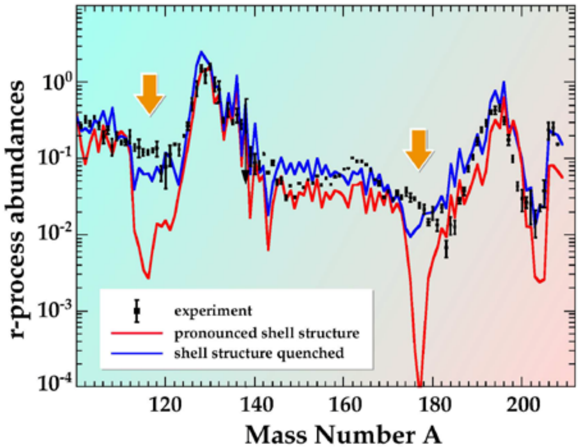
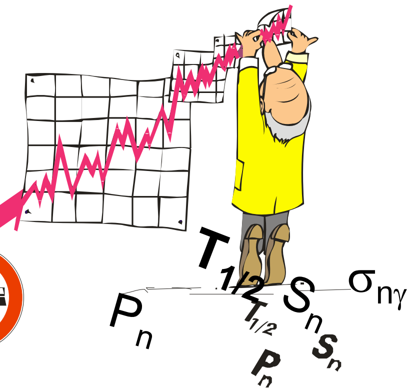
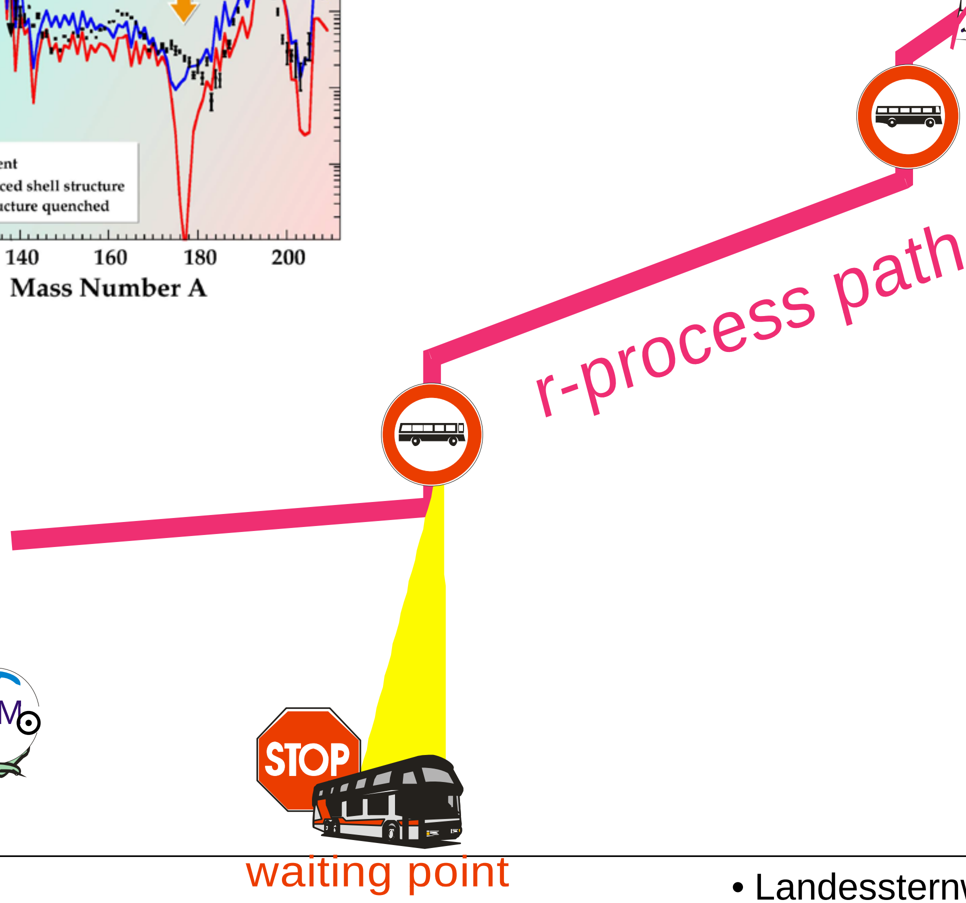
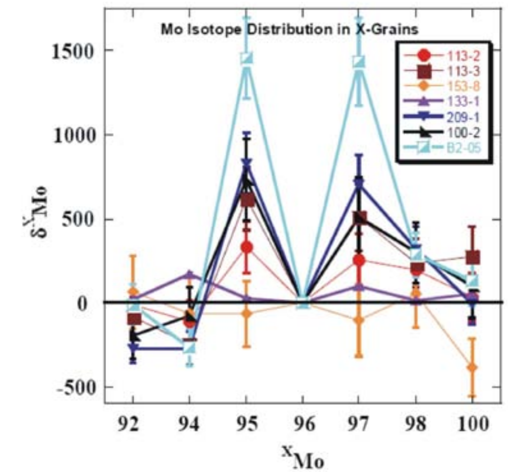
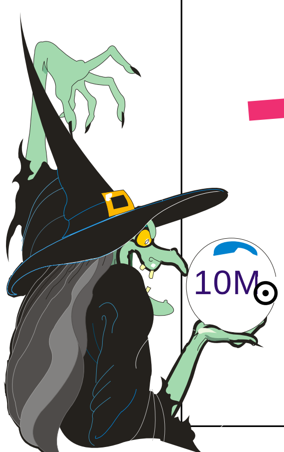
Co-production of light p-, s- and r-isotopes in the HEW scenario











NIC XI 2010

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Light p-process isotopes in the SS

Historical papers "p-process"

B^{2}FH (1957)
Arnould (1976)
Woosley & Howard (1978)

Main goal:
explanation of Mo nucleosynthetic origin in X-type SiC grains, and SS **^{92}Mo/^{94}Mo**

Selected subsequent papers / scenarios

Hoffman et al. (1996, 2008) — ν-driven winds in SN II
Schatz et al. (1998, 2003) — rp-process in X-ray bursters
Rauscher et al. (2002) — γ-process in pre-SN and SN
Fisker et al., (2006) — νp-process in SN II
Wanajo (2006) — rp-process in ν-driven winds
Wanajo et al. (2009) — p-production in EC SN
Kusakabe et al. (2010) — p-production in C-deflag. SN Ia
Kizivat et al. (2010) — νp-process in GRB-BH accretion disk
Travaglio et al. (2010) — p-process in SN Ia

Why an additional attempt…?

Motivation for another HEW study

As "by-product" of our current core-collapse HEW r-process studies…
(see, e.g. Farouqi et al., Ap.J. 694 (2009);
and Ap.J. 712 (2010)

Motivated by

- discussions with R. Gallino and C. Travaglio about the "LEPP" idea
- **discussions with U. Ott and A. Davis about isotopic anomalies in SiC grains**
- basic v-driven wind paper by R. Hoffman et al. (1996)
- …nature seems to disagree with all models – the one or other way ☹

Closer look into our HEW results for the production of light trans-Fe nuclei, historically designated as pure

"p-isotopes"
"s-isotopes"
"r-isotopes"

(see Farouqi et al., PASA 26 (2009) 194 – 202)

Mo isotopic abundances in the SS

Particularly **"hot topic"**

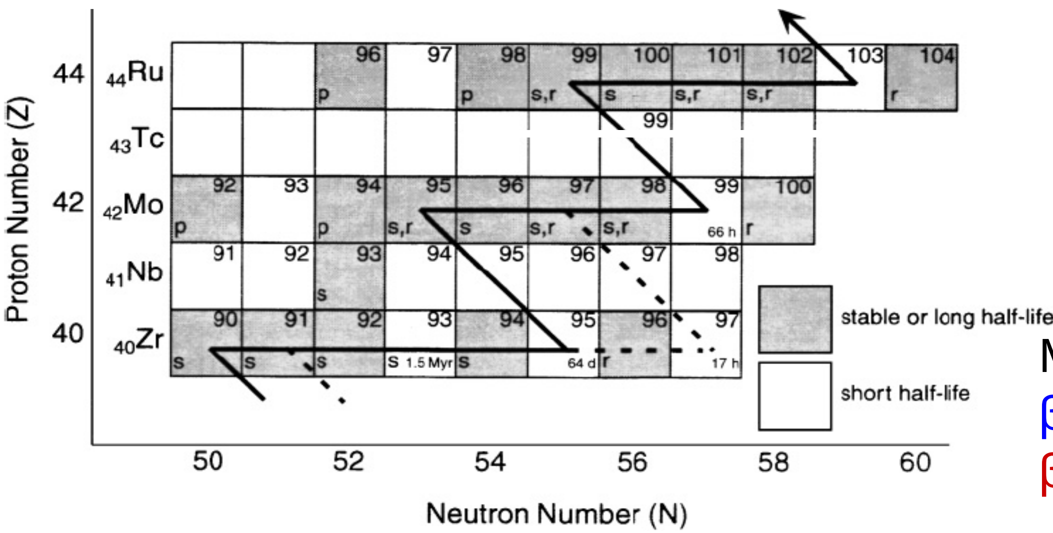
^{92}Mo/^{94}Mo

The two most abundant p-nuclei in the SS

	Lodders (2003)	**De Laeter (2008)**
^{92}Mo	14.836	14.525
^{94}Mo	9.247	9.151
^{92}Mo/^{94}Mo	**1.605**	**1.587**

…despite all attempts / scenarios studied up to now,

^{92}Mo/^{94}Mo has remained an "unsolved problem"



7 stable isotopes:

^{92,94}Mo p-only; ^{96}Mo s-only
^{95,97,98}Mo s+r, ^{100}Mo r-only

Mo isotopes "shielded" from both sides:

β⁻ **^{92,94,96}Zr** (Z=40)

β⁺ **$^{96,98\text{-}100}$Ru** (Z=44)

↷ **narrow Z-path for production!**

Note, however:

SS represents a **compound** of various nucleosynthesis processes**!**

Therefore, it may not be the **"ideal observable"…**

Are there better ones? **YES !**

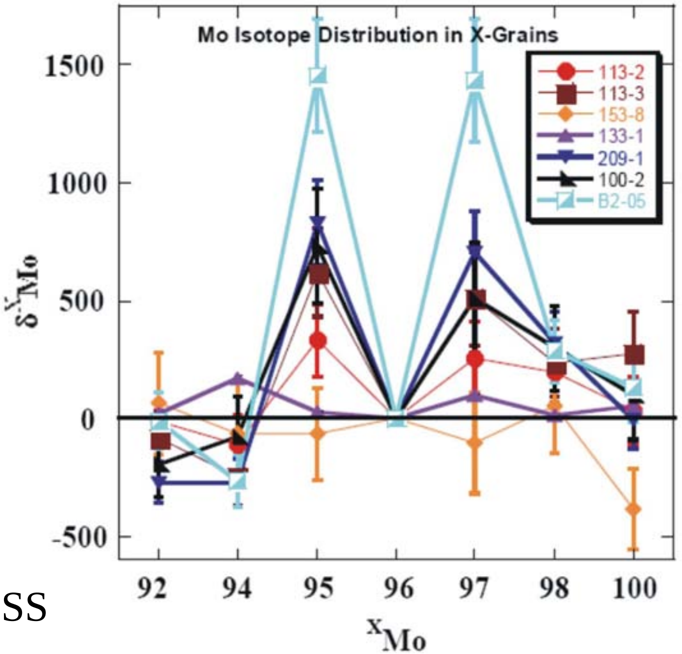
Mo isotope distribution in presolar X-grains

M.J. Pellin et al., Lunar and Planetary Science XXXVII (2006) 2041:

Presolar SiC grains, isolated from primitive meteorites, are ejecta of stars that contributed to the protosolar nebula. Due to SiC's refractory nature, these grains have survived SS formation to provide a record of the nuclear processing in their parent stars.
Among these grains are a rare fraction, called **Type-X**, which are believed to have formed in the stellar outflows of SN II explosions.
Surprisingly, the isotopic patterns are not consistent with a canonical r-process, but rather correspond to models producing a rapid, but limited neutron dose:
B. S. Meyer et al., ApJ 540 (2000) L49 – **"neutron burst process"**;
T. Rauscher et al., ApJ 576 (2002) 323 – "gamma process".

Both models are **secondary** processes starting from an initial SS seed distribution.

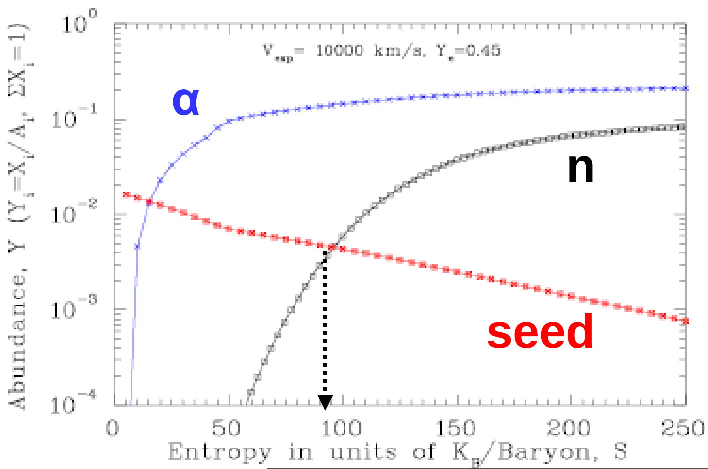
^{X}Mo deviation plotted relative to ^{96}Mo, which is taken as pure s-process isotope ⇨
„unusual isotopic pattern"
significant enrichment in ^{95}Mo, ^{97}Mo;
smaller enrichment in ^{98}Mo;
no clear signature of ^{100}Mo enhancement.



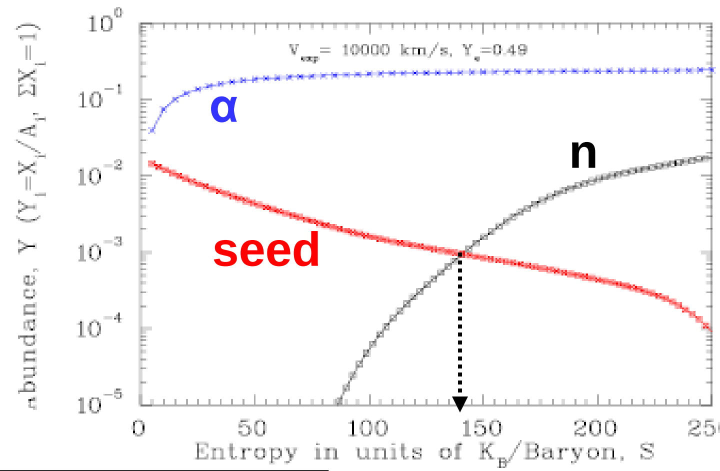
δ notation: deviation in permille from SS

Parameters HEW model ⇨ Y(Z)

Y_e=0.45

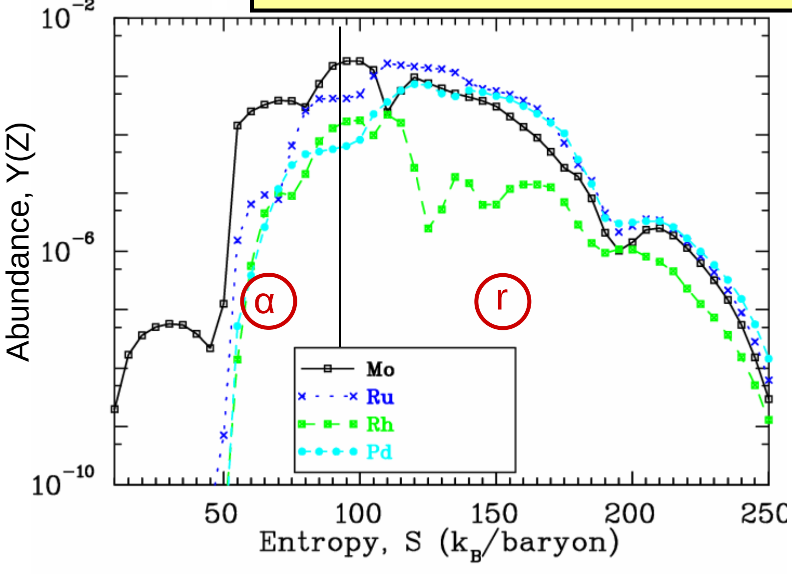


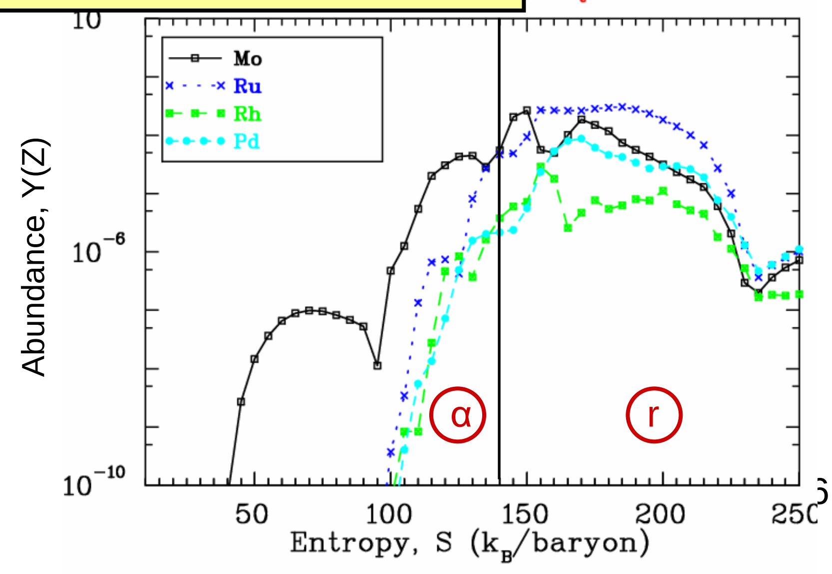
Y_e=0.49



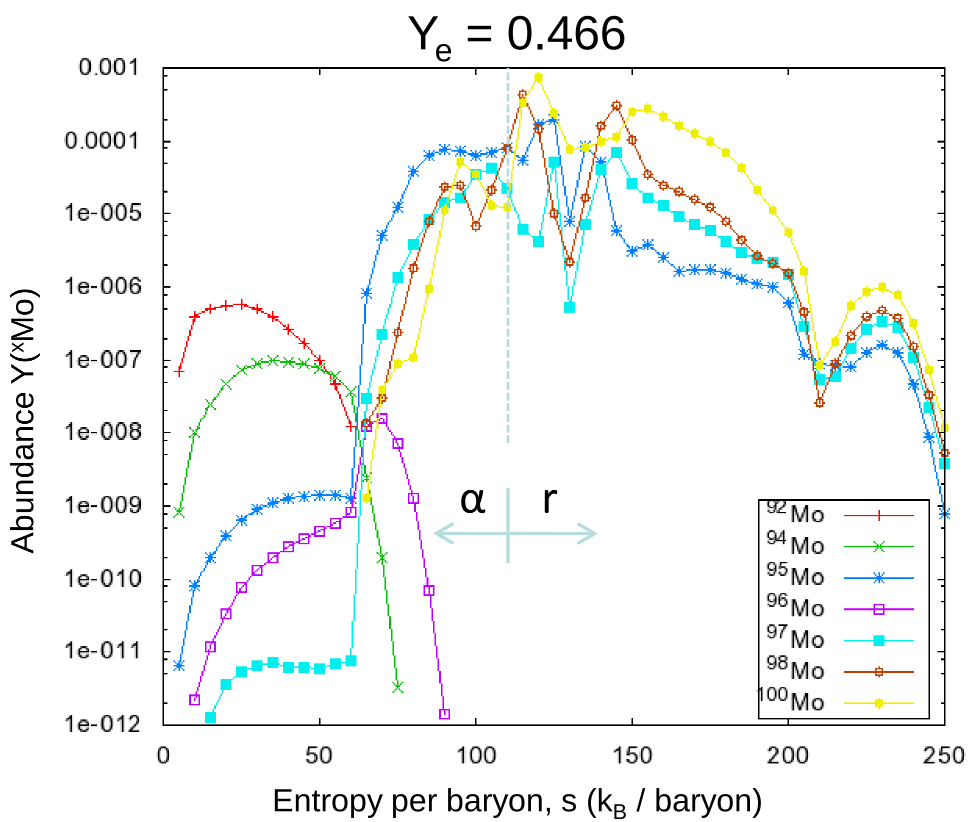
No neutrons ↷ no r-process!

Ye=0.45 ⇨ Ye=0.49 ↷ similar Y(Z) pattern shifts in S and α / r-components





Isotopic abundances Y(Z,A) as fct of entropy S



For Y_e =0.466 , S=115 is the threshold entropy, up to which Y_n/Y_{seed} < 1

^{92}Mo, ^{94}Mo, ^{96}Mo are solely produced in a **pure Charged-Particle Process**

The "neutron-burst" model

The **"neutron-burst model"**
is the favoured nucleosynthesis scenario in the cosmochemistry community,
so far applied to isotopic abundances of Mo, Zr, Xe, Ba, Pt

Basis:

Howard et al., Meteoritics 27 (1992)

"…neutron burst occurs in shocked He-rich matter in an exploding massive star…"

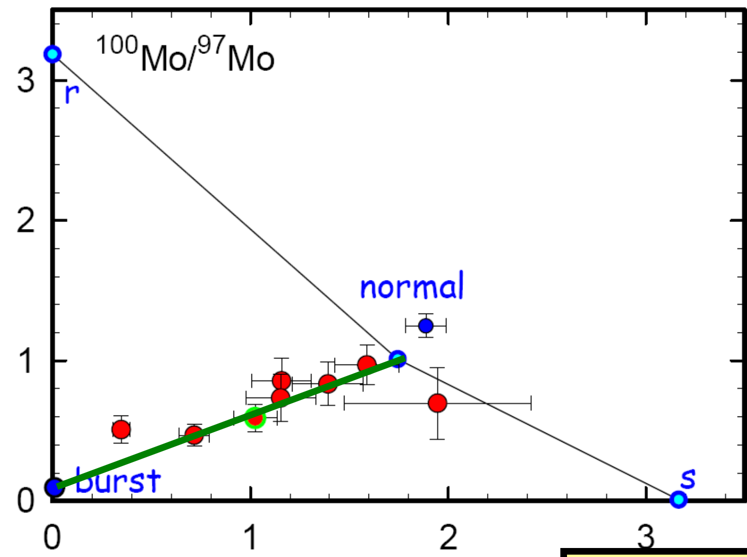
Several steps:

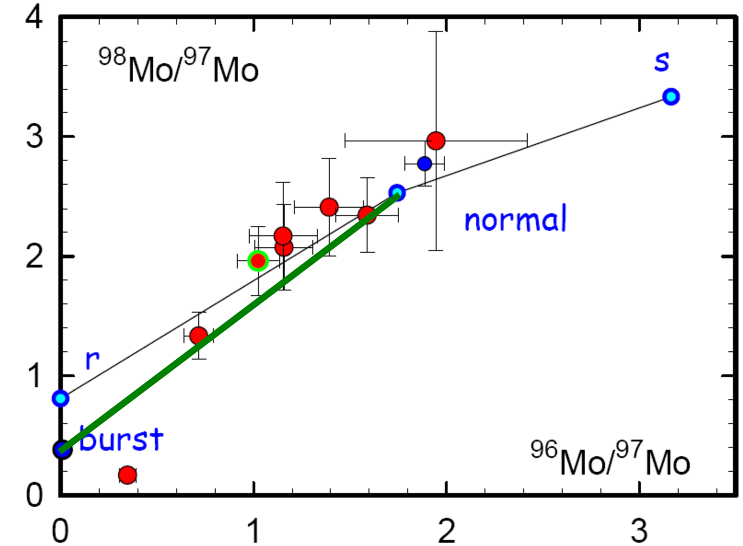
1) start with SOLAR isotope distribution
2) exposure to a weak neutron fluence ($\tau = 2 \cdot 10^{24}$ cm^{-2} = 0.02 mbarn^{-1})
   ➦ mimics weak s-processing during pre-SN phase
3) weak s-ashes (1500 g cm^{-3}) heated suddenly to $T_9 = 1.0$
4) expansion and cooling on 10 s hydrodynamical timescale
   ➦ resulting n-density (from (α,n) reactions) during burst $\approx 10^{17}$ n cm^{-3} for $\approx$1 s;
   ➦ final n-exposure 0.077 mbarn^{-1}

Conclusion by authors:

neutron-burst model can explain the **"anomalous and quite puzzling"** Mo isotopic pattern in SiC X-grains

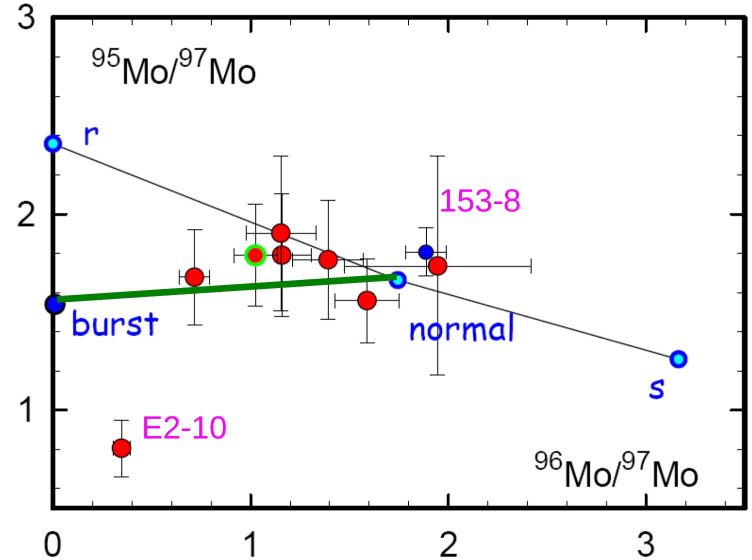
Predictions of “neutron-burst” model

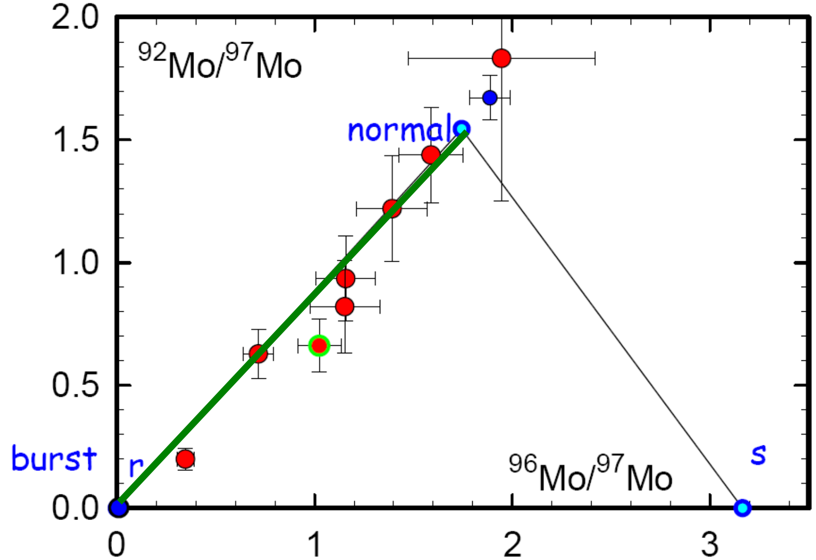




Convention cosmochemists: **“three-isotope plots”**

extrapolation of mixing lines yield clean nucleosynth. signature





Pure s- and r-process patterns definitely excluded!

Comparison with HEW predictions

Although the “neutron-burst model” is traditionally applied by cosmochemists, it is unsatisfactory for several reasons:

- it contains already ^{92}Mo and ^{94}Mo in SS proportions in the initial seed
- it is in principle a “ternary” model
- it requires quite tricky astro-parameter finetuning

Let’s see, if our parameterized HEW approach can **simultaneously** explain all 7 Mo isotopic abundances:

Historically	^{92}Mo, ^{94}Mo	**p**-only
	^{96}Mo	**s**-only
	^{100}Mo	**r**-only
	^{95,97,98}Mo	**s**+**r**

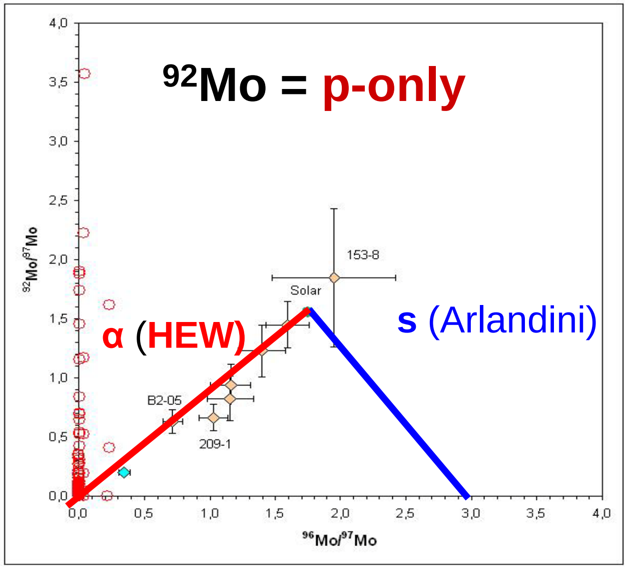
To recapitulate:

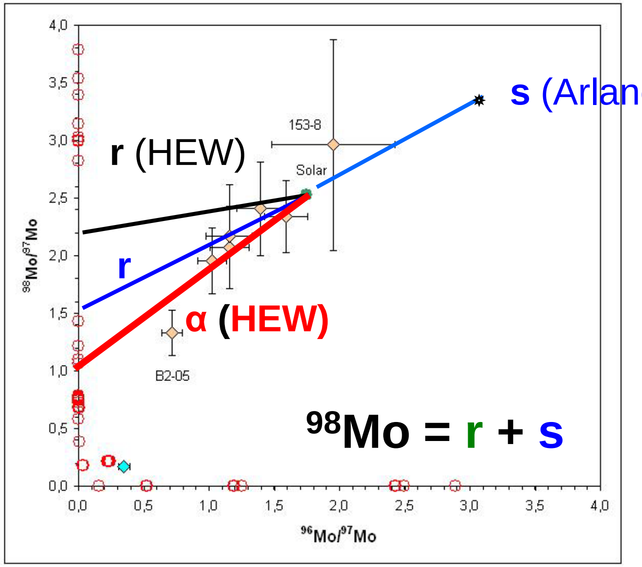
In contrast to e.g. Hoffman et al., who used individual Y_e values ($0.46 \leq Y_e \leq 0.50$) with a single entropy of $S/(N_A\ k) \approx 50$,
we use **superpositions** of different Y_e-trajectories ($0.458 \leq Y_e \leq 0.478$) combined with the corresponding S-components ($5 \leq S \leq 100$),
to cover the full range of charged-particle nucleosynthesis conditions

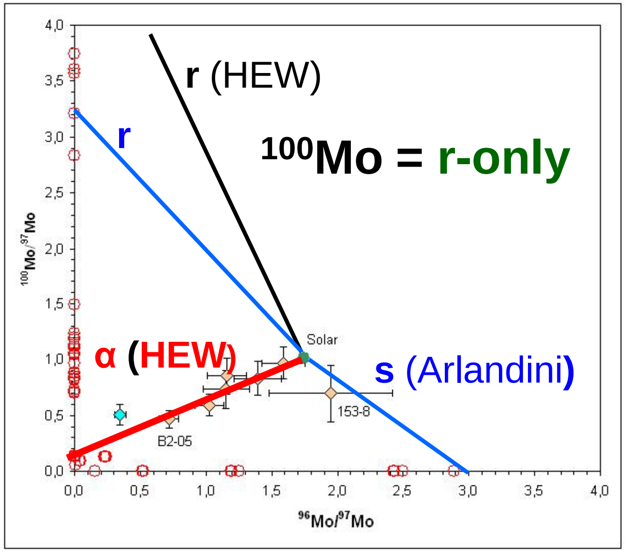
⇨ $\mathbf{Y_n/Y_{seed} < 1}$

No neutron-capture r-process components.

Mo 3-isotope plots







Definitely neither classical s nor classical r!

X-axis: ^{96}Mo/ ^{97}Mo

Y-axis: ^{XY}Mo/ ^{97}Mo

Comparison „neutron-burst“ vs. HEW model

Molybdenum isotopic abundances in Pellin‘s presolar SiC X-grains

$^{x}Mo/^{97}Mo$	Isotopic abundance ratios		
	SiC X-grains [a)]	This work [b)]	‚n-burst‘ model [c)]
$^{92}Mo/^{97}Mo$	$<10^{-2}$	$4.1*10^{-3}$	$1.43*10^{-3}$
$^{94}Mo/^{97}Mo$	$<10^{-2}$	$6.3*10^{-3}$	$3.27*10^{-4}$
$^{95}Mo/^{97}Mo$	2.1	3.12	1.539
$^{96}Mo/^{97}Mo$	0.12	$4.77*10^{-2}$	$1.02*10^{-2}$
$^{98}Mo/^{97}Mo$	1.2	0.950	0.382
$^{100}Mo/^{97}Mo$	0.25	0.225	$9.55*10^{-2}$

[a)] M.J. Pellin et al., LPSC 37 (2006) 2041
[b)] K. Farouqi et al., PASA 26 (2009) 194
[c)] B.S. Meyer et al., ApJ 540 (2000) L49

Summary

We confirm,

p-, s- and r-isotopes in the light trans-Fe region are co-produced in the ν-driven wind of core-collaps type II supernovae

……………………………………………………………………………………

As select examples,

- **the HEW scenario can provide a consistent picture for all seven Mo isotopic abundances in Pellin's presolar X-type SiC-grains**

- **it can also reproduce the $^{92}Mo/^{94}Mo$ SS ratio of ≈ 1.6**
  for Ye = 0.47 the predicted mass of ^{92}Mo per SN event is about $2.6*10^{-8}$ $M_{\odot}$

……………………………………………………………………………………

"Best" HEW conditions

superpositions of components
$0.46 \leq Y_e \leq 0.48$ with **$S \leq 100$**
⇨ $Y_n/Y_{seed} < 1$

} primary charged-particle process
after α-rich freezeout;
no n-capture component !

Main collaborators
N. Christlieb, K.-L. Kratz, U. Ott, B. Pfeiffer, F.-K. Thielemann, O. Hallmann

Reserve

The OLD "neutron-burst" model

THE ASTROPHYSICAL JOURNAL, 540:L49–L52, 2000 September 1

MOLYBDENUM AND ZIRCONIUM ISOTOPES FROM A SUPERNOVA NEUTRON BURST

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Received 2000 May 18; accepted 2000 July 7; published 2000 August 23

ABSTRACT

We analyze the nucleosynthesis implications of the recent discovery by M. J. Pellin and collaborators that two odd isotopes of molybdenum, ^{95}Mo and ^{97}Mo, are overabundant in type X SiC grains: X grains condensed within expanding supernova interiors. We find that a rapid release of neutrons (on a timescale of seconds) with fluence $\tau = 0.07$–0.08 neutrons mbarn^{-1} produces the observed pattern by way of abundant production of progenitor radioactive Zr isotopes. This suggests that the condensing matter was in a supernova shell in which rapid burning was occurring at the time of ejection, probably owing to the passage of the shock wave from the core. Which shell, and the exact source of the neutrons, is still unknown, but we present a model based on the shock of an He shell.

Subject headings: dust, extinction — nuclear reactions, nucleosynthesis, abundances — supernovae: general

The isotopic patterns discovered by Pellin et al. (1999, 2000) are anomalous and quite puzzling. In particular, four X grains show large excesses in ^{95}Mo and ^{97}Mo without similarly large excesses in ^{100}Mo. Such an isotopic pattern differs from that derived from either the pure *r*- or *s*-process; ^{96}Mo and ^{98}Mo excesses would prevail in pure *s*-process matter, while the largest excess would be at ^{100}Mo for pure *r*-process matter. The X grains show neither of these patterns.

Isotopic abundance ratios: SS vs. HEW

HEW model-inherently weighted superposition of different **Y_e-trajectories** ($0.46 \le Y_e \le 0.48$) with corresponding **S-components** ($5 \le S \le 100$);

⇨ **$Y_n/Y_{seed} < 1$**

charged-particle component of HEW;
no neutron-capture contribution **!**

Consistent picture?

Typical yields (M_o) for Y_e = 0.47			
^{64}Zn	$5.6*10^{-5}$	^{78}Kr	$4.0*10^{-8}$
^{70}Ge	$8.9*10^{-6}$	^{84}Sr	$1.2*10^{-8}$
^{74}Se	$5.4*10^{-8}$	^{92}Mo	$2.6*10^{-8}$

Isotopic pairs (nucleosynth. origin)	Isotopic abundance ratios	
	Solar System	HEW
^{64}Zn(p) / ^{70}Zn(r)	78.4	79.4
^{70}Ge(s,p) / ^{76}Ge(r)	2.84	4.61
^{74}Se(p) / ^{76}Se(s)	$9.4*10^{-2}$	$9*10^{-2}$
^{74}Se(p) / ^{82}Se(r)	0.101	0.113
^{78}Kr(p) / ^{86}Kr(r,s)	$2.1*10^{-2}$	$8*10^{-4}$
^{84}Sr(p) / ^{86}Sr(s)	$5.7*10^{-2}$	$4*10^{-2}$
^{90}Sr(s,r) / ^{96}Zr(r,s)	18.4	5.56
^{92}Mo(p) / ^{94}Mo(p)	1.60	1.86
^{96}Ru(p) / ^{98}Ru(p)	2.97	2.57

New observables for Mo

Presolar SiC grains (sub-micron size)

measured with NanoSIMS or RIMS

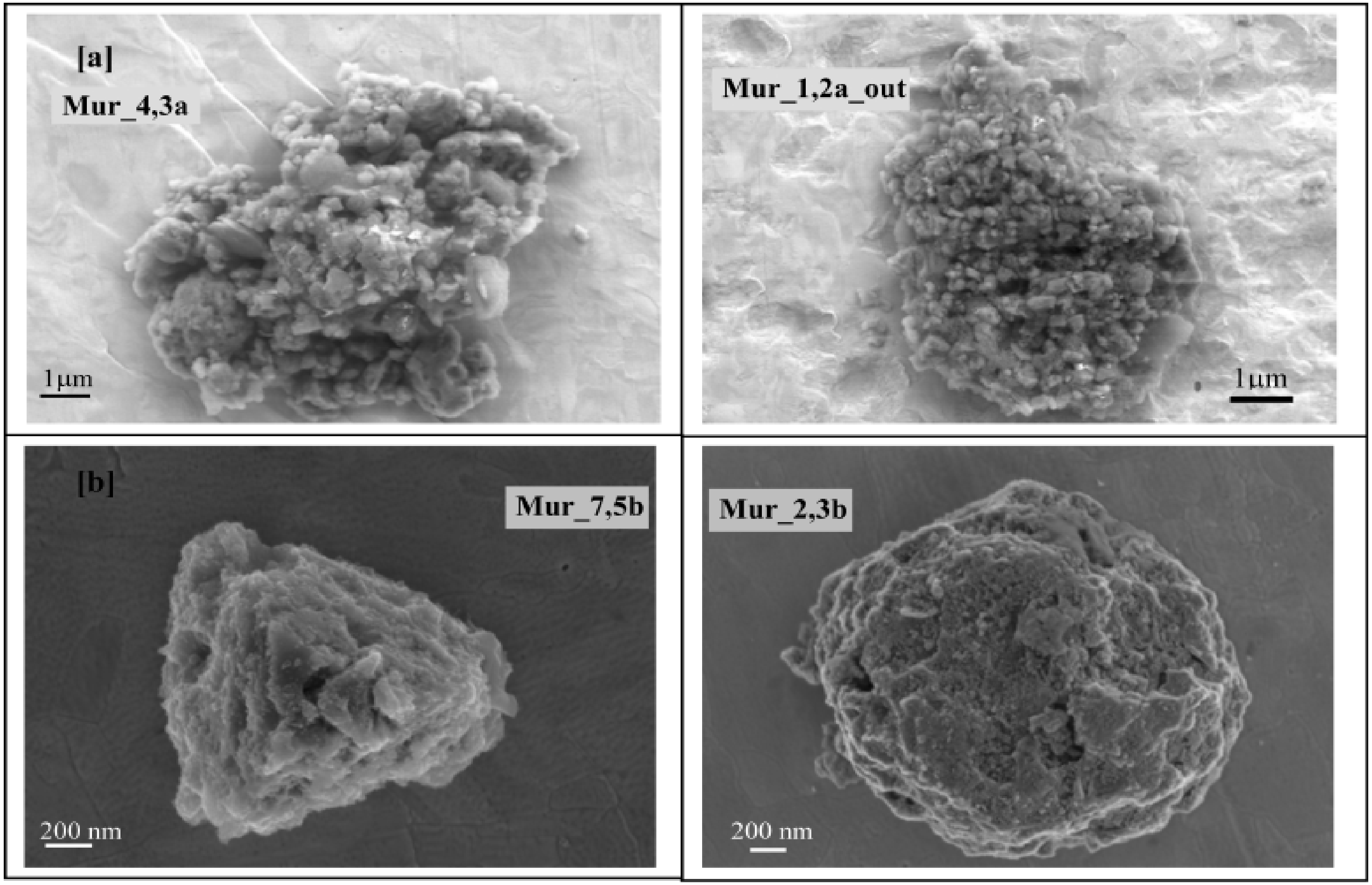


Fig. 1. SEM images of (a) agglomerate-like grains and (b) single mainstream SiCs measured in the present study. Note that the agglomerate-like grains may consist of very fine submicron-size SiC grains; but see also discussion in the text.

From: Marhas, Ott & Hoppe, MPS 42 (2007)

Relative elemental abundances, Y(Z)

From **Sr – Zr**

to **Mo – Pd** ↷ **different behaviour ?**

ELEMENT	Y(Z) as fct of entropy. S				
	$10 \leq S \leq 50$	$50 \leq S \leq 100$	$100 \leq S \leq 150$	$150 \leq S \leq 200$	$200 \leq S \leq 250$
$_{38}$**Sr**	80%	18%	2.3%	0.3%	0.01%
$_{39}$**Y**	61%	37%	1.3%	0.3%	0.02%
$_{40}$**Zr**	22%	67%	11%	0.35%	0.01%
$_{42}$**Mo**	0.7%	44%	53%	2.7%	0.05%
$_{44}$**Ru**	$5 \cdot 10^{-6}$ %	12%	77%	11%	0.09%
$_{46}$**Pd**	/	4.6%	74%	22%	0.2%

α-process → | n-rich α- freezeout →

βdn-recapt. → | weak comp. → | main comp. r-process →

uncorrelated with Eu → | **correlated with Eu** →

Comparison results ν-driven wind (1996) / HEW (2009)

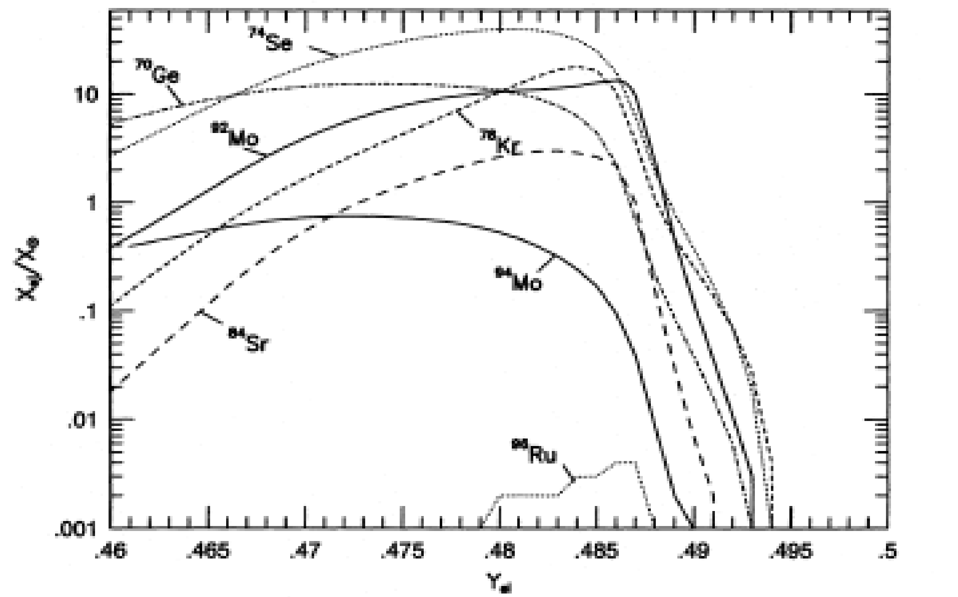
Hoffman et al. ApJ 460 (1996)

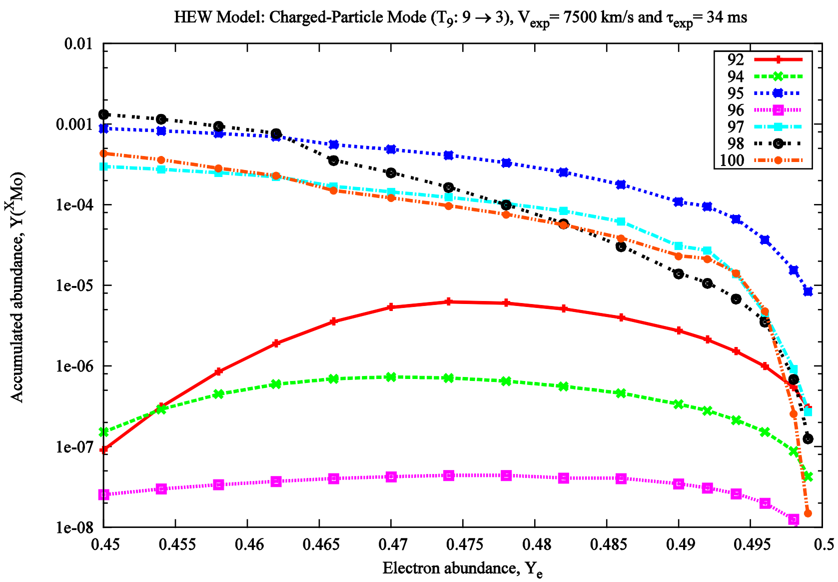
"normalized production factors"

$X_{ej}/X_{\odot} = f(Y_e)$

individual Y_e's; $S/(N_A k) \approx 50$

"No initial abundances of r- or s-process seed need be invoked,
⇨ this component of the p-process is primary rather than secondary."





Our approach (HEW 2009)

first step – individual Y_e's;
superposition of S-components ($S \leq 100$)

second step – superposition of Y_e-traject. ($0.46 \leq Y_e \leq 0.48$)
plus superposition of correspond. S-components

↷ total Y_e – S parameter range

$Y_n/Y_{seed} < 1$