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Co-Production of Light p-, s- and r-Process Isotopes in the High-Entropy Wind of Core-Collapse Supernovae

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We have performed a large-scale nucleosynthesis parameter study within the high-entropy-wind (HEW) scenario of core-collapse supernovae with the primary aim to obtain indications for the production conditions of the classical 'p-only' isotopes of the light trans-Fe elements in the Solar System (SS). We find that in moderately neutron-rich winds, sizeable abundances of p-, s- and r-process nuclei between ^{64}Zn and ^{104}Ru are co-produced. Taking the peculiar compositions of the 7 stable Mo isotopes in (i) the SS and (ii) in specific presolar SiC X-grains as particularly challenging examples, our results show that the HEW ejecta can reproduce both, (i) the SS-ratio of ^{92}Mo/^{94}Mo with isotopic yields per SN event in the 10^{-8} $M_{\odot}$ range, and (ii) the puzzling grain data of the Argonne / Chicago group. These results are in principal agreement with earlier studies, and may provide further means to revise the abundance estimates in the historical "light-p", "weak-s" and "weak-r" process regions.

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1. Introduction

The origin of the stable isotopes of the light trans-Fe elements (between Zn (Z=30) and about Cd (Z=48)) in the Solar System (SS) has been a fascinating area for nuclear astrophysicists over more than 50 years. It is commonly believed that these elements are produced by varying contributions from three historical nucleosynthesis processes, (i) the "p-process" (see, *e.g.* [1, 2, 3]), (ii) the "weak s-process" (see, *e.g.* [4, 5]), and (iii) the "weak r-process" (see, *e.g.* [6, 7, 8, 9]).
Apart from the SS **isotopic** abundances [10], astronomical observations in recent years of **elemental** abundances in ultra-metal-poor (UMP) halo stars (for a recent review, see, *e.g.* [11]) revived and intensified interest in the nucleosynthesis of these elements (see, *e.g.* [12, 13, 14, 15, 16, 17]). Additional interest has derived from the **isotopic** compositions of some refractory trans-Fe elements in presolar SiC grains of type X (see, e.g. [18, 19]). These have been discusssed so far in the framework of a secondary "neutron-burst" nucleosynthesis process [20], originally suggested as an explanation for the isotopic abundances of Xe in presolar diamonds [21]. However, even those recent models have major shortcomings the one or other way. In particular, all models seem to be unable to reproduce the SS abundance ratio of the two highly abundant p-isotopes ^{92}Mo and ^{94}Mo [10]. In this paper, we present results from a High-Entropy Wind (HEW) scenario, which offers a solution to the above problems by producing the light trans-Fe elements by a primary charged-particle (CP) process (for details, see [22]).

2. Calculations and Results

The concept of a high-entropy wind arises from considerations of the newly born proto-neutron star in core-collapse SNe. In this scenario, the late neutrinos interact with matter of the outermost neutron-star layers, which may lead to moderately neutron-rich ejecta with high entropies (see, *e.g.* [3, 12, 23]). As in [17], in the calculations presented here we follow the description of adiabatically expanding mass zones. Neutrino-accelerated nucleosynthesis, the so-called νp-process (see, e.g. [14, 24]), was neglected, because its supposed contribution to the Zr-Mo region is still controversely debated. While in [14, 24] an efficient synthesis of p-nuclei up to about Pd is predicted, more recent calculations seem to indicate that the νp-process does not play a significant role beyond Kr-Rb [16, 25]. From our parameter studies we found that the HEW predicts at least two different nucleosynthesis modes. For low entropies (S $\leq$ 100, where $Y_n/Y_{seed} \leq 1$) the concentration of free neutrons is negligible. Hence, the nucleosynthesis in this S-range is not a neutron-capture process but rather a CP-process. For higher entropies, the neutron yields are increasing smoothly, resulting in the classical "weak" and "main" r-process components.
After having focussed on *elemental* abundances in the past, in this paper we discuss selected HEW results on *isotopic* abundances of the trans-Fe elements between Zn (Z=30) and Ru (Z=44), in particular their decomposition into the respective fractions of the historical p-, s- and r-process nuclei. Several conclusions can be drawn from these simulations performed within a large Y_e – S – V_{exp} parameter space (for details, see [22]). The most important observation in the present context is, that for the range $0.450 \leq Y_e \leq 0.495$ the HEW low-S CP-process produces the lightest isotopes of all even-Z isotopes between Fe (Z=26) and Ru (Z=44), where all p-nuclei are involved. Above Ru, however, the abundance fractions of the CP-component become negligible compared to the now

	Isotopic abundance ratios			
Isotope pairs (nucleosynth. origin)	Solar System [10]	This work [22]	γ-process [13]	EC SN [16]
^{64}Zn(p)/^{70}Zn(r)	78.4	79.4	10.5	6.6 E+7
^{70}Ge(s,p)/^{76}Ge(r)	2.84	4.61	2.53	2.8 E+9
^{74}Se(p)/^{76}Se(s)	9.42 E-2	9.09 E-2	0.128	0.567
^{74}Se(p)/^{82}Se(r)	0.101	0.113	0.120	6.1 E+9
^{78}Kr(p)/^{82}Kr(s)	3.11 E-2	2.92 E-2	1.97 E-2	0.654
^{78}Kr(p)/^{86}Kr(r,s)	2.11 E-2	7.9 E-4	5.8 E-3	5.7 E+4
^{84}Sr(p)/^{86}Sr(s)	5.66 E-2	4.00 E-2	4.05 E-2	0.240
^{90}Zr(s,r)/^{96}Zr(r,s)	18.4	5.56	10.4	$>$ E+20
^{92}Mo(p)/^{94}Mo(p)	1.60	1.86	1.55	49.4
^{96}Ru(p)/^{98}Ru(p)	2.97	2.57	2.54	9.06

Table 1: Selected isotopic abundance ratios of light trans-Fe elements between Zn (Z=30) and Ru (Z=44).

dominating neutron-capture "weak" r-process.
In Table 1 we present typical HEW results for selected isotopic abundance ratios for several elements, and compare them to two recent nucleosynthesis models [13, 16]. From the detailed nucleosynthesis calculations for massive stars (from central H-burning through SN-II explosions) by Rauscher et al. [13], we have selected their 15 $M_{\odot}$ model S 15, starting with an initial SS seed composition which is then modulated by an s-process and subsequently by a γ-process. Wanajo et al. [16] have presented simulations on the nucleosynthesis in neutrino driven winds on the one hand, and in electron-capture (EC) SNe of AGB stars with an O-Ne-Mg core on the other hand. For the HEW model, an optimum range of $0.458 \leq Y_e \leq 0.478$ has been obtained, within which our calculated abundance ratios within isotopic chains agree quite well with the SS values for the whole mass region from Zn up to Ru. A more detailed discussion can be found in [22].

After these more general results for the whole light trans-Fe region, we now want to focus on the abundances of the Mo (Z=42) isotopes. There are several reasons for choosing this isotopic chain. In the light trans-Fe region, besides Ru (Z=44), Mo has with 7 nuclides the longest sequence of stable isotopes, from the two light "p-only" nuclei ^{92}Mo and ^{94}Mo, via the intermediate-mass "s-only" isotope ^{96}Mo, up to the "r-only" nuclide ^{100}Mo [10]; the remaining isotopes ^{95,97,98}Mo have mixed s + r origin. Therefore, it is of special interest to check whether our HEW simulations can account for the co-production of all 7 stable isotopes. Another challenge is the recent observation of the peculiar Mo isotopic composition of presolar SiC X-grains [18], which clearly differs from all classical nucleosynthesis processes.
Because of the specific position of Mo in the chart of nuclides, in principle there exists only a narrow nucleosynthesis path for the Mo isotopes in between the stable Zr (Z=40) and Ru (Z=44) isotopes. ^{92,94}Mo are shielded on the neutron-rich side by their isobars ^{92,94}Zr. And indeed, in our calculations the p-nuclide ^{92}Mo is only produced directly. Similarly, the heavier p-nuclide ^{94}Mo is predominantly produced directly and to some extent by β^+-decay of its proton-rich isobars and / or by β^--decay from ^{94}Nb. Only ^{95}Mo and ^{97}Mo can be reached by longer β-decay chains on

	Isotopic abundance ratios			
^{x}Mo/^{97}Mo	SiC X-grains	SS	"n-burst"	This work
^{92}Mo/^{97}Mo	< 0.19	1.55	1.4 E-3	0.10
^{94}Mo/^{97}Mo	< 0.10	0.97	3.3 E-3	1.3 E-2
^{95}Mo/^{97}Mo	1.83	1.66	1.54	3.65
^{96}Mo/^{97}Mo	$\equiv 0.05$	1.74	1.0 E-2	1.6 E-3
^{98}Mo/^{97}Mo	0.71	2.52	0.38	1.38
^{100}Mo/^{97}Mo	0.13	1.01	9.6 E-2	0.32

Table 2: Molybdenum isotopic abundance ratios (^{x}Mo/^{97}Mo). The initial data were obtained by RIMS measurements of the individual SiC grains [18]. They indicate a mixture of normal (SS) Mo and an (unknown) exotic component. The respective compositions have been derived by weighted fits to the grain data (two outliers omitted), forced through the respective SS value and extrapolated to ^{96}Mo/^{97}Mo $\equiv$ 0.05. They are compared with the SS values, the predictions of the "neutron-burst" model [20] and the CP-component in moderately neutron-rich SN winds (for details, see [22]).

both sides of stability. In contrast, the classical s-only isotope ^{96}Mo in between is "shielded" on both sides by its stable isobars ^{96}Zr and ^{96}Ru. Finally, the two heaviest Mo isotopes, ^{98}Mo and the classical "r-only" nuclide ^{100}Mo, are again "shielded" on the proton-rich side by their Ru isobars, but can be reached by the full A=98 and 100 β^{-}-decay chains on the neutron-rich side (for a more detailed discussion, see [22]).

As mentioned above, the puzzling pattern of the Mo isotopes in SiC X-grains [18] clearly differs from those derived from either a pure s-process or a classical r-process. So far, possible nucleosynthesis implications have only been analyzed within a rather complicated secondary "neutron-burst" scenario in shocked He-rich matter in an exploding massive star, specially designed to meet the experiments' requirements [20].
Cosmochemists conventionally compare their measured isotopic abundance ratios with predictions from different nucleosynthesis models in terms of three-isotope correlations (for example ^{100}Mo/^{97}Mo vs. ^{96}Mo/^{97}Mo; see, e.g. Fig. 1 of [19]). In Table 2 we compare the end members of the mixing lines of the SiC grain data with the predictions from our HEW simulations for slightly neutron-rich ejecta ($0.490 < Y_e < 0.495$) and the earlier "neutron-burst" model. It is evident, that our approach of synthesizing all 7 Mo isotopes in the presolar SiC grains by a primary CP-process offers a solution also to these isotopic anomalies.

3. Summary and conclusion

We have shown in a large-scale parameter study that moderately neutron-rich wind ejecta with low entropies can co-produce the light p-, s- and r-process isotopes between Zn and Ru by a rapid primary CP-process. Furthermore, we have found that our HEW calculations are able to reproduce the SS abundance ratio of the two p-nuclei ^{92}Mo/^{94}Mo $\simeq$ 1.6 [10], where both isotopes are produced with yields per SN event in the 10^{-8} $M_{\odot}$ range (see Table1 and discussion in [22]).

Finally, the likely nucleosynthesis origin of the peculiar Mo isotopic composition of the presolar SiC X-grains of [18] has been determined.

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References

[1] E.M. Burbidge et al., *Rev. Mod. Phys.* **29** (1957) 547.

[2] M. Arnould, *A & A* **46** (1976) 117.

[3] S.E. Woosley et al., *Ap. J. Suppl.* **36** (1978) 285.

[4] D.D. Clayton, *Principles of Stellar Evolution and Nucleosynthesis*, McGraw Hill, New York (1968).

[5] F. Käppeler et al., *Rep. Prog. Phys.* **52** (1989) 945; and Refs. therein.

[6] P.A. Seeger et al., *Ap. J. Suppl.* **11** (1965) 121.

[7] W. Hillebrandt, *Space Sci. Rev.* **21** (1978) 639; and Refs. therein.

[8] J.J. Cowan et al., *Phys. Rep.* **208** (1991) 267; and Refs. therein.

[9] K.-L. Kratz et al., *Ap. J.* **403** (1993) 216; *Ap. J.* **662** (2007) 39; *New Astronomy Reviews* **52** (2008) 390.

[10] K. Lodders, *Ap. J.* **591** (2003) 1220.

[11] C. Sneden et al., *Ann. Rev. Astr. & Astroph.* **46** (2008) 241.

[12] R.D. Hoffman et al., *Ap. J.* **460** (1996) 478; *Ap. J.* **482** (1997) 951; *Ap. J.* **676** (2008) L127.

[13] T. Rauscher et al., *Ap. J.* **576** (2002) 323; and Refs. therein.

[14] J. Pruet et al., *Ap. J.* **644** (2006) 1028.

[15] M. Pignatari et al., *Ap. J.* **687** (2008) L95.

[16] S. Wanajo et al., *Ap. J.* **647** (2006) 1323; *Ap. J.* **695** (2009) 208; and Refs. therein.

[17] K. Farouqi et al., *Ap. J.* **712** (2010) 1359 ; and Refs. therein.

[18] M.J. Pellin et al., *Lunar Planet. Sci. Conf.* **31** (2000) 1917 ; **37** (2006) 2041.

[19] K.K. Marhas et al., *Meteoritics & Planet. Sci.* **42** (2007) 1077.

[20] B.S. Meyer et al., *Ap. J.* **540** (2000) L52.

[21] D.D. Clayton, *Ap. J.* **340** (1980) 613.

[22] K. Farouqi et al., *Publications of the Astronomical Society of Australia* **26** (2009) 194.

[23] C. Freiburghaus et al., *Ap. J.* **516** (1999) 381.

[24] C. Fröhlich et al., *Phys. Rev. Lett.* **96** (2006) 14.

[25] J.W. Truran, C. Fröhlich, *priv. comm.* (2010).