Polyneutron theory and cosmology

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Abstract

The abstract is yet to come.

INTRODUCTION

In 195x Mayer and Teller considered the possibility that the elements might have formed by fragmentation of enormous polyneutrons early in the expansion of the universe. They did not explain how the polyneutrons might have formed, and the theory predicted far to few heavy nuclei. Shortly thereafter Peierls *et al.* refined and expanded this idea and confirmed that it did not explain the origin of the heavy elements.

A few years later Alpher, Beta and Gamov suggested that the elements had built up in the dense hot plasma of the early big bang by addition of neutrons to small nuclei beginning with hydrogen. This approach was refined and summarized by Alpher and Herman in 195y. It was by then recognized that a dynamic theory was essential, and it was also clear that although the generation of deuterium, tritium and helium was possible by neutron addition, further neutron addition was blocked because there are no nuclei with mass numbers 5 or 8. Alpher and Herman suggested that polyneutron formation might be able to bridge the mass gaps but they did not pursue this possibility.

All these authors assumed that polyneutrons are bound, in consequence of which polyneutrons in some concentration would have formed along with hydrogen isotopes and helium during element formation. They would have influenced the process of element formation, particularly if the energy of separation of a neutron from a polyneutron were to exceed the 2.2 MeV binding energy of deuterium. In that case polyneutrons would begin to form before deuterium and might have been created in substantial numbers. And if, as suggested below, their decay products include long-lived massive metastable isotopes of low-Z elements these isotopes would be observable today.

There is no empirical evidence for or against strong binding of large polyneutrons, nor is there any first-principle theory of binding. The current treatment is phenomenological, with theoretical models designed to fit observed nuclear properties. I expect that ^{A}n is a collective system of neutron pairs with a wave function analogous to that of electron pairs in superconductivity. This implies that the energy of separation is small for small polyneutrons, and does not reach full strength until the neutron number is on order of 10-100 neutrons. During the element synthesis phase of the big bang polyneutrons must be built up one neutron at a time, passing through ^{2}n, ^{3}n, ^{4}n, ... on the way to a larger ^{A}n. Because ^{2}n, ^{3}n, and possibly ^{4}n are not bound, but exist only as resonances, it will be difficult to initiate

polyneutron formation. Owing to the bottleneck of small polyneutrons, which will break down nearly as rapidly as they are formed, formation of a permanent bound polyneutron will likely be rare event. But after its separation energy has increased to exceed the energy of the big bang plasma a large polyneutron can do nothing but grow. Its size is limited only by the supply of neutrons and the time available for neutron capture.

To illustrate the range of possibilities I assume an average separation energy of 5 MeV per neutron, about 1/3 of that for ordinary nuclear matter when coulomb energy is neglected.[ref Krane]. Because of pairing this might correspond to 3 MeV for separation of an odd neutron, and 7 MeV for separation of a neutron that must break a pair. Then once a polyneutron reaches a sufficient size it will persist and grow in a plasma with tail energy less than 7 MeV. In such an environment large polyneutrons will form. At first they will exist in an environment where weak interactions are in thermal equilibrium with neutrons and protons and the neutron population is replenished by proton transmutation as polyneutrons grow. Early formation and growth of polyneutrons draws down the supplies of neutrons and protons equally until the neutrino fields are decoupled. Then polyneutrons draw down neutrons alone. Later when the energy drops below 2.2 MeV and deuterium formation becomes significant, deuterium becomes a competitor for neutrons and evolution of deuterium, tritium, and helium follows a modified path to that in the absence of polyneutrons.

POLYNEUTRON DECAY

Polyneutrons have finite lifetimes with respect to beta decay. Because beta decay can occur during element synthesis it may modify the role of polyneutrons. And the beta decay of cold polyneutrons after the plasma has cooled and element synthesis is complete can influence the decay chains that generate the residual charged nuclei that may exist today. For these reasons a more thorough discussion of polyneutron decay is useful.

The only decay channels available to polyneutrons involve beta decay in which one of the neutrons is replaced by a proton, reducing the total baryon mass by 0.782 MeV. The proton can share the paired state with the neutrons, maintaining an unchanged nuclear interaction energy. This reaction is always exothermic because no neutron separation energy is involved, nor is any coulomb energy involved beyond that included in the proton mass. Subsequently the proton may be emitted as a free particle or when bonded with one or two neutrons

it may be emitted as a deuteron or a triton. It also may be that the proton, deuteron, or triton remains attached to the residual polyneutron, forming a giant halo nucleus. The binding energy that stabilizes halo nucleus stability comes from an overall reduction of surface and interfacial energies. Formation of such composites is limited to those with halos that are polyneutrons or polyneutrons with one or two protons substituted for neutrons in the collective paired phase. The coulomb energy associated with halos having larger coulomb charges overwhelms the potential binding energy of the composite.

Because a halo nucleus has has lower energy than the pair of free particles from which it is assembled, halo nuclei are preferred as reaction products. In consequence, for simplicity I focus on reactions where the core remains in place.

When two neutrons combine with polyneutron $^{\mathrm{A}}\mathrm{n}$ the mass of the resulting polyneutron $^{\mathrm{A+2}}\mathrm{n}$ is reduced by the magnitude of the separation energy of the pair as it joins the collective phase. The reaction is exothermic,

$$^{\mathrm{A}}\mathrm{n} + 2\,\mathrm{n} \rightarrow {}^{\mathrm{A+2}}\mathrm{n} + S_2 \tag{1}$$

where S_2 is the separation energy for removal of the pair from the polyneutron. When a single neutron combines with an even-A polyneutron the mass of the resulting polyneutron is reduced by the separation energy of an odd neutron from a fully paired odd-A configuration,

$$^{\mathrm{A}}\mathrm{n} + 2\,\mathrm{n} \rightarrow {}^{\mathrm{A+1}}\mathrm{n} + S_1 \quad (\text{even A}) \tag{2}$$

where S_1 is the separation energy of the odd electron. Together these reactions lead to the mass relationships

$$\begin{aligned} \Delta(^{\mathrm{A+2}}\mathrm{n}) - \Delta(^{\mathrm{A}}\mathrm{n}) &= \Delta(\mathrm{n}) - S_2 \quad (\text{all A}) \\ \Delta(^{\mathrm{A+1}}\mathrm{n}) - \Delta(^{\mathrm{A}}\mathrm{n}) &= \Delta(\mathrm{n}) - S_1 \quad (\text{even A}) \\ \Delta(^{\mathrm{A+2}}\mathrm{n}) - \Delta(^{\mathrm{A+1}}\mathrm{n}) &= \Delta(\mathrm{n}) - S_2 + S_1 \quad (\text{even A}). \end{aligned} \tag{3}$$

The separation energies S_1 and S_2 depend on the value of A. They become smaller as A diminishes and approach zero at $\mathrm{A} \approx 4$. I do not attempt to model this behavior and limit the quantitative portion of the analysis to polyneutrons of sufficient size that S_1 and S_2 have approached their asymptotic values for large A.

I assume that polyneutron beta decay begins with

$$^{\mathrm{A}}\mathrm{n} \rightarrow {}^{\mathrm{A}}\mathbf{H} + 0.782 \tag{4}$$

where the proton shares the paired nucleon configuration with A−1 neutrons. This state is a member of the same isospin multiplet as ^{A}n, has the same nuclear binding energy, has no increment of coulomb energy, and differs in energy only by the reduction of 0.782 MeV mass on substituting a proton for a neutron. I use bold-faced type for charged members of the ^{A}n isospin multiplet.

Reaction (4) is relatively slow owing to the long half-life of a neutron. It can be followed by prompt but independent nuclear rearrangement. Rearrangement can lead to a free hydrogen isotope or to a bound hydrogen isotope that serves as core of a giant halo nucleus. The halo nucleus configuration has lower energy due to a net reduction of surface and interfacial energies of the two components, and is the more likely to be formed. In the following I consider primarily halo nuclei where the core is an ordinary nucleus and the halo is a polyneutron. I assume that the core and the halo maintain their individuality, including masses, excitation levels and symmetries, and that the energy consequences of halo formation is confined to a binding energy E_B that can depend to a degree on the nature of the core nucleus.

For $^{A}\mathbf{H}$ the only exothermal nuclear rearrangement is a halo nucleus with a hydrogen isotope core. The lowest energy rearrangement is that for which transfer of neutrons in either direction between the halo and the core is endothermic. This is the state we seek. Using polyneutron mass formulas 3 and the tabulated values for hydrogen isotopes the lowest energy configuration is a halo nucleus with a triton as core. I write this $^{3}\mathrm{H}^{\mathrm{A}-3}$n with the core and the halo written adjacent to each other in the manner of chemical molecules where bound Na and Cl atoms are written as NaCl. The rearrangement energy depends on whether the initial $^{A}\mathbf{H}$ has even or odd A,

$$^{A}\mathbf{H} \rightarrow {}^{3}\mathrm{H}^{\mathrm{A}-3}\mathrm{n} + 444(\text{even A}) + 555(\text{odd A}). \tag{5}$$

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