

Physics of Atomic Nuclei, Vol. 66, No. 8, 2003, pp. 1569–1573. From *Yadernaya Fizika*, Vol. 66, No. 8, 2003, pp. 1612–1616.
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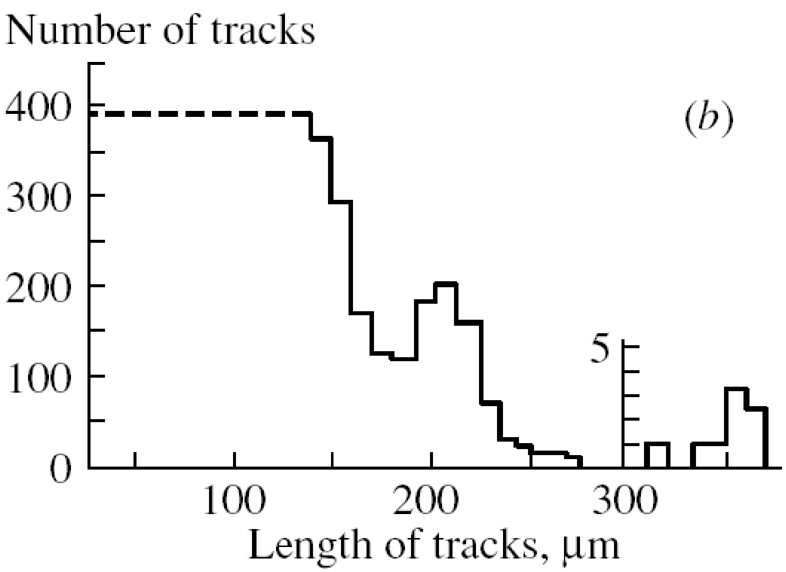
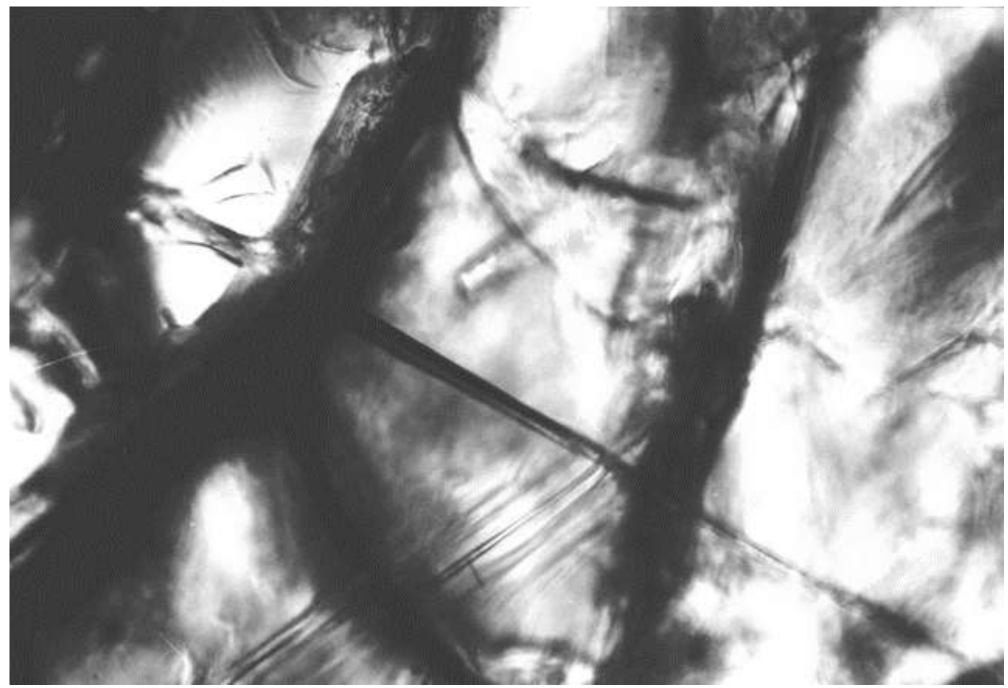
On Search and Identification of Relatively Short-Lived Superheavy Nuclei ($Z \geq 110$) by Fossil Track Studies of Meteoritic and Lunar Olivine Crystals*

V. P. Perelygin †1), Yu. V. Bondar 2), R. Brandt 3), W. Ensinger 3), R. L. Fleischer 4), L. I. Kravets 1)**, M. Rebetez 5), R. Spohr 6), P. Vater 3), and S. G. Stetsenko 1)





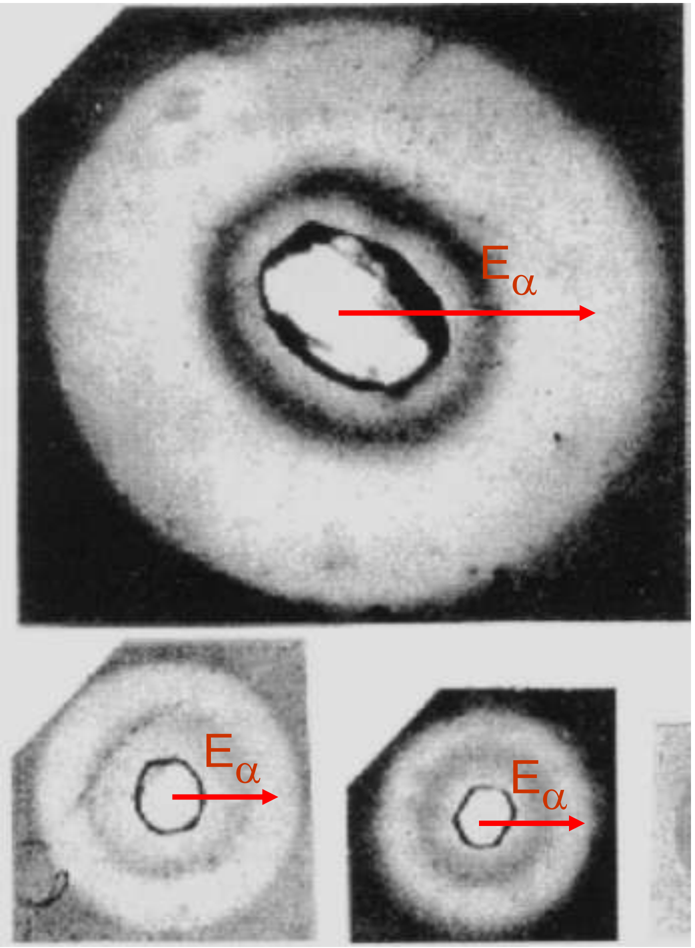
$Z \approx 90$, $N = 1600$

$Z \approx 114$, $N = 11$

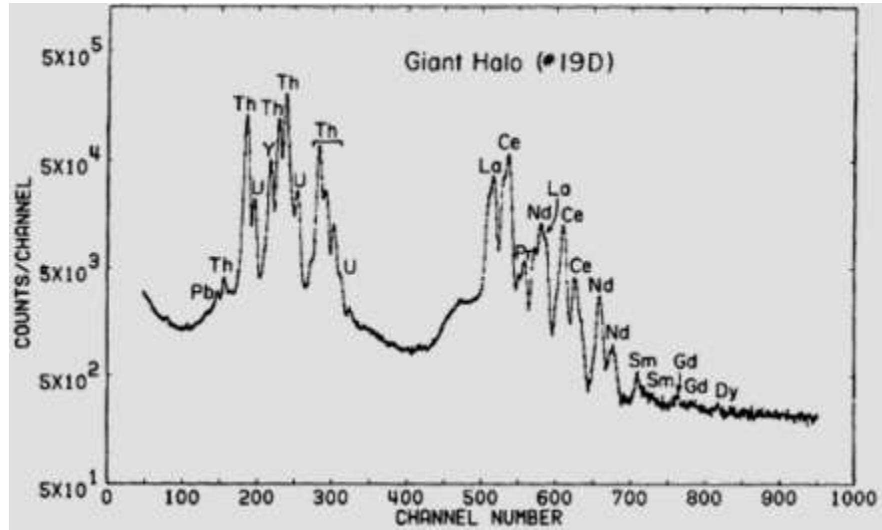
Search for SHE in terrestrial matter:

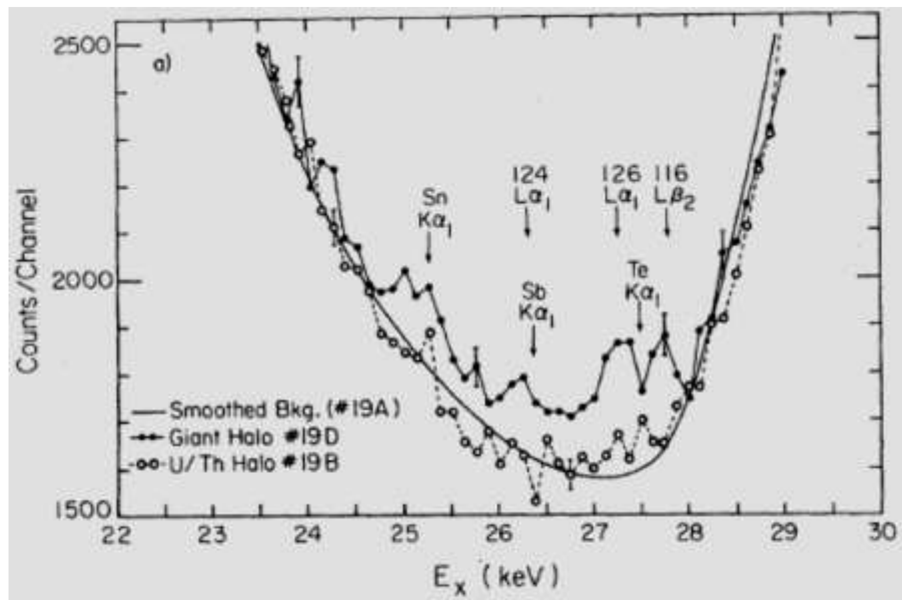
Giant halos (R.V. Gentry)

SHE ?



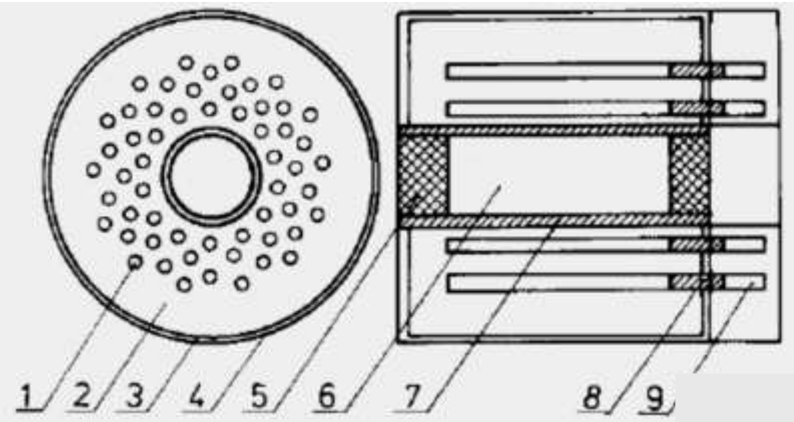
U **Th**

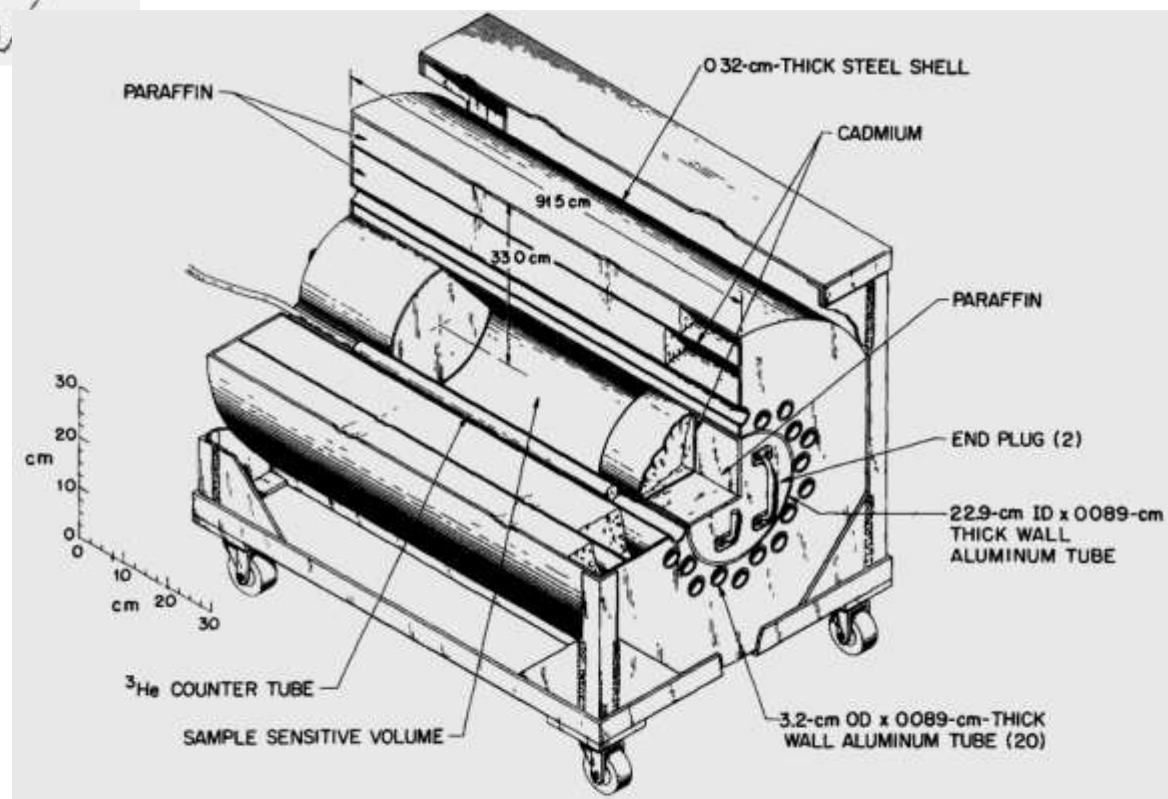




Search for spontaneous fission of SHE:
big proportional counters of fission fragments
(JINR, Dubna, 1970)

^{3}He-neutron multiplicity counters
(Solotvino mine, USSR, 1975)





Proc. Roy. Soc. A. **301**, 39–45 (1967)
Printed in Great Britain

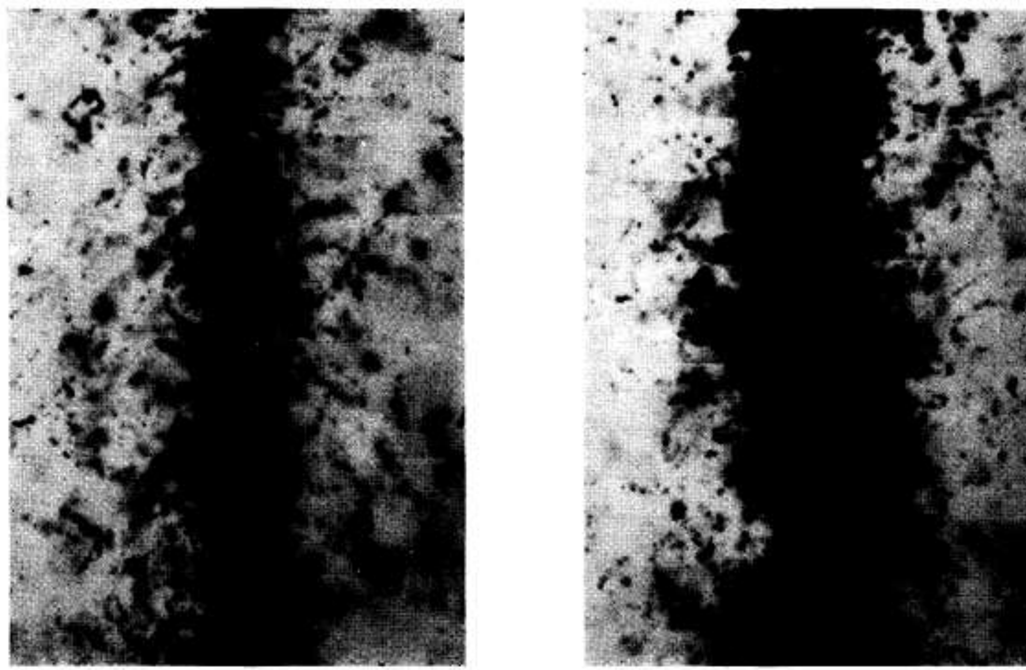
The charge spectrum of very heavy cosmic ray nuclei

By P. H. Fowler, F.R.S.
Royal Society Research Professor at the University of Bristol

and R. A. Adams, V. G. Cowen and J. M. Kidd*
H. H. Wills Physics Laboratory, University of Bristol

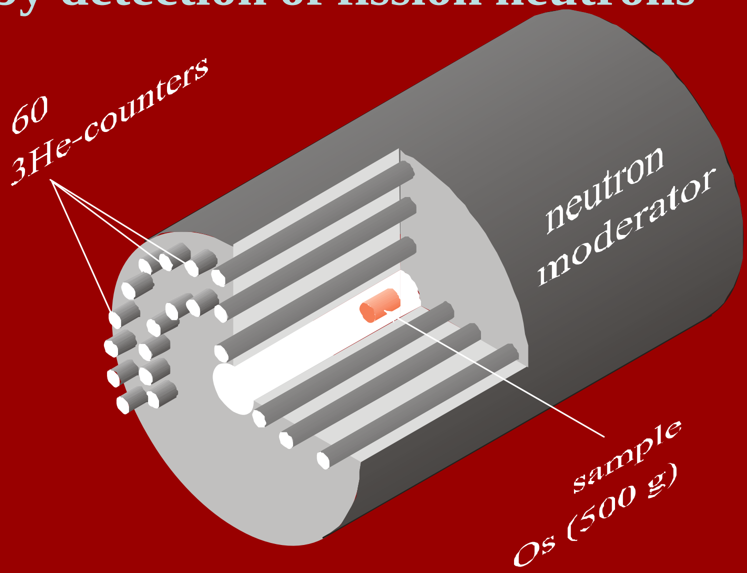
(*Paper based on a part of a Review Lecture delivered 9 February* 1967—*Received* 10 *April* 1967)

Z ≈ 26



Z = 90 ± 4

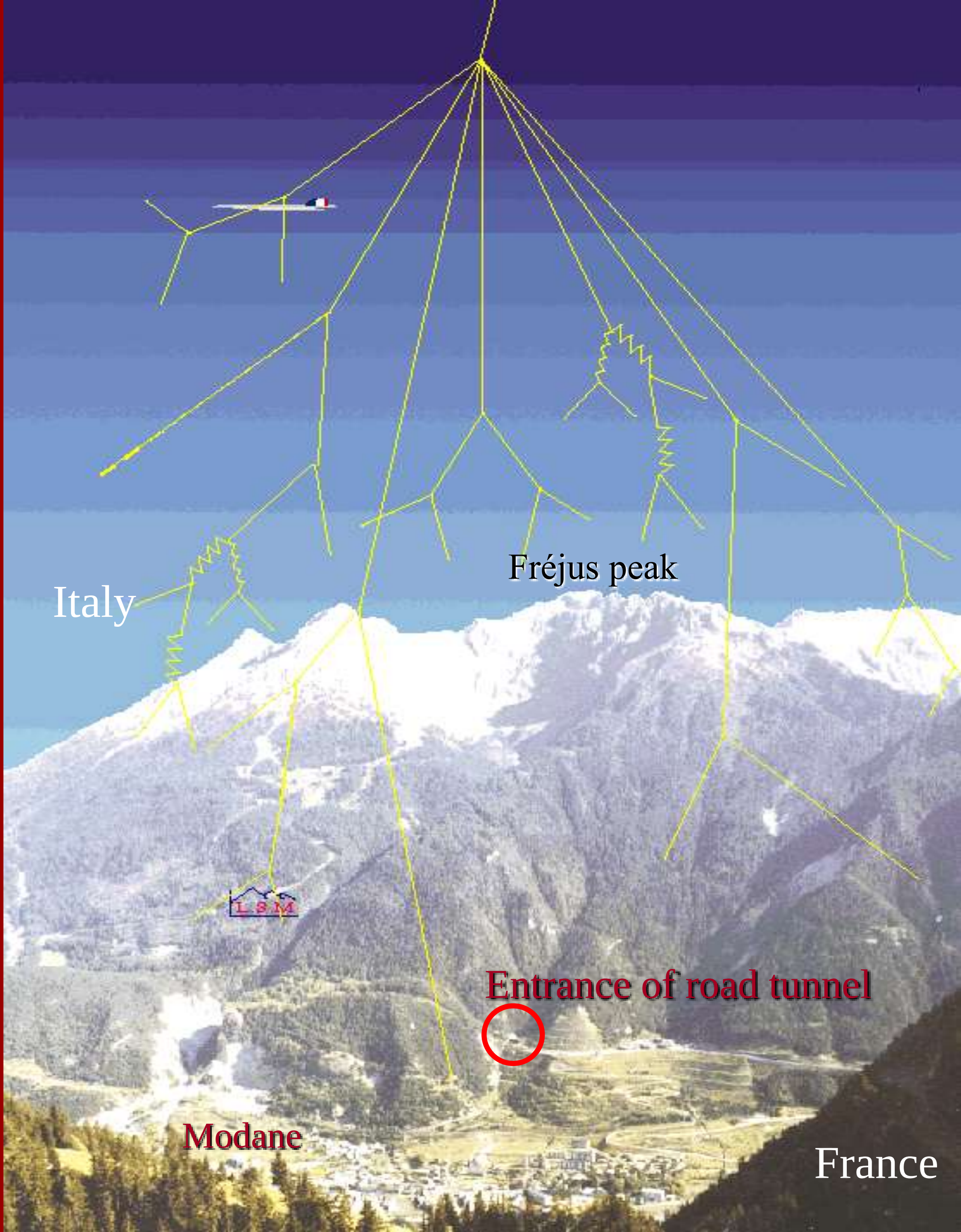
Search for Z=108, SF of natural Eka-Os by detection of fission neutrons



1 SF-event per year ($T_{1/2}=10^9$ yrs) corresponds to concentration:

$$EkaOs/Os = 5.10^{-15} g/g$$

(or 10^{-22}g/g in the terrestrial matter, or 10^{-16} of U)



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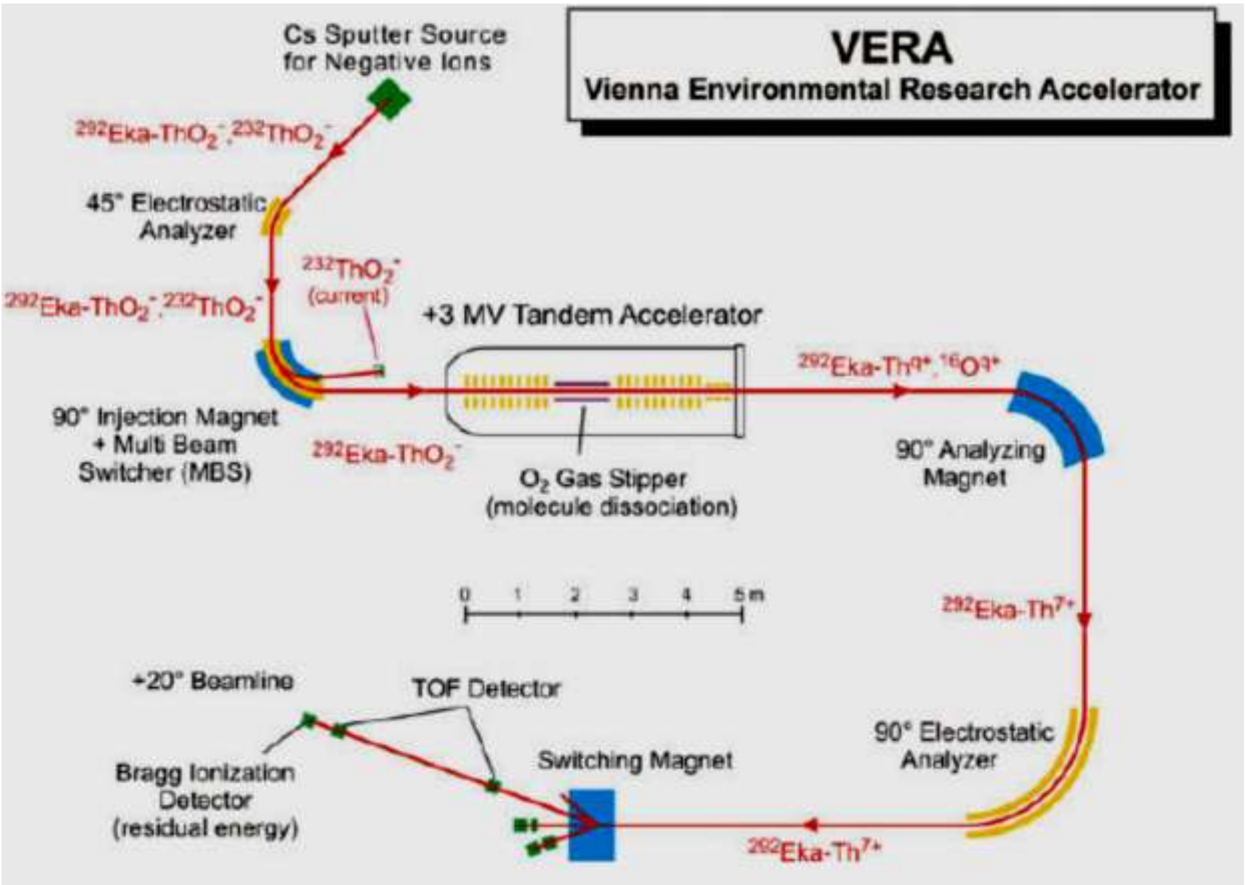
journal homepage: www.elsevier.com/locate/nimb

Search for a superheavy nuclide with A = 292 and neutron-deficient thorium isotopes in natural thorianite

F. Dellinger*, O. Forstner, R. Golser, W. Kutschera, A. Priller, P. Steier, A. Wallner, G. Winkler

VERA Laboratory, Fakultät für Physik, Universität Wien, Währinger Straße 17, A-1090 Wien, Austria



Search for SHE in nature

Several very exciting signals and indications have been found…

but

there are no well confirmed and quite clear findings

Nucleosynthesis by neutron capture

n_0 is the neutron flux

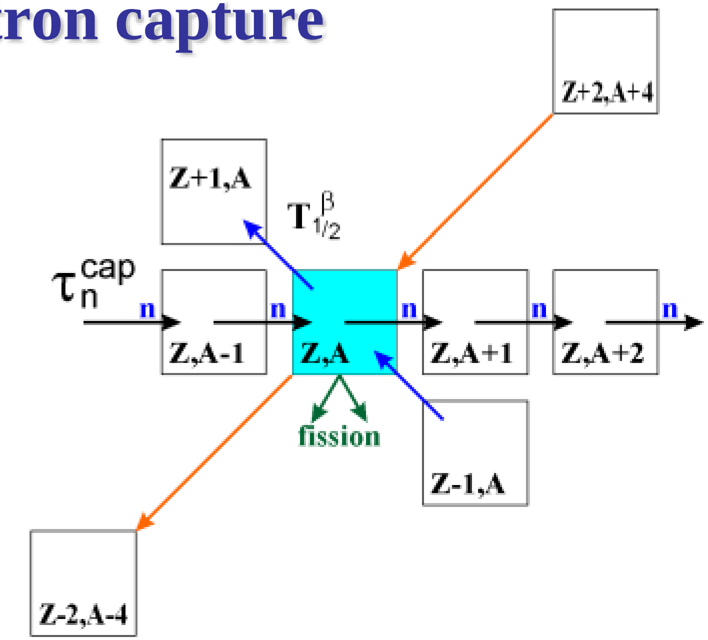
time of neutron capture

$$\tau_n^{cap} = \frac{1}{n_0 \times \sigma(n,\gamma)}$$

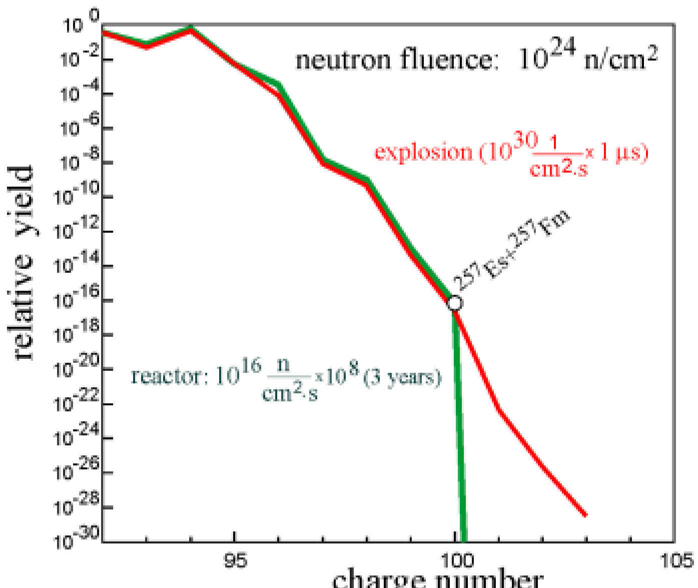
$$(Z,A) \rightarrow (Z,A+1) \text{ if } T_{1/2} > \tau_n^{cap}$$

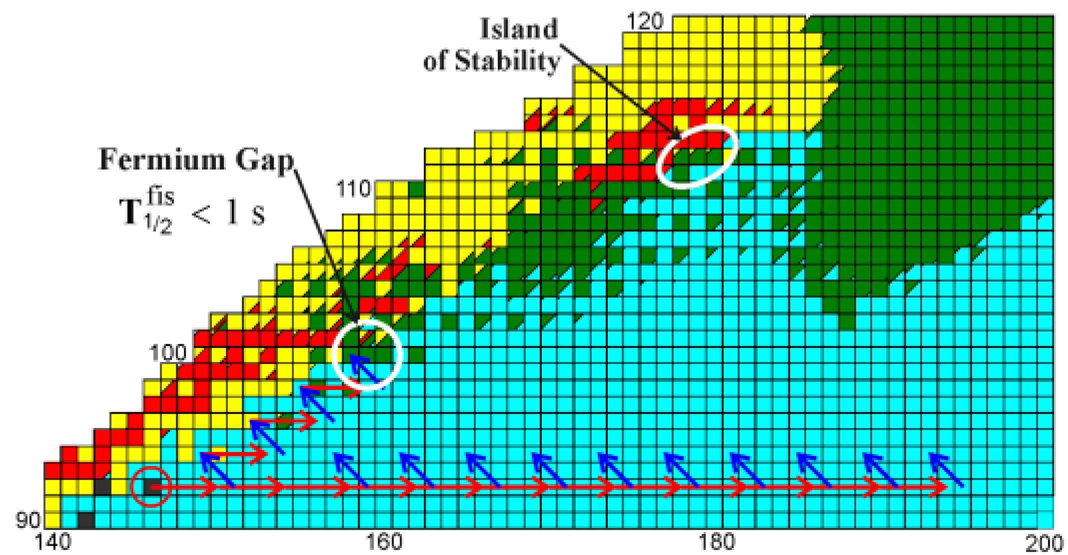
nuclear reactor: $\tau_n^{cap} \sim 1$ year

nuclear explosion: $\tau_n^{cap} \sim 1\ \mu s$



$$\frac{dN_{ZA}}{dt} = N_{ZA-1}\, n_0\, \sigma_{ZA-1}^{n\gamma} - N_{ZA}\, n_0\, \sigma_{ZA}^{n\gamma} - N_{ZA} \frac{\ln 2}{T_{ZA}^{\beta}} - N_{ZA} \frac{\ln 2}{T_{ZA}^{\alpha}} - N_{ZA} \frac{\ln 2}{T_{ZA}^{fis}} + N_{Z-1A} \frac{\ln 2}{T_{Z-1A}^{\beta}} + N_{Z+2A+4} \frac{\ln 2}{T_{Z+2A+4}^{\alpha}}$$

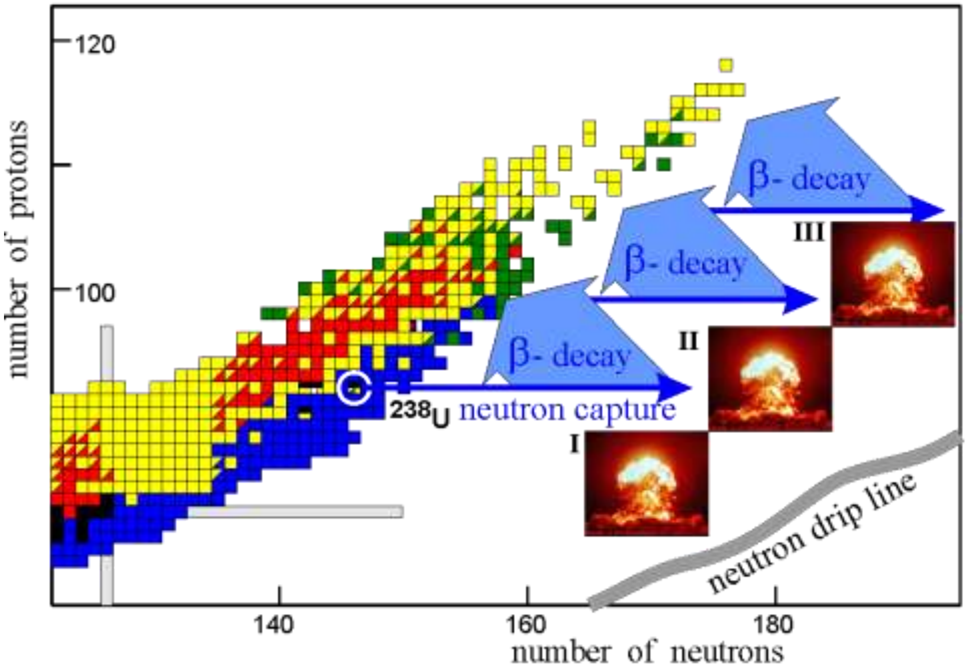


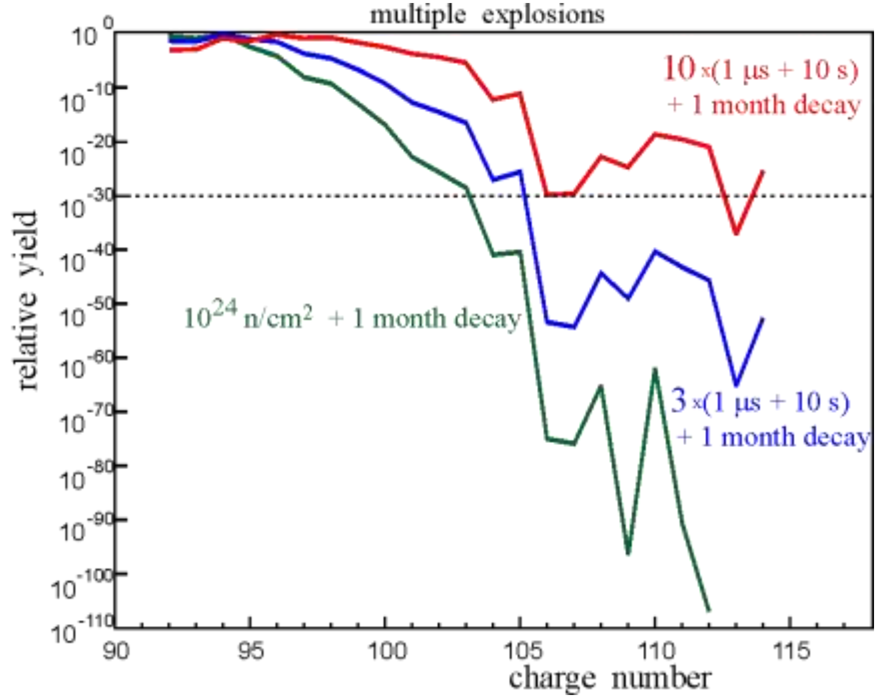


Multiple nuclear explosions

(proposed first by H.W. Meldner, PRL 28,1972)

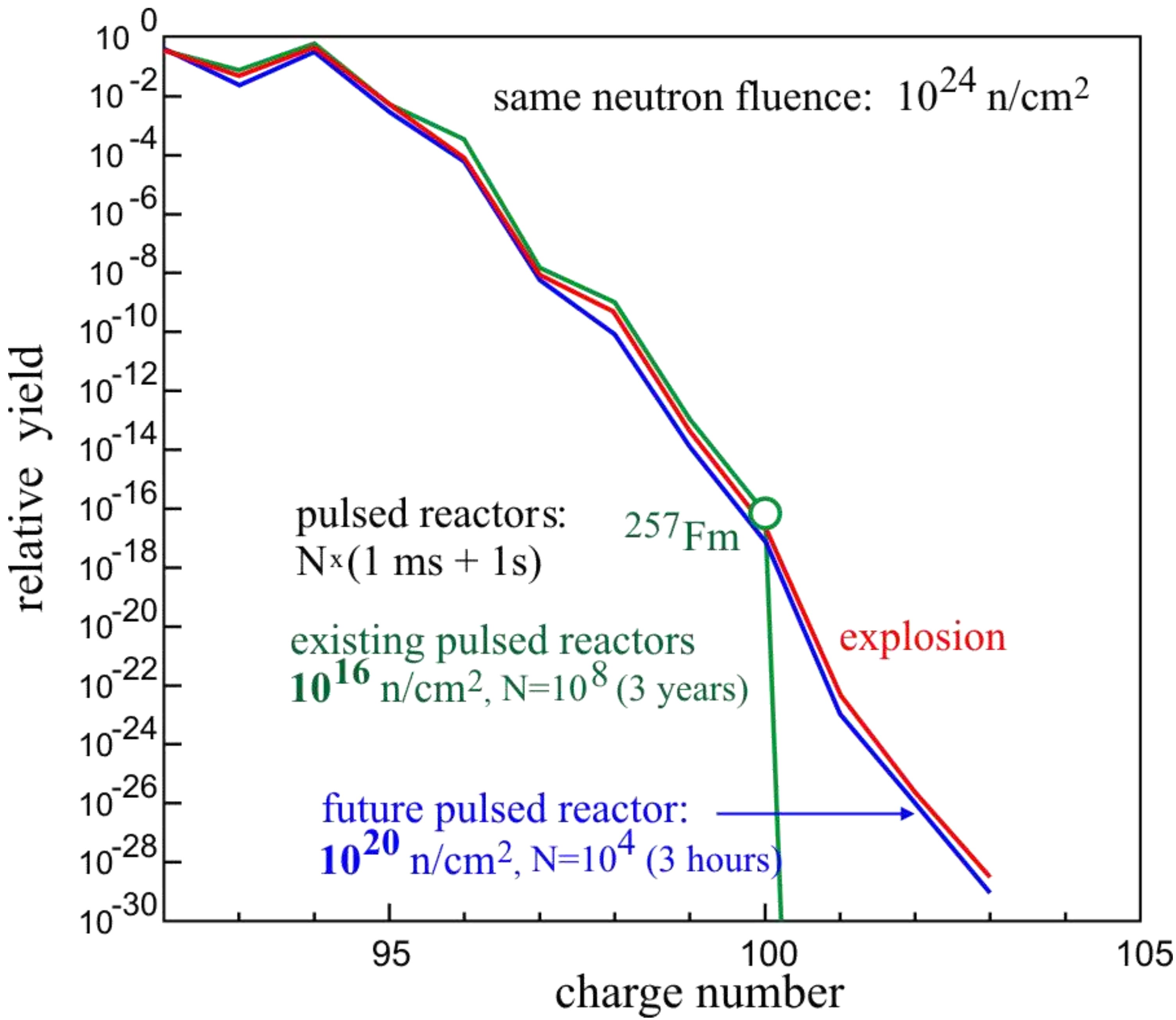
Edward Teller: Technically it is quite possible





Probability for formation of element 112 increases by **90 orders** of magnitude **!**

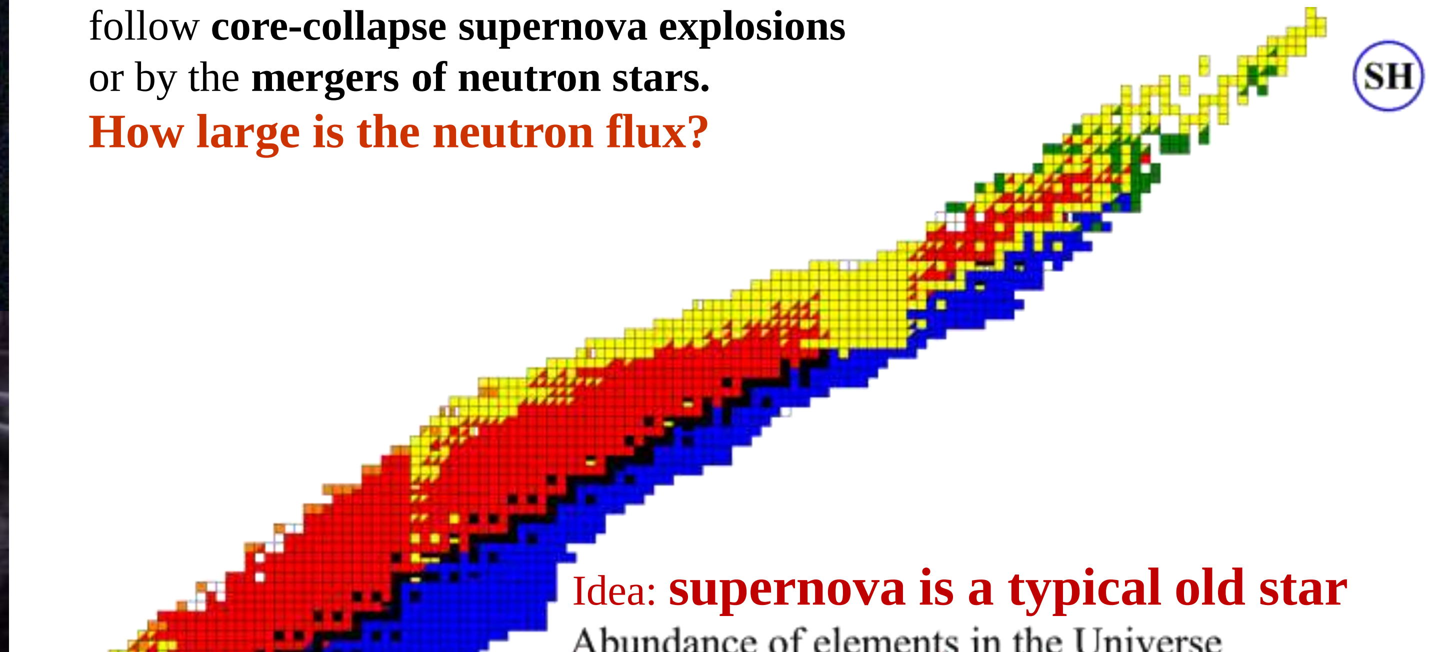
Next generation of pulsed reactors: We need factor 1000 only !



Formation of SH elements in astrophysical r-process

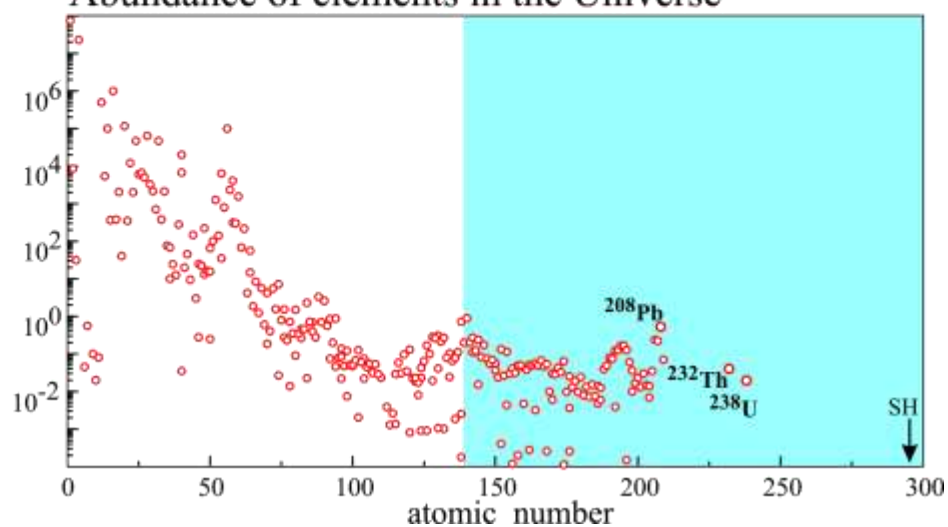
Strong neutron fluxes are expected to be generated by neutrino-driven proto-neutron star winds which follow **core-collapse supernova explosions** or by the **mergers of neutron stars.**

How large is the neutron flux?

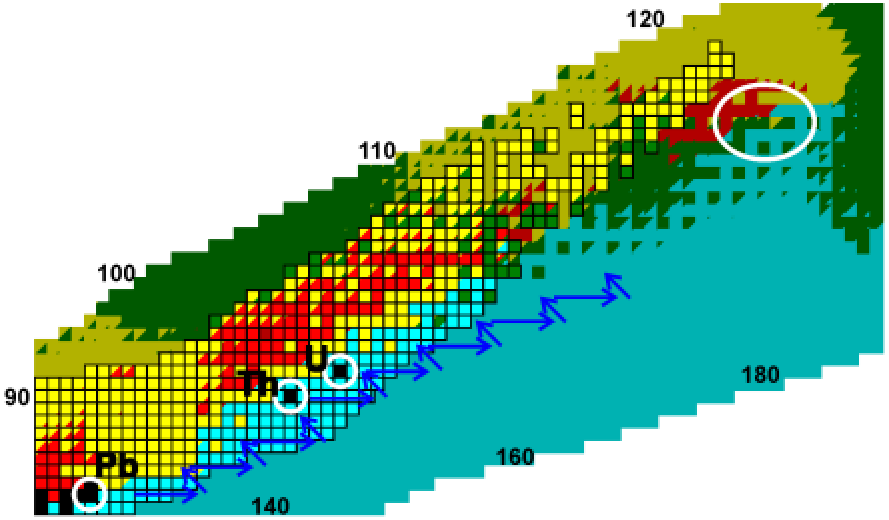


Idea: **supernova is a typical old star**

Abundance of elements in the Universe

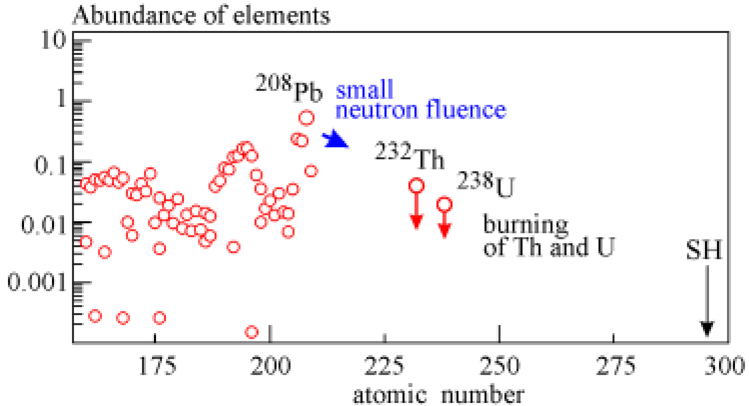


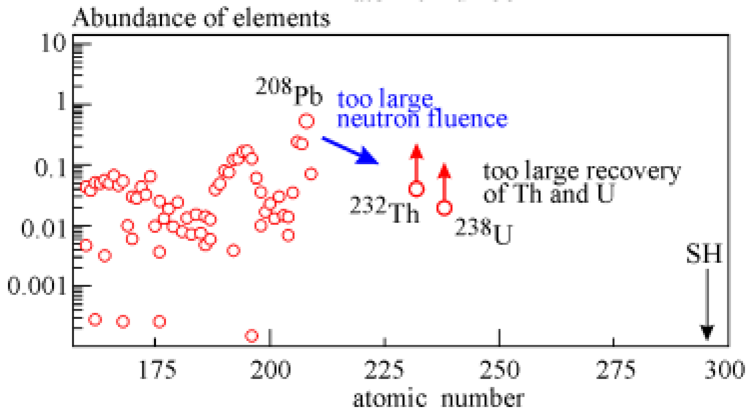
Formation of SH elements in astrophysical r-process

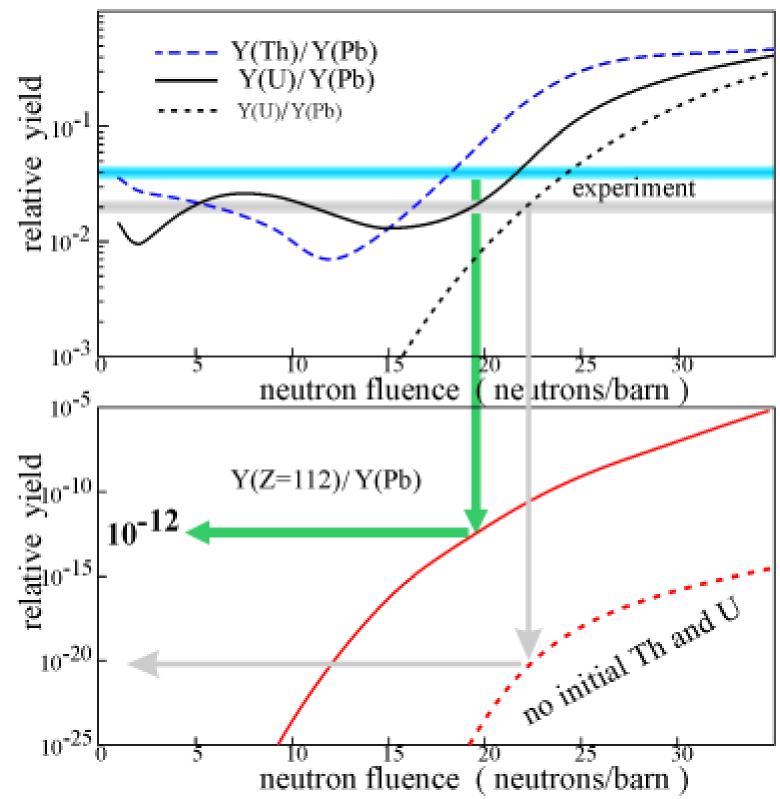


In the course of neutron irradiation initial Th and U material are depleted transforming to heavier elements and going to fission, while more abundant Pb and lighter stable elements enrich Th and U.

Unknown total neutron fluence is adjusted in such a way that the ratios **Th/Pb and U/Pb keep their experimental values.**







Summary

- **Elements 119 and 120 can be really synthesized in the Ti and/or Cr fusion reactions with cross sections of about 0.05 - 0.02 pb.**
  It is possible that they are the heaviest SH elements with $T_{1/2} > 1\ \mu s$?
- **New methods (multi-nucleon transfers, neutron capture, ?) need to be found for synthesis of neutron enriched long-living SH nuclei located along the beta-stability line.**
- **A macroscopic amount of the long-living SH nuclei located at the island of stability may be produced with the use of pulsed nuclear reactors of the next generation (factor 1000 is needed).**
- **Production of long-living SH nuclei in the astrophysical r-process looks not so much pessimistic: relative yield of SH / Pb may be about 10^{-12}.**
  The question: How long is their half-lives?

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