Search for slight violations of the Pauli principle

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It might be possible to search for slight violations of the Pauli principle by identifying and counting anomalous atoms with an incorrect (excessive) filling of electron shells. Estimates show that this approach would be several orders of magnitude more efficient than searching for x-ray transitions in NaI(Tl) which are forbidden by the Pauli principle.

Possible violations (which would of course be extremely small) of the fundamental principles of physics have attracted intense interest since the pionering papers on parity violation in weak interactions. The possible nonconservation of such quantities as the baryon number and the lepton number has recently been studied extensively. Somewhat fewer studies have been carried out on a possible nonconservation of electric charge,[1,2] a possible breaking of CPT symmetry,[3] and a possible violation of Lorentz invariance.[4]

The Pauli exclusion principle is also one of the fundamental principles of quantum theory. The possibility of a small violation of this principle was discussed in Ref. 5. A noncontradictory quantum-mechanical model was constructed in Ref. 6. That model is capable of describing small violations of the Pauli principle. The magnitude of the violations is characterized in this case by a small parameter in commutation relations. Greenberg and Mohapatra[7] have generalized this model to the case of a relativistic quantum field theory. It is accordingly pertinent to take up the question of the most effective methods for seeking processes whose occurrence involves a violation of the exclusion principle. One such method is to search for x rays which appear upon a transition to a filled atomic K shell. The formulation of the experiment is similar to that which is used in the search for an instability of the electron [specifically, x-ray transitions are sought in a NaI(Tl) crystal in this experiment]. The experimental limitation on the transition probability is[8] 3×10^{-23} yr^{-1}. The model of Refs. 6 and 7 is not tarred by the objections raised in Ref. 9 regarding the possibility of a test of the Pauli principle in the given experiment.

In this letter we would like to point out the possibility of a method for seeking these transitions in atoms which would be more efficient, by several orders of magnitude. The idea is to seek the products of such transitions, i.e., atoms with an incorrect (excessive) filling of electron shells. In other words, one would seek an integral effect. The higher efficiency of this new approach would result from the longer exposure time (at the geological scale) and the possibility of using a larger target mass.

The general features of the experimental layout can be summarized as follows. From the large mass of material containing an element with an atomic number Z we extract by chemical methods an impurity element with an atomic number $Z-1$. (Experiments on the detection of solar neutrinos[10] provide us an example of, and confidence in the ability to carry out, the extraction of a negligible number of atoms—as few as several tens—from a target with a mass of hundreds of metric tons.) The products of transitions that violate the Pauli principle in Z atoms, in which we are interested, are present chemically as $Z-1$ atoms and are contained in the extracted impurity. For brevity, we refer to such anomalous atoms as "monsters" of type $Z-1$. (In general, $Z-n$ monsters might also exist, but the probability for their formation falls off substantially with increasing N.) This point marks the end of the utilization of the chemical properties of the monsters and the beginning of the use of their nuclear properties for a further enrichment, which can be achieved by standard isotope separation methods. The problem now reduces to one of counting the rare anomalous atoms present in the sample. One suitable method for this purpose is a neutron-activation analysis of a sample, followed by a detection of the decays of radioactive isotopes that have formed. Neutron bombardment of this sample [which consists primarily of the element $(Z-1,N')$ and which contains a negligible impurity of the anomalous atoms in which we are interested, with nuclei (Z,N)] produces radioactive isotopes $(Z,N+1)$ and $(Z-1,N'+1)$ which would generally have different properties. The essential question is one of choosing the original element (Z,N) in such a way that the isotope $(Z,N+1)$ can be counted as easily as possible in a mixture with the elements $(Z-1,N')$ and $(Z-1,N'+1)$. Below we will discuss specific ways in which this choice can be made.

Another method for counting the anomalous atoms present in an impurity involves the use of laser spectroscopy. That method can detect an amount of a given impurity as small as a few atoms at a concentration $\gtrsim 10^{-16}$.

To estimate the sensitivity of the integral method in comparison with that based on a search for x-ray transitions in NaI, we consider a specific example of an experiment with sodium chloride (NaCl). The anomalous atoms with the sodium nucleus which are being sought behave chemically as neon atoms. For the purposes of this experiment, the salt should be taken directly from the mine (to prevent a leakage of Ne atoms). The comparative sensitivity of this method with respect to that of an experiment with NaI can be estimated roughly from

$$R \approx \frac{N_2}{N_1} \frac{t_2}{t_1} \frac{n_1}{n_2},$$

where N_1 and N_2 are the numbers of Na atoms in the experiments with NaI and NaCl, respectively; t_2 is the observation time in the NaI experiment; t_1 is the time over which the integral effect is accumulated in the NaCl experiment (a possible leakage of monsters from the salt bed is taken into account); n_2 is the minimum observable number of monsters in the hypothetical experiment (the background is taken into account); and n_1 is the minimum observable number of transitions in the NaI experiment. We have $N_2 \approx 10^{30}$ (this figure corresponds to 100 metric tons of NaCl), $N_1 \approx 4 \times 10^{25}$ (10 kg of NaI), $t_2 \approx 10^8$ yr, $t_1 \approx 1$ month, and $n_1 \approx 100$.

The estimate of n_2 depends strongly on the method used to calculate the anomalous atoms. In the method of neutron activation analysis, the small value of the neutron capture cross section of the sodium nucleus would make it impossible to achieve a high degree of activation of ^{23}Na over the lifetime of the ^{24}Na, so we estimate $n_2 \gtrsim 10^8$. As a result, with a NaCl mass ~ 100 metric tons we could advance to $R \sim 10^7$.

In the laser-spectroscopy method, in contrast, we would apparently have $n_2 \sim 10$–100 and thus $R \sim 10^{13}$.

With regard to the problem of the optimum choice of elements within a given method, it would seem suitable to use a long list of elements. The specific choice will be governed by the availability of the initial material, the feasibility of working with a large mass of the sample, the ease of extraction, and the ease of counting monsters. In particular, mineral salts of alkali metals and alkaline earths, in which monsters which chemically emulate inert gases would form, would seem to be good choices.

For the alternative method using a neutron activation of monster atoms, suitable elements would be ^{23}Na, ^{34}S, ^{71}Ga, etc.

In addition to anomalous atoms, anomalous nuclei might exist.[5] For a search for such nuclei, the integral method may again prove to be considerably more efficient than to search for nuclear γ-ray transitions forbidden by the Pauli principle.

In principle, the method proposed here would make it possible to progress so far in searches for a possible violation of the Pauli principle that this method would be adequate even in a case in which a violation of the exclusion principle arose at a Planckian scale as a result of quantum gravitational effects of some sort.

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