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NUCLEI WITH EXCESS NEUTRONS

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ATOMIC nuclei containing many more neutrons than the stable nuclei known on earth undoubtedly exist in nature and play an important role in the evolution of stars and in the nuclear chemistry of element synthesis. According to modern notions, the stars, which contain the bulk of the matter in the Universe, evolve from less dense states into states with growing density. The hydrogen constituting the original main mass of the star is burned out thereby, becoming transformed into heavier elements, i.e., the free protons are transformed into bound neutrons.

The increase in the star density places it into a condition with a degenerate electron gas, whose Fermi limiting energy increases. The increase of the Fermi energy shifts the nuclear-stability band from the region known for the nuclei that are abundant on the earth to a region with an ever increasing neutron excess. The neutron-excess nuclei, which are β^--active on earth, become stable inside the star with degenerate electron gas. Their decay is forbidden by the Pauli principle if the Fermi energy of the gas exceeds the decay energy of these nuclei. Therefore the condensation of the gas during the course of its evolution causes it to become neutronized, i.e., an ever increasing fraction of the protons is turned into neutrons. An appreciable number of the stars become what are known as neutron stars, in which practically all the protons have turned into neutrons.

In the course of the increasing neutronization, various neutron-excess nuclei are undoubtedly produced within the composition of the star. Their abundance in the star is determined by the average (for the given state) ratio N/Z of the number of neutrons to the number of protons, and by the conditions of thermal equilibrium. The nuclei most abundant at low temperatures are those having the highest binding energy for the given N/Z. In turn, the last complex nuclei arising in the history of the neutronization of the star and existing just before the transition to the pure neutron state will be those with the largest N/Z ratio in the bound states.

Which are the nuclei having bound states at the highest N/Z ratio? This question cannot be answered with assurance at present. But mention can be made, with a high degree of probability, of the recently discovered nucleus He^8. Its ratio $N/Z = 3$ is apparently the highest obtained for nuclei in a state bound by nuclear forces. Of course, N/Z of neutron stars is appreciably larger, but this is due to gravitational rather than nuclear forces. An analysis of the energy of pure neutronic matter without gravitation is contained in several theoretical papers [1-5]. Although their results are quantitatively at variance, all show that the neutron gas has a positive energy that decreases monotonically with decreasing density. The energy minimum necessary for the existence of a liquid drop apparently does not exist.

The limit of stability of the nuclei in the region of neutron excess (the limit of positive values of the neutron binding energy) was discussed a number of times [1,6-8] Cameron [7] published in 1957 a table of nuclear masses calculated from semi-empirical formulas; these are widely used for estimates of the masses of unknown nuclei, but they are apparently incorrect in the region of large neutron excesses. In 1959 Cameron, analyzing the formation of transuranic elements during nuclear explosions, has found [9] that the binding energy of the neutron decreases with increasing N/Z more slowly than given in his 1957 tables. Recently Cameron and Elkin [10] reviewed the semi-empirical formulas for the nuclear masses and presented two new versions of mass tables. One was calculated with a formula in which the isotropic term of the energy depends on $(A - 2Z)$ exponentially. With such a dependence, the neutron binding energy is always positive and there is no stability limit. This variant disagrees with calculations for a pure neutron gas and apparently does not correspond to reality. The stability limit should exist, but its location is unknown. If it does not reach values $N/Z = 3$, then the nucleus with the maximum relative neutron excess is He^8.

For light nuclei, the semi-empirical mass formulas are not applicable at all, since their masses and binding energies vary more irregularly than in medium and heavy nuclei. To predict the masses of unknown light nuclei, less general empirical rules were used. In one such paper Zel'dovich, [1] attempting to refine the stability limit of light nuclei with allowance for the shell effects and pairing of nucleons, predicted the existence of several neutron-excess light nuclei, including He^8. Later Gol'danskiĭ [11] supported this prediction on the basis of an analysis of the excited levels of Li^7. A number of experiments have by now been performed, proving the existence of He^8 and confirming the correctness of the prediction.

The first to observe He^8 were Lozhkin and Rimskiĭ-Korsakov in 1961 [12]. They observed in a nuclear emulsion exposed to very fast protons the characteristic T-decays of Li^8 nuclei at the ends of tracks of relatively low density. To explain these observations, they proposed that the low-density tracks were produced not by Li^8 but by He^8, and that the decay $He^8 \rightarrow Li^8$ occurs at the end of the track, prior to the $Li^8 \rightarrow 2\alpha$ decay. This assumption is apparently quite consistent and reliable, and there are no grounds for disputing the priority of Lozhkin and Rimskiĭ-Korsakov's observation of He^8, although their observation could not be regarded at that time as proving the existence of He^8.

In 1963 Nefkens[8] also reported observation of He^8. However, taking into account his earlier hasty and erroneous "discovery" of He^5, his report could not be readily taken to be positive proof of the existence of He^8. In fact, subsequent experiments refuted both the half-life indicated by Nefkens for He^8 and the end point of the β spectrum, and again showed Nefkens to be inconsistent.

Strong support for the predicted existence of He^8 was provided by Detraze et al.[14], who proved that Li^7 with 11.13 MeV excitation energy has an isospin $T = 3/2$. This confirmed Gol'danskiĭ's premises, and a refinement of his calculations led to the prediction of the following limits for the mass defect Δ of He^8:

$$31.6\ \text{MeV} < \Delta(He^8) < 32.4\ \text{MeV}$$

and to an energy of decay to the 0.98-MeV level of Li^8 between 9.7 and 10.5 MeV (10.1 ± 0.4 MeV).

The second direct observation of He^8 was by Whetstone and Thomas[15]. Using a two-dimensional analyzer, they investigated the light products of spontaneous fission of Cf^{252}. Each species of light nuclei corresponded on the dE/dx vs. E diagram to a separate band. Besides the well-known α particles, they registered as fission products the then-unknown He^6 nuclei, and in addition obtained about 10 counts in the band corresponding to He^8.

In a similar experiment, Cerny et al.[17] succeeded in a more definite observation of He^8, proving its occurrence as a product of spontaneous fission of Cf^{252}.

Decay of He^8 was observed in the experiments of Poskanzer et al.[16] They obtained He^8 by bombarding a target of porous plastic or cotton with protons of 2.2 GeV energy. The target was scrubbed with gas which passed into measuring chambers after going through two filtering traps. New activity was observed in the gas, with a half-life 122 ± 2 msec, and was ascribed to He^8 decay. Beta particles, γ quanta of 0.99 ± 0.02 MeV energy, and delayed neutrons with this half-life have been observed. The γ quanta are emitted when Li^8 goes over to the ground state from the first excited state 1^+ with energy 0.975 MeV. There is an allowed decay of He^8 to this level from the 0^+ state (proposed ground state of the even-even nucleus). The delayed neutrons are emitted following β decay of the He^8 to Li^8 levels with energy >2 MeV.

The experiments show that the probability of emission of delayed neutrons is 12%.

The mass of He^8 was determined by Cerny et al.[17] They measured with a semiconductor-counter telescope the energy of the He^8 nuclei produced in the $Mg^{26}(\alpha, He^8)Mg^{22}$ reaction when an Mg^{26} target is bombarded with α particles of ~ 80 MeV energy. They determined the mass of the Mg^{22} nucleus beforehand, using the reaction $Mg^{24}(p, T)Mg^{22}$. On the C^{12} scale, the mass defect of Mg^{22} was found to be − 0.38 ± 0.55 MeV.

The cross section for the pickup of four neutrons in the reaction (α, He^8) is very small, and therefore the sought He^8 nuclei appeared against a large background of other particles and random coincidences, brought about by products of the accompanying and more probable α-particle reactions in the target and its surroundings. Therefore not one dE/dx detector, but two, i.e., dual control with the dE/dx vs. E relation in lieu of single control, were used for the analysis of the reaction products. A small number of He^8 nuclei was registered (about 30), but their energy spectrum showed clearly the presence of two groups. One corresponds to the ground state of the final Mg^{22} nucleus, and the other to an excited state with energy 1.22 MeV.

The mass defect of He^8 was found from the energy of the ground-state group to be 31.65 ± 0.12 MeV (on the C^{12} scale), in good agreement with Gol'danskiĭ's prediction. It follows from this value that the binding energy of a neutron pair in He^8 is equal to 2.1 MeV, and that of four neutrons to 3.1 MeV. The binding energy of a pair of neutrons in He^6 is 0.96 MeV, i.e., half as large as in He^8. With such a tendency, it is not excluded that the next neutron pair, which completes the p-shell, will also have a positive binding energy and consequently there exists the still heavier isotope He^{10} with the magic neutron number $N = 8$ and $N/Z = 4$. To be sure, the existing mass estimates do not yield a bound state of He^{10}[19,20].

But if He^{10} has no bound state, then He^8 has apparently the exceptionally large ratio $N/Z = 3$, since the nuclei multiple to He^8, viz., Be^{16}, C^{24}, O^{32}, etc. lie, according to present estimates, beyond the stability limits. In principle, large amounts of He^8 can exist in a strongly neutronized star with degenerate electron gas. Lifting of the electron degeneracy allows the decay $He^8 \rightarrow Li^8 \rightarrow 2\alpha$, in which about 3 MeV per nucleon is released, approximately four times the energy released in the decay of free neutrons. These "explosive" properties of He^8 can be of interest for several astrophysical phenomena.

He^8 is of interest to nuclear physics since it is the lightest nucleus with isospin $T = 2$. By using it in experiments similar to those of [17] it is possible to carry out spectrometric investigations of nuclei differing from the target nuclei by 4 and 5 neutrons. It is possible to use for this purpose, besides the (α, He^8) reaction, also the reaction (He^3, He^8) in which 5 neutrons are picked up. On the other hand, collisions of He^8 with another nucleus will lead with high probability to the inverse reaction (He^8, α) with transfer of four neutrons. In spite of the difficulty of obtaining He^8, this reaction may be useful for investigations of neutron-excess nuclei.

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