Gallium-germanium neutrino experiment and conservation of electric charge

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A limit is imposed on the lifetime of ^{71}Ga with respect to decay involving a violation of the conservation of electric charge. This limit can be established in a gallium-germanium neutrino experiment. The lifetime of the nuclei for which such a decay is possible is shown to be related to a possible deficiency of electrons in the universe.

Feinberg and Goldhaber[1] were the first to point out that if two nuclei A_z and A_{z+1} have a mass difference $M_{\text{nucl}}(A_z) - M_{\text{nucl}}(A_{z+1})$ which is less than the mass of an electron, the nuclide A_z could be used to test the conservation of electric charge, since the decay of such a nucleus,

$$A_z \to A_{z+1} + X^0 , \tag{1}$$

where X^0 is an electrically neutral particle or group of particles with a mass smaller than the mass difference of the nuclei A_z and A_{z+1} (e.g., γ or $\nu + \tilde{\nu}$), is not forbidden by anything except conservation of electric charge.

One such nuclues is[2] ^{71}Ga, which is of particular interest in connection with two gallium-germanium experiments which are currently being set up to detect solar neutrinos.[3,4] The results of these experiments will substantially improve the limit on the half-life of the decay of ^{71}Ga in reaction (1) from the value found in Ref. 5. For example, if the measured effect is the value predicted by the standard solar model[6] without boron neutrinos, which are not observed in a chlorine-argon experiment,[7] this limit would be

$$T_{1/2}(^{71}\text{Ga}) \gtrsim 2\times 10^{26} \text{ yr}.$$

The nucleus A_{z+1} which is formed in reaction (1) decays back into A_z:

$$A_{z+1} + e^- \to A_z + \nu_e , \tag{2}$$

The set of processes (1), (2) should result in a buildup of a number of protons in excess of the number of electrons. Over the lifetime of the universe ($\sim 2\times 10^{10}$ yr), this excess would be

$$\delta q = \frac{N_p - N_e}{N_p} \approx 10^{10} \frac{\epsilon(A_z)}{\mu(A_z)} \frac{1}{T_{1/2}(A_z)} \tag{3}$$

(provided that the decay half-life of the nuclide A_{z+1} is much shorter than the lifetime of the universe). In expression (3), N_p and N_e are the densities of protons and electrons in the matter of the universe, $\epsilon(A_z)$ is the weight concentration of the nuclide A_z, $\mu(A_z)$ is its molar weight in grams, and $T_{1/2}(A_z)$ is the decay half-life of the nucleus A_z in reaction (1). If an upper limit $\overline{\delta q}$ could be found on the deficiency of electrons in the universe in some independent way, it would be possible to establish the following limit on the decay half-life of ^{71}Ga:

$$T_{1/2}({}^{71}\mathrm{Ga}) \gtrsim \frac{0.1}{\overline{\delta q}}\ \mathrm{yr} \tag{4}$$

(here and below, we are taking the nuclide abundances from Ref. 8).

If we make certain assumptions, we can establish a limit on $T_{1/2}({}^{71}\mathrm{Ga})$ which is more stringent than (4). Let us assume that the nuclear matrix element for process (1) is written as the product of an ordinary β-decay matrix element and a matrix element which does not conserve electric charge. Let us also assume that a term which violates charge conservation appears in the weak-interaction Hamiltonian in the form $\alpha J_\mu^{(+)}\,\overline{\nu_e} O^\mu \nu_e J_\mu^{(+)}$ which is the charged current of nucleons.[9] Summing the right side of (3) over all nuclides for which reactions (1) and (2) would be possible, we can find a limitation on α^2 [cf. Eq. (54a) in Ref. 9]. An analysis shows that of the more than 20 such nuclides (^{41}K, ^{55}Mn, ^{71}Ga, ^{73}Ge, ^{87}Rb, ^{93}Nb, ^{97}Mo, ^{109}Ag, ^{125}Te, ^{131}Xe, ^{139}La, ^{145}Nd, ^{151}Eu, ^{153}Eu, ^{157}Gd, ^{159}Tb, ^{170}Er, ^{165}Ho, ^{179}Hf, ^{181}Ta, ^{189}Os, ^{193}Ir, ^{197}Au, ^{201}Hg, ^{204}Hg, ^{205}Tl) the value of $\overline{\delta q}$ would be dominated by ^{55}Mn. The ^{71}Ga contribution would be smaller by about an order of magnitude. The other nuclides would make negligible contributions. As a result, the following limitation is imposed on α^2:

$$\alpha^2 \lesssim 0.5\,\overline{\delta q}\,.$$

For the decay half-life of ^{71}Ga we then find

$$T_{1/2}({}^{71}\mathrm{Ga}) \gtrsim 4/\overline{\delta q}\,. \tag{5}$$

It follows from limitation (5) that the background created in a gallium-germanium experiment due to nonconservation of electric charge should not exceed $\sim 6\times 10^{27}\,\overline{\delta q}$ solar neutrino units, corresponding to the formation of $\sim 10^{26}\,\overline{\delta q}\,{}^{71}$Ge atoms per day for a 60-metric-ton detector.

At the moment, the study by Barabanov *et al.*[5] gives us our best limitation on the lifetime of ^{71}Ga with respect to decay (1). The following upper limit can thus be set on the deficiency of electrons caused by processes (1) and (2):

$$\overline{\delta q} \lesssim 2\times 10^{-23}\ .$$

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