Light Elements in the Universe
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The search for the origin of the light nuclei Li, Be, B

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Abstract. My aim is to show how the abundance ratios of the light elements (6 to 11) are related to the properties of the strong nuclear interaction and, in particular, to the major influence of closed shells of neutrons and protons, (the magic numbers : 2, 8, etc) on the binding energies of the nuclei.

Keywords. Nuclear reactions, nucleosynthesis, abundances – ISM: cosmic rays

1. Introduction

The α-particle has a very high binding energy, resulting from its doubly magic structure : two protons and two neutrons. This fact results, on the one hand, on the relatively high binding energies of the nuclei containing the equivalent of an integer number of α-particles (C-12, O-16, Ne-20, Mg-24, Si-28 : the so-called α-nuclei) but also on the very low binding energy of the light nuclei : lithium, beryllium, and boron, the most extreme case being the instability of the mass-5 and of the mass-8. Immediately after their formation these nuclei rapidly decay in an α-mix (a group of nuclei containing the maximum number of α-particles.)

As shown in Table 1, Be-9 is hardly bound, and B-11 in more bound than B-10. Lithium -6 and Lithium-7 are quite comparable to the Bs. These low binding energies with respect to the α-mix are the reasons why these elements can not withstand the high temperatures of the stellar interiors.

2. Where were they made?

There are several hints for the identification the formation mechanisms of lithium, beryllium, and boron.

<u>Hint no 1:</u> The amplitude of the nuclear cross sections for their formation by high energy protons on heavy nuclei (spallation) are closely related to their cosmic abundances.

We consider high energy processes in a cold region. For instance cosmic ray protons on C-12 or 0-16 on interstellar gas. The physics of these reactions is best described by the Enrico Fermi hot ball model. The target nucleus is first heated to very high temperatures by the energy of the incident bolid. It thermalizes and cools by evaporation of part of

Table 1. Table of binding energies of the light nuclei with respect to an α-mix The number in MeV gives the energy release by the break up of the nucleus in a group of light particles containing the maximum amount of α-particles (dubbed an α-mix)

Li-6	2.45 MeV
Li-7	1.24 MeV
Be-9	88 KeV
B-10	5.97 MeV
B-11	11.2 Mev

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its nuclear constituents (neutrons, protons, alphas). The residual nucleus can be Li, Be, or B.

One of the tenets of quantum physics is that the probability of a reaction leading to a specific result is proportional to the number of equivalent ways of producing this result. This, in turn, is a measure of the volume of phase space available for the reactions, hence of the amount of kinetic energy released by the reactions. The products with low binding energies release a larger volume of space phase and have hence a larger formation probability. This is well illustrated when one considers the cross-sections for the formation of the light nuclei by high energy protons on C-12. As expected, Be has the smallest value, followed by Li and B. The cross-section for B-11 is larger than for B-10. The case of Li will be considered later.

Hint no 2: These nuclei are much more abundant in galactic cosmic rays than in nature. Note that boron is more abundant than nitrogen!

3. Nuclear physics data

In the 1960 when this model was presented, practically no data on the nuclear cross sections were available. In the following years I visited a number of nuclear laboratories (Los Alamos, CERN, Darmstad, Berkeley, Moscow, Leningrad, Erivan) to present this proposal. The reactions of the nuclear physicists was typically "Yes, this is interesting but because of the need of obtaining highly purified targets, it would take many years to complete this project. We can not get involved for such a long period of time."

Fortunately, in 1965, I met a group of physicists of Orsay, France led by René Bernas, who were already pursuing such experiments. We joined forces to interpret the results in the nucleosynthesis context.

Taking into account the fact that each accelerator works at a given energy, and that the cosmic ray particles span a large range of energies, from MeV to GeV and more, it became necessary for the nuclear physicists to bring their isotope separators to different accelerators in France, Germany, USSR, and Switzerland (CERN) in order to patiently build the full cross sections of the various reactions involved.

I want here to give credit to these scientists by giving their names : Marcelle Epherre, Elie Gradstajn, François Yiou, Robert Klapisch.

4. Comparison of abundances with the calculated values

Calculations were then performed of the abundances and isotopic ratios, taking into account the spectrum of energy in galactic cosmic rays and the nuclear cross sections obtained in the laboratories. The results and their astrophysical implications are discussed in the following.

The beryllium abundance can be taken as a measure of the integral activity of the bombardment of the cosmic rays throughout the life of our Galaxy. Indeed the product of the present formation rate of Be times the life of the Galaxy yields an abundance quite comparable to the observed abundance.

The relative probabilities of formation of the various isotopes can be used to evaluate the contribution of GCR to the other light isotopes. We define a term $F(obs/calc)(x/y)$ as the ratio of the observed abundances of two nuclei x and y over the calculated ratio of their formation rates in GCR.

Boron over beryllium

The observed ratio in the solar system SS (sun and meteorites) is 23. The calculated GCR ratio is 15. We have also observations of this ratio in the metal poor stars of ~ 20, constant with metallicities down to (-3) (one thousand solar).

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The observed isotopic ratio in the solar system is 11/10 = 4.0, while the formation ratio is 2.5. We probably need an extra source of B-11, which could come from stellar processes. One possibility is the C-12 desintegration by neutrino collisions in supernovae which would generate B-11 but no B-10. However the uncertainties involved in the calculations of the yields are so large that no meaningful comparison can be made.

We consider the case of B-10.

$$F = (10/9)obs/(10/9)calc = (116/22)/5 = 1.04$$

showing that this isotope is a pure GCR product.

Lithium 7/lithium-6

The GCR ratio is ~ 2 while the SS is 12.5. This was the first indication of a possible other source of Lithium-7. Thanks to the observations of François and Monique Spite, we associate this source to the Big Bang Nucleosynthesis. Studies of the fossil radiation (CMB) by the satellite WMAP have confirmed this association.

However, since the contribution of BBN to the formation of Li-6 is negligible, we may ask if this element is a pure product ot GCR. Computing the ratio of its abundance to the Be-9 abundance we find:

$$F(6/9)(obs)/calc) = 6.5/5 = 1.3$$

confirming the value of the hypothesis.

Some observations of lithium in interstellar gas, in particular around the star Rho Ophiucus, have locally given values much smaller than the solar system values. One possibility is the collision of fast alphas on Helium-4 which generates Li-6 and Li-7 with ratios around 2. We note that the respective cross-sections involve alphas of energies around ten to one hundred Mev per nucleon, appreciably smaller than the mean particle energy in the GCR (hundreds of Mev). This may involve special astrophysical contexts such as the activity of high energy emitting particles stars in these area.

To complete this operation we compute the ratio of B-10 to Li-6

$$F(10/6)obs/calc = (116/144)/1 = 0.8$$

confirming that the nuclei of Li-6, Be-9, and B-10 are pure products of the GCR.

5. Conclusions

It is of interest to note that the three nucleosynthetic processes : Big Bang, Galactic cosmic rays, and stellar nucleosynthesis cover suitably well the light elements abundances (A<12).

The Big Bang is responsible for the atoms with mass number 2, 3, most of 4, and 7 (mostly in old stars).

The GCR is responsible for 6, 9, 10, and also a part of 7 and most of 11.

Stellar nucleosynthesis is responsible for most of 7, some 4, and perhaps some 3 and 11. And also of the elements from carbon to the heaviest elements : thorium and uranium.

References

The references are given in the paper of Nicolas Prantzos.

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