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LETTER TO THE EDITOR

HELIUM PRODUCTION IN NUCLEAR REACTORS AND EXPLOSIONS: A POSSIBLE TEST OF THE PAULI PRINCIPLE

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A very sensitive test of the validity of the Pauli exclusion principle in nuclei is proposed. It involves the use of accelerator mass spectrometry in the search for stable ^{5}He nuclei in helium samples from nuclear reactors or nuclear explosions.

The Pauli exclusion principle (PEP) is one of the fundamental principles in physics. As it was pointed out$^{1)}$, although there is no selfconsistent theory for a description of PEP violation, different experimental tests of this fundamental concept should be investigated. Recently we have proposed a test of the PEP validity in nuclei$^{2)}$. The technique involves the search for stable non-Paulian $^5\widetilde{\mathrm{Li}}$ nuclei in natural lithium using the accelerator mass spectrometry (AMS). These nuclei were supposed to be formed in nuclear reactions during stellar nucleosynthesis and in nucleosynthesis triggered by primordial explosions. The results of the first experiment of this type will be published elsewhere$^{3)}$.

Another more direct approach was proposed by Greenberg and Mohapatra$^{4)}$. They suggested the observation of energetic γ-rays from neutron absorption in nuclei. If PEP is violated neutrons can fall into inner shells which normally would be filled, and γ-rays with energy of 30 MeV and above can be emitted, while normal neutron capture in almost all nuclei gives γ-rays with energies below 10 MeV. However, it would be impossible to achieve in these measurements the same high sensitivity as in those using AMS.

In this Letter we propose another type of experiments, which seem to be more suitable to search for PEP violation in nuclei. It involves the search for $^{5}\widetilde{\mathrm{He}}$, which could be produced under well understood and controllable conditions. $^{5}\widetilde{\mathrm{He}}$ is non-Paulian nucleus having all three neutrons in 1s shell. It could be expected that α-n separation energy for this nucleus is not much different from the ^{3}He-n separation energy of ^{4}He (20.6 MeV). Both $^{5}\widetilde{\mathrm{He}}$ and $^{5}\widetilde{\mathrm{Li}}$ are favourable cases for AMS, because there are no particle stable Paulian nuclei consisting of five nucleons. Also, one can easily obtain relatively high currents of helium and lithium ions. With the help fo AMS one could achieve sensitivity for $^{5}\widetilde{\mathrm{He}}$ detection in helium below 10^{-16} 3). In order to achieve this sensitivity, gram quantities of helium should be produced in nuclear processes and then efficiently recovered. At present this can be achieved in a reasonable period of time only in nuclear reactors and nuclear explosions. In a typical nuclear power plant (3 GW thermal power) every month a kilogram of neutrons (6×10^{26} n) is produced and most of them end up inducing nuclear processes. Similarly, energy release of 0.4 PJ (equivalent to 100 kt of TNT) from the fusion part of a hydrogen bomb explosion is the result of more than 10^{26} nuclear reactions between light nuclei. In both cases a part of these processes are helium producing reactions. Here we will discuss four processes as possible $^{5}\widetilde{\mathrm{He}}$ producers: X (n, $^{5}\widetilde{\mathrm{He}}$) Y, ^{4}He (n, γ) $^{5}\widetilde{\mathrm{He}}$, ^{2}H (t, γ) $^{5}\widetilde{\mathrm{He}}$ and ^{3}H (t, n) $^{5}\widetilde{\mathrm{He}}$. In the discussion which follows, standard nuclear physics arguments will be used only.

(i) X (n, $^{5}\widetilde{\mathrm{He}}$) Y. — These reactions may be the most suitable for $^{5}\widetilde{\mathrm{He}}$ production. Many nuclei have appreciable α-particle clustering and they could be used as α-particle targets. A natural choice could be ^{6}Li, which has pronounced α-d cluster structure. It can be estimated that tons of helium have been produced in tritium production reactors in the world with the help of the ^{6}Li (n. t) ^{4}He reaction5). This reaction has very large cross section at thermal energies (1 kb). It was shown6,7) that deuteron exchange mechanism (Fig. 1a) is responsible for the major part of low energy $1/v$ cross section. By analogy one can also expect that α-particle exchange mechanism (Fig. 1b) has similar role in the ^{6}Li (n, $^{5}\widetilde{\mathrm{He}}$) ^{2}H reaction. Using formalism from Ref. 7 one can show that the ratio of the cross sections at these low energies is:

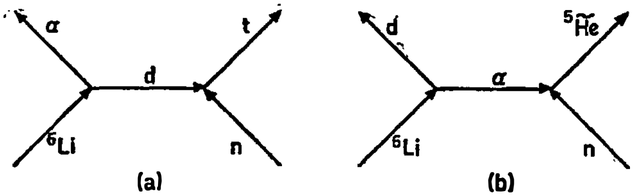

Fig. 1. (a) The deuteron exchange graph in the ^{6}Li (n t) ^{4}He reaction. (b) The α-particle exchange graph in the ^{6}Li (n, $^{5}\widetilde{\mathrm{He}}$) ^{2}H reaction.

$$\frac{\sigma_a}{\sigma_b} \approx \frac{C^2\,(\text{t-dn})}{C^2\,(^{5}\widetilde{\mathrm{He}} - \alpha\mathrm{n})} \approx \frac{1}{\beta^2} \qquad (1)$$

Factors C^2 are the t-dn and $^{5}\widetilde{\mathrm{He}}$-$\alpha n$ vertex constants. In the case of measurable PEP violation it would be possible to directly obtain the PEP violation parameter, β^2, in this way.

$^{10}\mathrm{B}$ is another light nucleus with large (n, α) cross section. It is very often used in nuclear reactors as neutron absorber. It would be interesting to collect helium produced in this way and look for $^{5}\widetilde{\mathrm{He}}$ from the $^{10}\mathrm{B}$ (n, $^{5}\widetilde{\mathrm{He}}$) $^{6}\mathrm{Li}$ reaction.

Most or in some cases all isotopes of the elements commonly used in reactors (e. g. carbon, oxygen, sodium) have negative Q-values for the (n, α) reactions. However, Q-values for the (n, $^{5}\widetilde{\mathrm{He}}$) reactions should be positive and whole reactor neutron spectrum will be used by them. In the case of PEP violation it could be expected that for some of these isotopes (e. g. $^{12}\mathrm{C}$, $^{16}\mathrm{O}$) (n, $^{5}\widetilde{\mathrm{He}}$) reaction cross section at thermal energies would be as large as for $^{6}\mathrm{Li}$. All this could help to »concentrate« $^{5}\widetilde{\mathrm{He}}$ in reactor produced helium and make its detection easier.

(ii) $^{4}\mathrm{He}\,(\mathrm{n}, \gamma)\,^{5}\widetilde{\mathrm{He}}$. — This process would proceed via the electromagnetic interaction and it would probably be slower than the (n, $^{5}\widetilde{\mathrm{He}}$) reactions.

The best way to search for $^{5}\widetilde{\mathrm{He}}$ products is to analyze helium gas used as a coolant in high temperature reactors (HTGR). Two operational HTGRs (Fort St. Vrain, USA, and THTR-300, FR Germany) have thermal powers close to 1 GW each (10 grams of neutrons per day). Helium from another German HTGR, 50 MW AVR, which operated for 20 years and was closed in 1988, could also be very useful for $^{5}\widetilde{\mathrm{He}}$ search from this process.

However, it should be mentioned that the thermal neutron cross section for $^{3}\mathrm{He}\,(\mathrm{n}, \gamma)\,^{4}\mathrm{He}$ reaction is only 54 μb[8] (1b = $10^{-28}\mathrm{m}^2$). This could mean that, if PEP is violated, the cross section for the $^{4}\mathrm{He}\,(\mathrm{n}, \gamma)\,^{5}\widetilde{\mathrm{He}}$ reaction would be many orders of magnitude lower than for the $^{6}\mathrm{Li}\,(\mathrm{n}, ^{5}\widetilde{\mathrm{He}})\,^{2}\mathrm{H}$ reaction.

(iii) $^{3}\mathrm{H}\,(\mathrm{d}, \gamma)\,^{5}\widetilde{\mathrm{He}}$ and $^{3}\mathrm{H}\,(\mathrm{t, n})\,^{5}\widetilde{\mathrm{He}}$. — In some hydrogen bomb explosions kilograms of helium were produced with $^{3}\mathrm{H}\,(\mathrm{d, n})\,^{4}\mathrm{He}$, $^{3}\mathrm{H}\,(\mathrm{t, 2n})\,^{4}\mathrm{He}$, $^{6}\mathrm{Li}\,(\mathrm{n, t})\,^{4}\mathrm{He}$ and other processes. If small amounts of it were recovered, they would also be useful in the search for PEP violation. For the same purpose one should collect helium »ashes« from the planned tritium experiments at present fusion facilities. At fusion reactor energies reaction rate for $^{3}\mathrm{H}\,(\mathrm{d}, \gamma_0)\,^{5}\mathrm{He}$ is two orders of magnitude lower than the one for $^{3}\mathrm{H}\,(\mathrm{t, n})\,^{5}\mathrm{He}$, and this is two orders lower than $^{3}\mathrm{H}\,(\mathrm{d, n})\,^{4}\mathrm{He}$ reaction rate[9,10]. This could be used as an indication for the possible ratio of the rates for two PEP violating reactions, $^{3}\mathrm{H}\,(\mathrm{d}, \gamma)\,^{5}\widetilde{\mathrm{He}}$ and $^{3}\mathrm{H}\,(\mathrm{t, n})\,^{5}\widetilde{\mathrm{He}}$

At the end of this list of possible $^{5}\widetilde{\mathrm{He}}$ producers one can mention some other more exotic processes like ternary fission or $^{5}\widetilde{\mathrm{He}}$ decay of non-Paulian heavy nuclei produced in fission reactors.

In conclusion, a feasible search for small violations of the Pauli exclusion principle is proposed. It involves looking for non-Paulian $^{5}\widetilde{\mathrm{He}}$ nuclei in the samples of helium produced in nuclear reactors or nuclear explosions. The use of accelerator mass spectrometry can assure the sensitivity for $^{5}\widetilde{\mathrm{He}}$ detection in helium below 10^{-16}. In the absence of any theoretical description of small violations of PEP one can use only standard nuclear physics arguments for the choice of the best process for $^{5}\widetilde{\mathrm{He}}$ production. They seem to favor the (n, $^{5}\widetilde{\mathrm{He}}$) reactions on light nuclei.

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PROIZVODNJA HELIJA U NUKLEARNIM REAKTORIMA I EKSPLOZIJAMA:

MOGUĆA PROVJERA PAULIJEVOG PRINCIPA

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Predlaže se vrlo osjetljiva provjera valjanosti Paulijevog principa u jezgrama. Koristi se akceleratorska masena spektrometrija u traženju stabilnih jezgara ^{5}He u uzorcima helija iz nuklearnih reaktora ili nuklearnih eksplozija.