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COSMIC RAY NUCLEI

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NUCLEOSYNTHETIC CLUES TO SOURCES OF ULTRAHEAVY COSMIC RAY NUCLEI¹

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Abstract

As a result of recent successful International Collaboration Experiments, a statistically significant sample of reasonably well resolved charge composition of Ultra Heavy(UH) Cosmic Rays near Earth, will be available in the very near future. Though propagation calculations are riddled with considerable uncertainties, due mainly to the lack of experimentally measured relevant cross-sections, some broad trend of source characteristics can nevertheless be inferred from the available bulk composition ratios, as was done earlier with a much smaller sample from Ariel-VI and HEAO-3 results. With the very large expansion of the database, it is hoped to make this inference about the sources of cosmic rays more quantitative. This hope is strengthened in view of new experiments planned in the near future, to remove major uncertainties in the propagation calculations. However, comparison of detailed relative abundances of individual elements has to still contend with considerable ambiguities in the calculation of source abundances, arising due to lack of full understanding of several quantitative details of the site as well as the involved nuclear physics of the $r - process$ of building nuclei heavier than Fe. These are brought to light here.

1 Introduction

The importance of Ultra Heavy (UH) Nuclei in giving clues to the nature of sources of cosmic rays can hardly be overemphasized. The relative abundances of these nuclei can potentially give information on almost all aspects of cosmic ray physics. The propagation of UH Nuclei, with their very small interaction mean free paths and very high collision energy losses will be able to effectively constrain the propagation models. Then the determination of the presence or otherwise of the preferential selection of Nuclei with low First Ionization Potentials, observed in the low charge region, will be able to give clues about the physical conditions like temperature and density, of the region, where these nuclei are accelerated. With several short-lived isotopes, Th/U ratio can potentially give the mean age of cosmic rays. The presence of trans-Uranic elements will indicate the admixture of products of recent supernova explosion in the local cosmic rays. Thus a large amount of qualitative

information of immediate relevance to cosmic ray astrophysics can and has already been gathered from an analysis of relative abundances of UH Nuclei /1-5/. However, in order to arrive at detailed quantitative model, it is necessary to take into account several pitfalls in this adventure. For any important conclusions, it is first necessary to have individual charge resolution, so that odd-even effects can be clearly obtained. At the moment this is still not achieved. Even assuming that the future experiments will be able to achieve this, at least at the detector level, as outlined by Binns and Westphal in their talks this morning /6,7/, Waddington informed us very clearly the uncertainties in the various fragmentation cross-sections /8/, which make it harder to get the individual abundances in the local interstellar space, in the first place. Then we heard from him as well as the Dublin-ESTEC Collaboration /9/, the uncertainties in the extrapolation to the sources through the interstellar medium, with several propagation models. Assuming that over the next few years, all these uncertainties are removed and a good determination of the relative abundances of various nuclei are obtained, even then a direct quantitative comparison with the source abundances is still a far cry, as there exist considerable ambiguities, in even determining the $r - process$ site/s and the consequent abundance estimates. So the prospects for the distant future are very optimistic for more detailed work to ward off the present pessimistic situation! Here, after a brief summary of the main qualitative conclusions from the results obtained so far, an overview of the recent nucleosynthetic calculations, with their inherent limitations, and the plausible sites of their occurrence, will be attempted. The future outlook forms the main concluding remarks.

2 Current Status of UH Nuclei Data and Its Implications

Though early Skylab and Balloon measurements gave the first indications of the presence of Ultraheavy Elements ($Z \geq 30$) /10-12/, no confidence could be placed on their results, due to several inherent technical problems of the detectors /5/. Thus the first reliable experimental estimate of the UH Nuclei abundances in cosmic rays, though of limited statistical significance, came from experiments carried by Ariel-VI and HEAO-3 /1,2/. The abundances obtained by these experiments, some of which are confirmed by the latest LDEF Results are shown in Table 1. As can be seen, the abundances are given for pairs of elements and not individually. This is due to the fact that reliable estimates of only even elements are obtained and it is best to combine the result with the odd elements. This situation, though not very satisfactory at present, will be redeemed when detailed results from the US-Russia Collaboration Experiment becomes available, as was outlined by Westphal this morning and by the experiments, planned for the near future, described by Binns. The latest solar system abundances compiled by Anders and Grevasse /13/ are also shown in the Table. In order to make a proper comparison with the sources of cosmic rays, it is necessary to extrapolate the abundances obtained near Earth for propagation through the interstellar medium. There are several propagation models, which have been tried, to take into account the propagation from source to Earth, ranging from the Closed Galaxy Model, Leaky Box Model, Nested Leaky Box Model, Model with Reacceleration etc. In all these models (see /14/ for a recent summary), basically a set of abundances of various nuclei at the sources are assumed with a particular form of energy spectra (usually a power

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Table 1: Abundances of UH Nuclei in GCR and Solar System (Fe=10⁶)

Z	HEAO-3 /2/	Ariel-VI /1/	LDEF /5/	UHGCR ^a	Solar /13/	Process ^b /13 ^c /
32	-	-	-	91±12	132.2	S,e ^c
33-34	51.2±3.7	66±5	-	61.1±4.1	76.3	S,R ^c
35-36	35.1±3.0	39±4	-	36.6±2.5	63.1	S,R ^c
37-38	39.6±3.1	36±4	-	37.8±2.9	34.0	S,r ^c
39-40	22.2±2.6	24±4	-	22.8±2.3	17.8	S ^c
41-42	[15.4±2.1] ^d	17±4	-	11.0±3.4	3.6	R,s
43-44	4.6 ±1.2	3±2	-	4.1±1.1	2.1	R,s
45-46	6.7 ±1.4	5±2	-	6.2±1.1	1.9	R,s
47-48	5.5 ±1.3	5.5±1.3	-	5.5±0.9	2.3	R,s
49-50	6.3±1.5	5.3±1.0	-	5.6±0.8	4.4	S,r
51-52	5.2±1.4	7.4±1.0	-	6.7±0.8	5.7	R,s
53-54	3.1±1.2	4.3±1.1	-	3.8±0.6	6.2	R
55-56	6.3±1.6	7.9±1.2	-	7.4±1.0	5.4	S,r
57-58	3.5±1.3	1.8±1.0	-	2.4±0.8	1.8	S,r
59-60	1.5±1.1	2.3±0.8	-	2.0±0.7	1.1	R,S
LS(62-69)	6.4±0.9	7.3±0.9	-	6.9±0.6	1.7	R
HS(70-73)	2.0±0.6	1.9±0.5	1.9±0.2	1.9±0.2	0.5	R,S
Pt(74-80)	5.1±0.8	5.7±0.8	5.5±0.2	5.5±0.2	3.8	R
Pb(81-83)	1.2±0.5	2.0±0.6	2.1±0.2	2.0±0.2	3.9	S,R
Actinides(88-100)	-	0.4±0.2	1.0±0.2	0.9±0.2	0.2	RA

Notes to Table 1

^aThe UHGCR refers to estimate by Binns et al/2/ for Z≤69 and to present work (including the LDEF Results) for Z≥70.

^bThe dominant neutron addition process is indicated by Capital letters.

^cFor Z≤40, α-process/27/ may make a non-negligible contribution

^dFor Z=41-42, earlier HEAO measurement, with better resolution, yields a value of 11.0 ±3.0

spectrum in Total Energy). Then an exponential pathlength distribution with an assumed mean pathlength(which may or may not vary with energy) is used to derive abundances at the local interstellar space. In some cases, there is a cut-off for the pathlength distribution at the lower end. There are some cases of reacceleration during propagation introduced in the calculations. The chief aims of all the models is to fit the Secondary/Primary ratio like B/C or (Sub-Fe)/Fe etc. The main conclusions from such an exercise can be summarized as follows:

1. The abundance of UH elements with $Z \leq 60$ seem to follow the pattern of elements with lower charges, namely, the selection by First Ionization Potential. Essentially the solar system abundances with the FIP selection yields the observed abundances.

2. The UH Nuclei with their short interaction mean-freepaths are ideally suited to test the assumptions of reacceleration as well as any other modifications to the pathlength distribution like cut-off of the exponential distribution for shorter pathlengths etc. Though there are considerable uncertainties in the assumed parameters, a broad consensus exists that the standard leaky box model leading to an exponential pathlength distribution, with a rigidity dependent mean pathlength, seems to fit the observations reasonably well, provided the source abundances are properly taken into account, like enhanced abundances of *r-process* nuclei/2/. (see, however, /9/ for an alternate point of view).

3. This enhanced abundance of *r-process* elements in the source regions of cosmic rays is confirmed by the much higher Pt/Pb ratio in UHGCR, compared to the solar system ratio.

4. The very much enhanced relative abundance of actinides, compared to the solar system value, indicates the admixture of products from recent nucleosynthetic events, in the UHGCR near Earth.

From the foregoing one is tempted/4/ to conclude that the source region is having an enhanced abundance of *r-process* products and hence probably a model of the origin of cosmic rays in an OB-Association/15,16/ is supported by these observations. However, an equally compelling case can be made about the origin of these UH Nuclei from the envelope of a supernova in recent times, especially in view of the presence of actinides. There is one way to distinguish between the two alternatives. This is by finding out the presence or otherwise of the selection through First Ionization Potentials. If the origin is directly from the recent supernova envelope, then it is unlikely to show any FIP Selection effects, as at the temperature-density conditions prevailing in the Supernovae-envelope regions, all the elements will be fully stripped and hence there is no possibility of selection of elements with low FIPs. On the other hand, if the nuclei are thrown into an OB-Association, the physical conditions may allow the preferential selection. Thus detailed abundance measurements of individual UH Nuclei carry this reward, provided the estimate of abundances from the nucleosynthetic processes as well as the UHGCR abundances extrapolated to the source regions are accurate enough. Since Waddington has already detailed the great uncertain future for the extrapolation to the source regions/8/, this talk will cover the ambiguities in the nucleosynthetic calculations. Again, basically what is needed is an accurate estimate of the abundances of *r-process* nuclei from their proper sites. It is shown below the great

thermodynamical conditions of the Nuclear Statistical Equilibrium (NSE) freeze-out. This build-up of elements upto $A \simeq 100$ is termed as the α Process/26,27/, which is discussed next.

3.1.2 α Process

Following the collapse and bounce of the 'Iron' core in a Type-II Supernova, the rapid expansion/cooling phase starts. At low densities and relatively high temperatures, NSE favours α particles. At temperatures of $\sim (8-7) \times 10^9$ K the matter of the bubble contains mainly α particles with a small admixture of neutrons and almost no protons. Below $\sim 7 \times 10^9$ K, the triple α reaction starts alongwith the $\alpha\alpha n \rightarrow {}^9\text{Be}(\alpha, n){}^{12}\text{C}$. The large presence of α particles ensures the transformation of ${}^{12}\text{C}$ into heavier nuclei by successive α captures, until either the coulomb barrier or the combination of photodisintegration, (n, p) and (n, α) reactions prevent the further build-up of the heavy nuclei. This process is very important for the UH Nuclei, in view of the suggestion from the preliminary results of the Russia-US Collaboration Experiment of the presence of neutron rich Ni isotope in their sample/7/. Indeed in the neutron rich α freeze-out calculations of Witt et al/27/. ${}^{60}\text{Ni}$, ${}^{62}\text{Ni}$, ${}^{64}\text{Zn}$, ${}^{66}\text{Zn}$ and ${}^{70}\text{Ge}$ are produced in large amounts, in addition to nuclides with the neutron magic number $N=50$ like ${}^{88}\text{Sr}$, ${}^{89}\text{Y}$, ${}^{90}\text{Zr}$ etc. While the abundance does not come in serious conflict with the production of iron-peak group upto ${}^{66}\text{Zn}$, the nuclides near $A \simeq 90$ poses a serious problem, as these nuclei are produced easily by the well understood s - process. Actual calculation of the contribution of supernovae to a nuclide like ${}^{88}\text{Sr}$ yields an unacceptable overproduction factor of 150 for this nuclide alone. Thus it is very clear that this is a very severe shortcoming of the model, though this may be interesting from the UH Cosmic Ray point of view. In addition, this overabundance of neutron rich nuclei upto Z of ~ 40 , leads to a situation where there is very little room left for r - processing, as there are very few neutrons left for that. This brings us to the discussion of the main ambiguities in the operation of r - process in the seemingly most favourable environment for its occurrence.

3.1.3 r -Process in the High-Entropy Neutrino Energised Supernova Bubble

The ambiguities in calculations arise from two major physical problems. The first one is to do with the thermodynamic history of the neutrino-energised hot bubble (or as Witt et al would like to call in the neutrino driven winds from proto-neutron stars). This is intimately related to the details of the model of the Type-II Supernova Explosion of a $20 M_\odot$ star, investigated originally by Mayle and Wilson/28/, which formed the basis of the suggestion of the hot bubble as a r - process site/26/. The crucial parameters involved here are the entropy per baryon and the electron concentration. The computed supernova conditions yield values in the range of 75-300 for the specific entropy s and in the range of 0.460-0.425 for the electron concentration Y_e . Unfortunately these conditions, as already mentioned above, result in mopping up of almost all neutrons in the form of neutron rich heavy nuclei of mass number below ~ 100 by the α process in the bubble/26-31/. A parametric study of the mass-fraction of heavy nuclei synthesised as a function of s reveals the rather steep

decrease of the heavy nuclei mass fraction as the specific entropy increases. This is easily understood from the fact that the reaction rates for the crucial triple α as well as the $\alpha\alpha n \rightarrow {}^9\text{Be}(\alpha, n){}^{12}\text{C}$ sequence depend on the third power of density. The only way to avoid this catastrophe is to have exceedingly large value for s or decrease of density by a large factor. This ensures that sufficient number of neutrons are left for the further build-up of heavier nuclei, in addition to ensuring that no overabundance of nuclides with mass numbers close to 90. Essentially this is the first problem plaguing the reliable quantitative prediction of abundances of r - nuclides.

The second important uncertainty in getting the reliable estimate has to do with the nuclear physics problems. Many of the cross-sections used in the detailed reaction network are calculated using the presently available best methods. These calculations including the β - decay and β delayed neutron emissions rely indirectly on the correct knowledge of the nuclear masses. Mostly one has to rely on model predictions for obtaining these values. These models require considerable improvements. Until that is achieved, the abundance estimates necessarily have to suffer from huge uncertainties.

It is a pity that after getting very close to what looks like an ideal site for the operation of the r - process, lack of nuclear physics data as well as the development of detailed hydrodynamical model, prevents us from making the next step of reliable quantitative estimates of the abundances of r - nuclides. Since this is going to be the case in the foreseeable future, one is forced to look for some other specific tests for the identification of sources of UH Nuclei. In that respect, neutrino induced nucleosynthesis offers the best hope from the nucleosynthesis point of view. This is discussed next.

3.2 Neutrino Induced Nucleosynthesis

Soon after discovery of neutral currents in the CERN Experiments, the Domogadskii and Nadyozhin/32/ worked out in great detail the synthesis of light nuclei like Li, Be and B as well as the nuclides attributed by B²FH/18/ to what they termed as p - process by the neutrino induced processes/33/. This process essentially consists of neutral current inelastic scattering of neutrinos off the target nuclei, raising them to excited states. The excited target nuclei decay by the emission of a proton, or neutron or α particle, depending on the branching ratio. So in order to get the abundances of nuclides by this process it is necessary to have reliable estimate of the neutrino excitation cross-sections as well as the branching ratios. The calculation of cross-section involves detailed shell-model techniques. But fortunately at temperatures of about 10 MeV, characteristic of Supernovae neutrinos of muon and tau type, the cross-section per nucleon are roughly independent of the nuclear species and may be taken as about 10^{-42} cm^2 . In order to compute the branching ratios detailed Hauser-Feshbach studies are needed, but the most probable value estimate is not too far wrong and hence they are used in the estimates. Though the cross-sections are very small as mentioned above, the large number of the neutrinos of all species emitted make this process a very important one. Almost all the total binding energy of the neutron star of about 3×10^{53} ergs are carried away by neutrinos of all types with a mean energy of about 10 MeV during the cooling phase of the hot neutron star born in the final stages of the core

collapse, which takes place in about 10-20 seconds. Though there is a severe competition between efficient neutrino induced production and destruction due to photodissociation in the regions very close to the core, the detection of neutrino signal from the SN1987A has revived interest in this process. Actually it was suggested as a proper mechanism to generate the neutrons to activate the r - process/34/. Subsequent detailed work/35/ has shown this to be totally inadequate for the operation of the r - process. But it has been shown that some of the nuclides, like especially solar ^{180}Ta , ^{138}La , whose origin was not clearly understood earlier, are very efficiently produced by this process/35-37/. Hence if the experimental set up in cosmic rays is improved to such an extent as to detect the presence of these very very rare nuclides in cosmic rays, the supernova source can be conclusively proved.

4 Concluding Remarks and Future Outlook

It has emerged from this meeting that really a huge database for the flux of cosmic ray UH Nuclei will be available before possibly the next cosmic ray conference in Rome next year. Further the detailed and careful determination of the relevant cross-sections necessary for extrapolating the abundances at the near-Earth space to the sources, will also be realised very soon. Hence the task of nuclear astrophysicists to come up with quantitative detailed abundances of the various nuclides under realistic astrophysical environments has become very urgent. While the abundances of s - process nuclides seem to be more or less well determined for diverse astrophysical environments, a beginning has been made in realising a reasonable site for the r - process in the neutrino energised high entropy supernova bubble. The remaining task of understanding the physical and dynamical development of the 'hot bubble' in such a detailed manner so as to calculate the abundances of r - nuclides is going on at present in several laboratories. In the meantime, we will end the talk by suggesting an Utopian experiment to determine the isotopic abundance of ^{180}Ta and ^{138}La in order to confirm both the supernova source for cosmic rays and the operation of neutrino induced nucleosynthesis in Nature!

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