COMMENTS

Another Method of Searching for Proton Decay*

S. P. Rosen
Physics Department, Purdue University, West Lafayette, Indiana 47907
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A geochemical method of searching for proton decay, similar to the one used for double-β decay, is discussed. If a proton inside such nuclei as ^{23}Na, ^{39}K, ^{85,87}Rb, and ^{133}Cs can decay, then anomalous amounts of the rare-gas isotopes ^{22}Ne, ^{38}Ar, ^{84,86}Kr, and ^{132}Xe may be found occluded in ancient ores.

Several gauge theories of weak, electromagnetic, and strong interactions[1] predict that the proton is not absolutely stable, and the experimental lower limit on its half-life has recently been extended to 2×10^{30} yr.[2] This limit has been obtained[2] by observing a large number of nucleons ($\sim10^{31}$) for a limited period of time (1–2 yr) and failing to detect energetic decay fragments such as muons. Here we discuss another method of searching for proton decay in which one observes few nucleons ($\sim10^{24}$) over a much longer time ($\sim10^{9}$ yr) and thereby gains, at least in principle, one or two orders of magnitude in sensitivity. In addition, one can detect the decay without knowing the specific decay modes.

Our approach is based upon the same geochemical methods as have been used to detect double-β decay.[3] Whenever the daughter nucleus in double-β decay is an isotope of noble gas, for example, $^{130}\mathrm{Te}\to{}^{130}\mathrm{Xe}$, anomalous quantities of it can accumulate over billions of years in ores which are rich in the parent nucleus. Detection of such anomalies has led to the observation of several $\beta\beta$ transitions with lifetimes ranging from 10^{20} to 10^{24} yr.[3,4] Now, if a proton bound in a nucleus can decay without breaking up the daughter nucleus, and if the daughter nucleus happens to be a noble gas, then anomalous amounts of it will accumulate over geological time in ores bearing the parent isotope. As long as there are no other ways of generating these anomalies, detection of them would prove the proton to be unstable, and would provide us with an estimate of its half-life. However, because we detect only the residual nucleus, we cannot learn what particles are actually emitted in proton decay.

Since the anticipated lifetime is so long[1] ($\sim10^{28}$–10^{34} yr) and the anomaly so small ($\sim10^{7}$–10^{1} atoms), our chances of detecting it will be most favorable when the parent isotope has a very high natural abundance, and the daughter a very low one. From the viewpoint of *relative* abundance, this condition is best satisfied by the transition $^{39}\mathrm{K}\to{}^{38}\mathrm{Ar}$: ^{39}K comprises 93.10% of natural potassium and ^{38}Ar is a mere 0.063% of atmospheric argon.[5] In the case of $^{23}\mathrm{Na}\to{}^{22}\mathrm{Ne}$ the parent isotope forms 100% of natural sodium, but the daughter is as much as 8.82% of atmospheric neon.[5] Transitions involving the heavier gases, ^{85}Rb(72%)$\to{}^{84}$Kr(57%), ^{87}Rb(28%)$\to{}^{86}$Kr(17%), and ^{133}Cs(100%)$\to{}^{132}$Xe(27%), have even less favorable relative abundances.[5]

It is important to note, however, that the atmosphere contains much more argon (0.93%) than neon (1.8×10^{-3}%), krypton (1.1×10^{-4}%), or xenon (0.87×10^{-5}%). Therefore, if we use the abundance of each isotope in the atmosphere as our standard, then neon is favored over argon by a factor of 3, krypton is favored by one order of magnitude, and xenon by two orders of magnitude. Besides the smaller backgrounds, the heavier gases also have the advantage of being much less subject to diffusion losses than the lighter ones.

The decay of a proton inside a nucleus releases a considerable amount of energy, and so the residual nucleus could well break up into smaller fragments. Indeed one of the earliest experiments in this field[7] was based on the possibility that the energy released by proton decay would induce fission in ^{232}Th. Whether or not the breakup does occur is likely to depend upon the decay modes of the proton, and on the partitioning of the excess energy. If most of the excess energy is carried off by the decay products, and if the decay products consist solely of leptons and photons (e.g., $p\to\mu^+\nu$, $e^+e^+e^-$, or $e^+\nu\nu^-$), then breakup is unlikely. If one of the final-state particles is a pion (e.g., $p\to\pi^+\nu$), then it will interact strongly with the nucleus and may fragment it. To estimate the probability for this we note that in the appropriate kinetic energy range (~300 MeV), the cross sections for elastic scattering of pions from ^{12}C are roughly 40% and 60% of the total cross section, respectively.[8] As long as there are no dramatic changes as we pass from ^{12}C through ^{22}Ne and ^{38}Ar to the krypton and xenon isotopes, we may assume that about one half of the residual nuclei will break up, and one half will remain intact when a pion is emitted in the decay.

Should it happen that the nucleus absorbs most of the excess energy, then it is likely to undergo some kind of spallation reaction and lose several nucleons. In this case we would find anomalous amounts of isotopes lighter than the rare gas for which we are looking. Alternatively, the proton may decay into a diquark [(e.g., $p\to(qq)+\nu$], in which case the energy release itself will be rather small. For the purposes of this note we shall assume that there is a reasonable chance of the rare gas atoms remaining intact.

Before we can interpret an anomaly as evidence for proton decay, we must be able to show that alternative ways of producing it are unimportant. Consider, for example, the case of ^{38}Ar: Since 6.88% of natural potassium is the isotope ^{41}K, the reactions[9]

$$\begin{aligned} &p+{}^{41}\mathrm{K}\to\alpha+{}^{38}\mathrm{Ar},\\ &n+{}^{41}\mathrm{K}\to\alpha+{}^{38}\mathrm{Cl},\quad {}^{38}\mathrm{Cl}\xrightarrow{\beta^-}{}^{38}\mathrm{Ar}\end{aligned}\tag{1}$$

can produce ^{38}Ar. The proton-induced reaction need only be considered in the case of meteorites because they will have been exposed to cosmic-ray protons. Ores located in the earth's crust are not particularly exposed to protons, but they will be irradiated by neutrons if they are near uranium deposits. They may also be bombarded by α particles, and if chlorine happens to be present, the reactions

$$\begin{aligned} \alpha+{}^{35}\mathrm{Cl}&\to p+{}^{38}\mathrm{Ar}\\ &\to n+{}^{38}\mathrm{K},\quad {}^{38}\mathrm{K}\xrightarrow{\beta^+}{}^{38}\mathrm{Ar}\end{aligned}\tag{2}$$

will give rise to ^{38}Ar. Whether these, or any other, reactions make a substantial contribution to an observed anomaly may depend on the life history of the ore being examined and will have to be decided sample by sample.

If the anomaly of rare gas $(A, Z-1)$ found in an old ore is compared with the content of the parent element $(A+1, Z)$, then the half-life of the proton can be estimated from the formula

$$T_{1/2}^{(p)} = (\ln 2)Z[(A+1)(t)/A(t)]t,\tag{3}$$

where t denotes the age of the ore, and $(A+1)(t)$ and $A(t)$ represent the present abundances in the ore of the parent and daughter isotopes, respectively. The factor Z appears in the formula because we assume, as a first approximation, that the decay probability for $(A+1, Z)$ is equal to the number of protons it contains times the probability for free-proton decay. It is amusing to note that by attributing the entire ^{38}Ar content of the earth's crust[9,10] to proton decay in ^{39}K we obtain a lower limit of 10^{20} yr for $T_{1/2}^{(p)}$.

Approximately 0.01% of natural potassium consists of the metastable isotope ^{40}K which undergoes electron capture to form ^{40}Ar at a rate[9] $\lambda_K\approx 6\times10^{-11}$ yr^{-1}. Consequently any potassium-bearing ore will always contain a background of radiogenic ^{40}Ar, and its age can be computed from the magnitude of this background.[9,11] This enables us to determine $T_{1/2}^{(p)}$ from the observed ratio of ^{38}Ar to ^{40}Ar:

$$\begin{aligned} T_{1/2}^{(p)} &= \frac{\ln 2}{\lambda_K}(19)\left[\frac{^{39}\mathrm{K}(t)}{^{40}\mathrm{K}(t)}\right]\left[\frac{^{40}\mathrm{Ar}(t)}{^{38}\mathrm{Ar}(t)}\right]\\ &\approx 2\times10^{15}\times\left[\frac{^{40}\mathrm{Ar}(t)}{^{38}\mathrm{Ar}(t)}\right]\ \mathrm{yr}.\end{aligned}\tag{4}$$

Present experimental techniques are limited in their sensitivity to one atom of ^{38}Ar in no more than 10^8 atoms of ^{40}Ar, and so the transition ^{39}K $\to{}^{38}$Ar will not be a practical means of detecting the decay of the proton unless its half-life is less than 2×10^{23} yr. Although this is a much shorter time than the present limit of 2×10^{30} yr,[2] the outlook need not be entirely pessimistic. It could be that the proton decays in such a way that no energetic fragments are emitted [e.g., $p\to e^+ + 5\nu + 5\bar{\nu}$, or $p\to(qq)+\nu$], and so the experiments performed up to now[2] would not be sensitive to it. Thus the half-life could be much shorter than

10^{30} yr, and the $^{39}Kr \to {}^{38}Ar$ experiment, not being dependent upon the mode of decay, might be a good one to perform.

In this regard it is interesting to note that in 1956, Gerling, Levskii, and Afanasyeva[12] claimed to have found ^{38}Ar anomalies in potassium micas and feldspars which increased with age, and which could not be attributed to the background processes of Eqs. (1) and (2). Other workers[13] subsequently analyzed different potassium minerals which were several billion years old, but they did not find effects as large as would have been expected from the results of Gerling, Levskii, and Afanasyeva. If we treat these experiments as giving a lower limit on the proton half-life, we obtain $T_{1/2}^{(p)} > 10^{20}$ yr. ^{38}Ar anomalies have been found in iron meteorites but they are generally attributed to spallation.[14]

The other elements we have considered, namely sodium, rubidium, and cesium, do not have metastable isotopes which decay into rare gases, and so they are not subject to the same kind of limitation as occurs in $^{39}Kr \to {}^{38}Ar$. The daughter nuclei (^{22}Ne, ^{84}Kr, ^{36}Kr, ^{132}Xe) have much higher *relative* abundances than ^{38}Ar, but their *absolute* abundances in the atmosphere are so much smaller than argon that contamination by atmospheric rare gases may not be too serious a background problem. It may then be possible to extend the sensitivity of the geochemical method well beyond 10^{23} yr.

Finally, we would like to point out that in addition to ancient ores, the analysis of ocean waters and meteorites might prove helpful. Traces of noble gases, in particular neon, have been found[15] in deep ocean waters which are rich in such potential proton-decaying parents as sodium. However, the abundance of isotopes like ^{22}Ne and ^{38}Ar has not been measured because the mass spectrometers used in these experiments are "spiked" with these very isotopes![16] An unexplained excess of ^{86}Kr has been found in certain meteorites,[17] but not enough is known about the ^{87}Rb content to estimate a limit on the proton half-life.

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