^{92}Nb/^{93}Nb AND ^{92}Nb/^{146}Sm RATIOS OF THE EARLY SOLAR SYSTEM: OBSERVATIONS AND COMPARISON OF *p*-PROCESS AND SPALLATION MODELS

C. L. Harper, H. Wiesmann, and L. E. Nyquist, SN2, NASA Johnson Space Center, Houston, TX, 77058 USA; W. M. Howard, LLNL, Livermore, CA 94550 USA; B. Meyer, Dept. of Physics and Astronomy, Clemson Univ., Clemson, SC 29634-1911 USA; Y. Yokoyama, UA 184 du CNRS, 1, rue René Panhard, 75013 Paris, France; M. Rayet and M. Arnould, Institut d'Astronomie et d'Astrophysique, Univ. Libre de Bruxelles-CP 165, 50 ave. F. D. Roosevelt, B-1050, Bruxelles, Belgium; H. Palme, B. Spettel, and K. P. Jochum, Max-Planck-Institut für Chemie, Saarstrasse 23, D-6500 Mainz, FRG.

^{92g}Nb ($T_{1/2}$ = 36 My) and ^{146}Sm ($T_{1/2}$ = 103 My) are both shielded '*p* -only' nuclei, not produced in either the *s* - or *r* - processes. Stable *p* -process abundances in the bulk solar system (BSS) are a cumulate of supernova inputs into the protosolar 'reservoir' over pre-solar galactic history. The presence of two long-lived *p* -nuclides in the early solar system presents the prospect of a well-defined *p-process nucleocosmochronology,* analagous to that inferred from ^{235}U, ^{238}U and ^{232}Th for the *r* -process. In principle, a measurement of the BSS *ab initio* ^{92}Nb/^{146}Sm abundance ratio will strongly constrain the history of *p* -processing in the protosolar region over the last few 100 My prior to 4.56 By, dependent on the development of adequate astrophysical models and accurate production ratio estimates. A significant complication is the possibility that ^{92}Nb was made 'locally' by early T-Tauri protons [1], in which case, the loss of a *p* -process cosmochronometer could be the gain of a very early pre-main sequence *p* -monitor--- an attractive trade-off! (^{92}Nb could also be made by neutrino spallation in supernovae [2], and in the new "α-process" scenario of [3].) Here we report: (i) evidence that ^{92}Nb was live in the early solar system; (ii) the resulting BSS *ab initio* ^{92}Nb/^{146}Sm ratio from ^{146}Sm/^{144}Sm determinations, and (iii) production ratio estimates for two contrasting *p* -process supernova models, and a range of spallation conditions.

A well-resolved ^{92}Zr anomaly has been measured in a 110μg Nb-rutile sample from the Toluca type IAB iron meteorite (fig. 1): [8.8 ± 1.3, 2σ]ε. A result of [2 ± 2, 2σ]ε was also obtained for a group II fine-grained Allende inclusion: 4b-1, having Ta/Hf ~22 x the CI ratio (fig. 4). Nb/Zr ratios of the analysed rutile sample was ~150, as estimated by electron probe (Nb, table 1) and by isotope dilution (Zr) of the sample solution, (which contained ~84% Zr from inclusions and blank). A direct Nb/Zr ratio of 0.09 (1.4 x CI) was obtained by SSMS on an aliquot of 4B-1, (demonstrating that Ta/Nb can be strongly fractionated in type II CAI). The rutile datum yields an initial ^{92}Nb/^{93}Nb ratio of [2 ± 1] x 10^{-5}. For $[^{146}Sm/^{144}Sm]_{4.55\ By}$ = 0.006 ± 0.002 [4, fig. 3], $[^{92}Nb/^{146}Sm]_{4.55\ By}$ = 0.3 ± 0.2 is obtained. Data will be presented for EK5-3-2, a type II inclusion having Nb/Zr = 1.7 (27 x CI).

Two contrasting supernova models have been proposed recently for reproducing the BSS stable *p* -abundances: a Type Ia carbon deflagration model [5], and a Type II scenario based upon modelling of core-collapse explosion in massive stars [6]. These differ in both their processing conditions and initial (*s* -process) seed distributions. The Type I model erodes a strongly enhanced AGB-type (He shell flash) seed distribution assumed to exist at the edge of the C-O core, whereas the Type II model erodes a 'weak' *s* -process distribution produced during hydrostatic He core burning in a massive star. Reaction channels in the ^{92}Nb region for the Type Ia model are shown in figure 2. Production ratio estimates for ^{92}Nb/^{93}Nb, ^{92}Nb/^{92}Mo, ^{146}Sm/^{144}Sm, ^{92}Nb/^{146}Sm, ^{53}Mn/^{92}Mo, ^{53}Mn/^{55}Mn, and ^{97}Tc/^{92}Mo are given in table 2. The Type II results refer to detailed modelling of SN1987A [7]. It is interesting that the Type Ia and Type II models give different predictions for the ^{92}Nb/^{146}Sm ratio, which may therefore provide a test for these models. At the present stage, it is difficult, however, to exclude or favor one or other. The astrophysical plausibility of the Type Ia scenario remains somewhat speculative, while the Type II results correspond to modelling of an observed object in the Large Magellanic Cloud. Many nuclear physics uncertainties also remain. Moreover, ^{92}Nb could have been produced 'locally', as our spallation models (table 3) suggest. However, we note that $\tau(^{92}Nb)/\tau(^{146}Sm)$ ~0.3 is in good agreement with $[^{92}Nb/^{146}Sm]_{4.55\ By}$ / $[P(^{92}Nb)/P(^{146}Sm)]$ for the Type Ia model, consistent with a galactic origin of ^{92}Nb in these supernovae.

Results are shown in table 3 for ^{26}Al, ^{53}Mn, ^{92g}Nb, and ^{146}Sm produced in a 'local irradiation' spallation model, similar to that of [8]. Meteorite data are consistent only with ^{92}Nb and ^{53}Mn, which are the most sensitive proton monitors. Interpretation of ^{92}Nb as a T-Tauri spallation product yields a proton fluence of ~2 x 10^{19} cm^{-2} , (into the parental reservoir of Allende and Toluca). This is ~2x greater than the rough limit estimated from the BSS ^{6}Li/^{4}He ratio, (for associated α-irradiation of *unfractionated* solar material), but is well below the limits obtained from ^{138}La/^{139}La and ^{180}Ta/^{181}Ta ratios [1]. It is also consistent with rough estimates for T-Tauri activity inferred from X-ray and radio astronomy [9]. In summary, the source of ^{92}Nb is unclear. Of course, if it was made 'locally' (and hence with significant ^{53}Mn: *cf.*, table 3) in the early solar system, then ^{92}Nb is not a *p* -process cosmochronometer. A 2% upper limit is obtained for 'local' production of ^{146}Sm, which is therefore a galactic *p* -process product. ^{26}Al/^{27}Al ~ 5 x 10^{-5}, according to our spallation model, is ~5x that predicted for the fluence required to produce ^{92}Nb, and ~13x that predicted from ^{53}Mn. As an extended irradiation period and/or decay interval *increases* these discrepancies, ^{26}Al cannot be explained as a local irradiation product by our model.

Refs: [1] D.D. Clayton *et al.*, (1977). *Ap. J.*, 214: 300; [2] S. E. Woosley *et al.*, (1990). *Ap. J.*, 356: 272; [3] S. E. Woosley and R. Hoffman (1991 preprint); [4] Lugmair *et al.*, (1975). *EPSL*, 27: 79; --- (1983). *Science*, 222: 1015; Lugmair and S. J. G. Galer, (1989). *Meteoritics*, 24: 296; S. B. Jacobsen and G. J. Wasserburg, (1984). *EPSL*, 67: 137; A. Prinzhofer *et al.*, (1989). *Ap. J.*, 344: L81; --- (1990). *LPSC XXI abstract:* 981; L. E. Nyquist *et al.*, (1990). *GCA*, 54: 2195; --- (1990). *LPSC XXI abstract:* 903; --- (1991). This volume; [5] W. M. Howard, *et al.*, (1990, in press). In: H. Oberhummer and W. Hillebrandt (eds.) *Nuclei in the Cosmos* (MPI, Garching); --- (1991, in press). *Ap. J.*; [6] M. Rayet *et al.*, (1990). *Astron. Astrophys.*, 227: 271; [7] N. Prantzos *et al.*, (1990). *Astron. Astrophys.*, 238: 455; *Cf.*, also S. E. Woosley and W. M. Howard, (1990). *Ap. J.*, 354: L21, for a discussion of ^{146}Sm production mechanisms; [8] G. J. Wasserburg and M. Arnould, (1987). *Lect. Not. Phys.*, 287: 262; [9] E. D. Feigelson *et al.*, (1990). In: C. P. Sonett and M. S. Giampapa (eds.) *The Sun in Time* (U. Arizona), and references therein.

^{92}Nb/^{93}Nb AND ^{92}Nb/^{146}Sm RATIOS OF THE EARLY SOLAR SYSTEM...: Harper, C. L., *et al.*

Table 1. **TOLUCA Nb-RUTILE:**
ELECTRON PROBE COMPOSITION DETERMINATION SUMMARY
(Concentrations are *parts per million* unless otherwise indicated. Uncertainties are 2σ.)
n. d. = not detected [above ~ 10 - 50 ppm]; n. a. = not analysed. Analyst: S. Vincent Yang)

Spot #:	(1)	(2)	(3)	(4)	(5)
TiO_2	99.7 ± 0.8%	97.08 ± 0.8%	98.3 ± 0.8%	n. a.	n. a.
NbO_2	0.66 ± 0.03%	1.48 ± 0.03%	1.47 ± 0.02%	1.22 ± 0.02%	1.20 ± 0.02%
ZrO_2	180 ± 60	240 ± 60	220 ± 40	220 ± 40	210 ± 40
Nb/Zr (atom ratio)	37 ± 13	63 ± 16	67 ± 12	56 ± 10	58 ± 11
Cr_2O_3	0.39 ± 0.02%	0.35 ± 0.02%	0.37 ± 0.01%	n. a.	n. a.
Al_2O_3	270 ± 40	20 ± 20	50 ± 20	n. a.	n. a.
(SiO_2)	(90 ± 20)	(70 ± 10)	(130 ± 20)	n. a.	n. a.
FeO	n. d.	n. a.	n. a.	n. a.	n. a.
NiO	n. d.	n. a.	n. a.	n. a.	n. a.
MgO	n. d.	n. d.	n. d.	n. a.	n. a.
MnO	n. d.	n. d.	n. d.	n. a.	n. a.
V_2O_3	n. d.	n. d.	n. d.	n. a.	n. a.
TaO_2	n. d.	n. d.	n. d.	n. a.	n. a.
SnO_2	n. d.	n. d.	50 ± 40	n. a.	n. a.
Total:	100.8 ± 0.8%	98.9 ± 0.8%	100.2 ± 0.8%	---	---

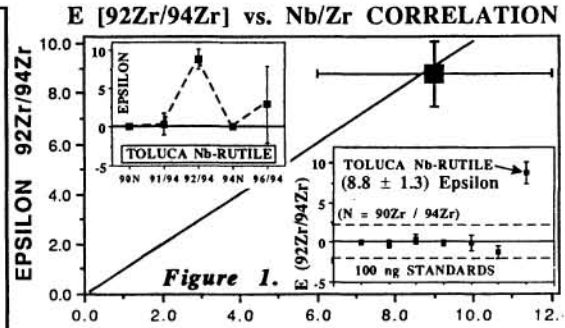

Figure 1.

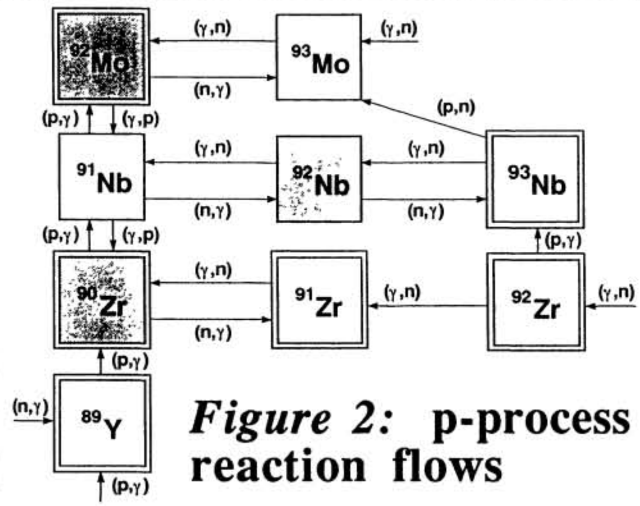

Figure 2: **p-process reaction flows**

Table 2.
SUPERNOVA MODEL
P-PROCESS PRODUCTION RATIOS

MODEL	^{92}Nb/^{93}Nb	^{146}Sm/^{144}Sm	^{92}Nb/^{146}Sm	^{53}Mn/^{92}Nb	^{97}Tc/^{92}Mo
Ia:	**~0.05 *(~0.004)**	**~0.4**	**~1**	**~60**	**~0.03**
II:	**~0.12 *(~0.003)**	**~0.7**	**~0.005**	**~$3x10^4$ **(~0.1)**	**~0.014**

The Type Ia model environment includes a much larger proton fluence and *s* -process seed enhancements than the Type II model, thus enhancing the 92Nb and 92Mo production. (See figure 2.) [*(^{92}Nb/^{92}Mo); **(^{53}Mn/^{55}Mn)]

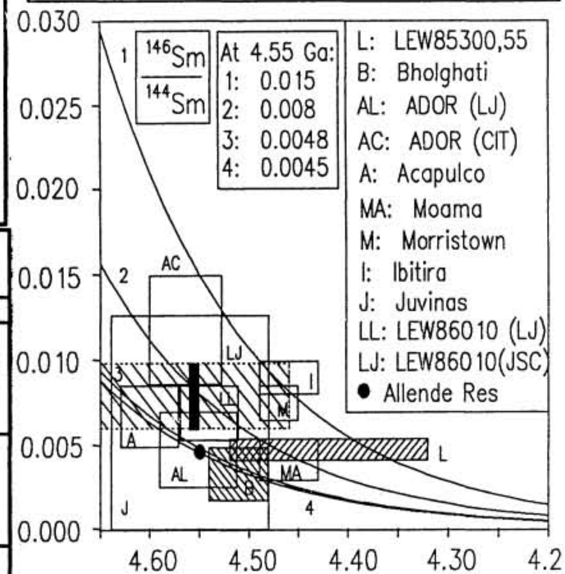

Figure 3.

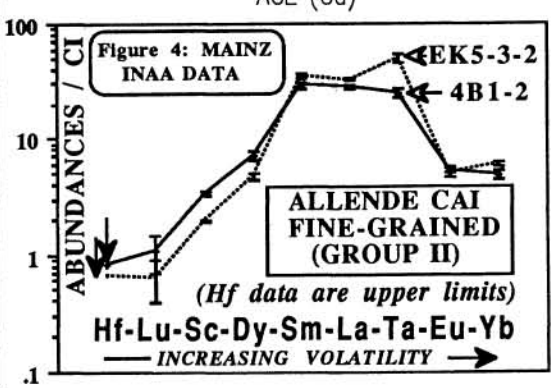

Table 3. **SPALLATION MODEL: ^{26}Al, ^{53}Mn, ^{146}Sm and ^{92}Nb PRODUCTION RATIOS BY SOLAR ENERGETIC PARTICLES ('Thin' Solar Gas Target; Interval 5-200 MeV; Short-T-Irradiation)**					
Rigidity Parameter, R_0 (MV):	**50**	**100**	**150**	**200**	**250**
(^{26}Al/^{27}Al) / (^{53}Mn/^{55}Mn)					
alpha / proton = 0	0.068	0.060	0.059	0.059	0.059
alpha / proton = 0.1	0.080	0.076	0.075	0.075	0.075
alpha / proton = 0.2	0.093	0.092	0.091	0.090	0.090
	[(~5 x 10^{-5}) / (~4 x 10^{-5}) ~1]: *NO*				
(^{146}Sm/^{144}Sm) / (^{26}Al/^{27}Al)					
alpha / proton = 0	22	21	19	18	18
alpha / proton = 0.1	21	19	18	18	17
alpha / proton = 0.2	20	19	18	17	17
	[(~0.006) / (~5 x 10^{-5}) ~10^2]: *NO*				
(^{146}Sm/^{144}Sm) / (^{53}Mn/^{55}Mn)					
alpha / proton = 0	1.5	1.2	1.1	1.1	1.1
alpha / proton = 0.1	1.6	1.5	1.4	1.3	1.3
alpha / proton = 0.2	1.8	1.7	1.6	1.6	1.5
	[(~0.006) / (~4 x 10^{-5}) ~10^2]: *NO*				
(^{92}Nb/^{93}Nb) / (^{26}Al/^{27}Al)					
alpha / proton = 0	2.6	2.9	2.7	2.5	2.4
alpha / proton = 0.1	2.4	2.4	2.3	2.2	2.1
alpha / proton = 0.2	2.2	2.2	2.0	1.9	1.9
	[(~2 x 10^{-5}) / (~5 x 10^{-5}) ~0.5]: *NO*				
(^{92}Nb/^{93}Nb) / (^{146}Sm/^{144}Sm)					
alpha / proton = 0	0.12	0.14	0.14	0.14	0.13
alpha / proton = 0.1	0.11	0.13	0.13	0.12	0.12
alpha / proton = 0.2	0.11	0.12	0.11	0.11	0.11
	[(~2 x 10^{-5}) / (~0.006) ~0.003]: *NO*				
(^{92}Nb/^{93}Nb) / (^{53}Mn/^{55}Mn)					
alpha / proton = 0	0.18	0.17	0.16	0.15	0.14
alpha / proton = 0.1	0.19	0.18	0.17	0.17	0.16
alpha / proton = 0.2	0.20	0.20	0.18	0.17	0.17
	[(~2 x 10^{-5}) / (~4 x 10^{-5}) ~0.5]: *CLOSE!!*				