Brief Reports

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Possibility of observing recoilless resonant neutrino absorption

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Low Q value weak nuclear decays are considered which have two-body final states (electron captures and bound-state beta decays). This opens the possibility for the observation of a process analogous to the Mössbauer effect, where the emitted (anti)neutrinos would be resonantly absorbed by atoms in a suitable absorber. Candidates for such a process are examined. Linewidths as small as the narrowest observed in Mössbauer spectroscopy may conceivably allow a new class of ν (disappearance) oscillation experiments.

[NUCLEAR REACTIONS Discuss recoilless resonant neutrino absorption by nuclei.]

The fact that electron captures, in certain circumstances, might provide neutrinos with a sharp energy and may allow resonant absorption in analogy to the Mössbauer effect was pointed out long before current astrophysical and elementary particle interest in the neutrino mass developed.[1] The outgrowth of a study of tritium decay in light of recent topical interest in neutrino mass measurements led one of us (W.K.) to an independent proposal with respect to beta decay.[2,3]

For resonant neutrino absorption it is essential that the decays be between neutral atoms in their ground states. Thus, only neutrinos from nuclear electron captures of electrons in outermost orbits can contribute to such a process, since any absorber nucleus will have to undergo the inverse process and must be able to place an electron in an equivalent electronic state. The symmetric situation is also conceivable, when in a beta decay the emitted electron is created directly in a valence state of the emitting atom.[4] The neutrino may be reabsorbed in another equivalent atom, inducing the nuclear capture of an exactly similar valence electron.

To the extent that these atomic physics conditions can be satisfied, resonant absorption of neutrinos could, in principle, proceed with the same large cross sections that one has for the Mössbauer effect

$$\sigma = \frac{\pi}{2} \lambda\!\!\!^{-2} g^2 (f_R{}^2 \alpha^2) \ , \tag{1}$$

where g includes statistical factors, $\lambda\!\!\!^{-}$ is the wavelength, divided by 2π, of the neutrino, f_R is the recoilless Mössbauer-like fraction (assumed, for the sake of simplicity, to be the same for source and absorber), and α is the fraction of the weak decay capturing electrons from or to the last valence orbit (assumed here to be the same for source and absorber). Even with rather conservative estimates this cross section would be huge in many cases, if it were not for effects that could broaden the line beyond the very sharp value determined by typical weak decay times (e.g., $\sim 10^{-24}$ eV). A variety of effects will broaden lines, such as fluctuations in hyperfine fields, magnetic and quadrupole, and so-called chemical shifts from small fluctuations in electron densities. The proper expression should, therefore, be

$$\sigma = \frac{\pi}{2} g^2 \lambda\!\!\!^{-2} (f_R{}^2 \alpha^2 \gamma) \ , \tag{2}$$

where $\gamma \equiv \Gamma/\Gamma_{\rm br}$, with Γ the natural linewidth of the weak decay and $\Gamma_{\rm br}$ the width due to line broadening.

We wish to briefly consider the various factors that enter into Eq. (2).

The recoilless fraction f_R is approximated by the Debye-Waller factor

$$f_R = \exp[-3/2(E_\nu{}^2/Mc^2 k\Theta)]$$

for temperatures $T \ll \Theta$, where E_ν is the neutrino energy, M the mass of the emitting atom, k the Boltzmann constant, and Θ the Debye temperature of the solid lattice. For an atom *imbedded* in a lattice of different atoms $\Theta_{\rm eff} \approx (M/M_{\rm host})^{1/2} \Theta_{\rm host}$. Since $(k\Theta Mc^2)^{1/2} \lesssim 100$ keV at best, f_R will decrease very rapidly for energies above 100 keV. Estimates are given in Table I assuming all atoms are imbedded in tungsten ($\Theta = 400°$) and $T \ll \Theta$. In some cases the assumption of $\Theta_{\rm eff}$ with a tungsten host may be overly optimisitc.

The "atomic" fraction α may be estimated very roughly from atomic wave functions of electrons. Any electron density at the nucleus implies s electrons and the fraction captured from various s-electron orbitals compared to K capture should be approximately proportional to the density at the nucleus, with some corrections for phase space. Phase space considerations, of course, may become overwhelming

TABLE I. Candidates for recoilless neutrino absorption.

Nuclide	Q (keV)	τ (yr)	f_R[a]	α (10^{-4})	γ (10^{-16})	σ_{eff} (10^{-36} cm^2)	σ_{eff}/τ[b]
^{3}H	18.6	12.3	0.40	200[c]	8	0.1	1.0
^{63}Ni	68	92	0.07	1	1	10^{-9}	10^{-9}
^{93}Zr	60	1.5×10^{6}	0.18	1	7×10^{-5}	10^{-12}	10^{-16}
^{107}Pd	33	6×10^{6}	0.62	1	2×10^{-5}	10^{-11}	10^{-16}
^{151}Sm	76	90	0.11	1	1	10^{-9}	2×10^{-9}
^{171}Tm	97	1.9	0.04	1	50	5×10^{-9}	3×10^{-7}
^{187}Re	2.6	4×10^{10}	1.0	1000[d]	10^{-9}	2×10^{-7}	10^{-15}
^{193}Pt	61	50	0.29	1	2	3×10^{-8}	8×10^{-8}
^{157}Tb	58	150	0.29	0.4[d]	0.7	2×10^{-9}	10^{-9}
^{163}Ho	2.6	7000	1	73[d]	0.01	7×10^{-3}	1×10^{-4}
^{179}Ta	115	1.7	10^{-2}	0.5[d]	60	10^{-10}	6×10^{-9}
^{205}Pb	60	1.4×10^{7}	0.3	8[d]	10^{-5}	10^{-11}	10^{-16}

[a] Recoilless fraction calculated for effective Debye temperatures assuming that the nuclei are imbedded in W, and that the simple approximations in the text are valid.
[b] Normalized to 1.0 for ^{3}H.
[c] From Ref. 4.
[d] Estimated from atomic wave function calculations of the relevant shells.

when the Q value of the weak decay is so small that the process cannot proceed by capturing the inner electrons, as happens in some cases. The extent to which a beta decay will produce electrons in specific atomic states in competition with emitting them into the continuum is a more detailed question—some such calculations have been made,[4] but the general question is more complicated. Clearly, the lower the energy of the emitted electron the higher the probability of its being captured in an atomic state. After looking at tables of electron wave functions, we assume, as a very rough average estimate, $\alpha=10^{-4}$ for all cases of β decay in Table I, except for ^{3}H and ^{187}Re, and overlook the question of variations in the degree of occupation of the outermost s orbital. For the process to take place it must be possible to place an electron into the valence orbit in the source atom and capture it in the absorbing one (or vice versa), leaving the same atomic and lattice final state. In many solids this partially occupied outer orbital will be modified by the conduction band and again it will be important to have similar environments for source and absorber.

The *line broadening* γ arises from a number of effects. Magnetic hyperfine fields will be present, at least from spin-spin interactions, and fluctuations in chemical shifts may come about from *any* inhomogenieties in a crystalline solid. Quadrupole hyperfine fields can be avoided when spin-$\frac{1}{2}$ or spin-zero states are involved. Magnetic hyperfine fields would not matter if decays were between spin-zero nuclides, but there is no such obvious candidate. An estimate of $\Gamma_{\text{br}}=2\times10^{-9}$ eV is used in the table. Widths smaller than this have certainly been seen in Mössbauer studies, but they require ultra-pure samples that would be difficult to prepare in bulk. This is equivalent to $\hbar/\Gamma_{\text{br}}\approx0.3$ μs, whereas the weak decay times are measured in years. Clearly this is an area where better control of the solid-state environment would be of considerable help.

Assuming that any atoms having undergone neutrino absorption will most likely have to be detected by counting their radioactive decay, the relevant figure of merit is σ_{eff}/τ. It is clear from the results in the table that ^{3}H is by far the most favorable case, with ^{163}Ho almost four orders of magnitude worse. If mass-spectroscopic techniques could be used for detection σ_{eff} would be the figure of merit. If one were to consider a 10 kCi source (or ~1 g) of ^{3}H surrounded by a spherical shell of ^{3}He 50 mg/cm^2 in thickness, both would have to be imbedded in a suitable lattice since the Debye temperatures of solid ^{3}H and ^{3}He are very low. One may estimate 10^{6} captures in the ^{3}He shell in 30 days, and after separating the ^{3}H from the ^{3}He absorbing medium this should yield ~20 distintegrations per hour.

For a spherical shell 20 cm in radius the induced concentration of ^{3}H in ^{3}He would be $\approx2\times10^{-20}$ and for a 1-m radius it would be 10^{-21}. It is perhaps questionable whether ^{3}He can be obtained free of ^{3}H initially and whether it can be maintained uncontaminated in the immediate vicinity of $\sim2\times10^{23}$ ^{3}H atoms. For the experiment to be feasible it is also necessary that source and absorber be maintained in an identical microscopic environment. While hydrogen is easily trapped in a metal host lattice, forming hydride bonds, the sites and environment of these hydrogen atoms are likely to be very different from those for He atoms diffused into a similar metal. One could, at least in principle, conceive of an experiment in which the ^{3}H were trapped in a shell of say Ar ice, where the sites may be more nearly equivalent for ^{3}H and for ^{3}He atoms. The recoilless fraction would be somewhat lower, but still manageable. ^{3}H and ^{3}He both have spin $\frac{1}{2}$ so no quadrupole hyperfine effect would contribute to line broadening.

The case of ^{163}Ho is somewhat different. With a 1-kg source of ^{163}Ho and an absorber of ^{163}Dy in a spherical shell 10 g/cm^2 thick one would expect ~100 captures/h. This seems undetectable by counting radioactive decays (from $\sim10^{6}$ atoms) and would be a very difficult if not impossible

problem in mass spectroscopy and chemistry (detecting concentrations of $\sim 10^{-17}$), not to speak of the practicality of producing ^{163}Ho in kg quantities and ^{163}Dy in 100's of kg.

Clearly the ^{3}H-^{3}He case appears the least impractical. Should a better understanding of the sources of line broadening be achieved (widths of 10^{-10} eV have been obtained in some Mössbauer experiments), an experiment may come to be on the threshold of feasibility. Unfortunately there are no ready ways of testing linewidths short of trying the full experiment.

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[1]W. M. Visscher, Phys. Rev. 116, 1581 (1959).
[2]W. P. Kells, Fermilab Internal Report No. FN-340, 1981.
[3]For a different discussion, containing further information related to the resonant absorption mechanism, see W. Kells, in *Neutrino Mass and Gauge Structure of Weak Interactions,* AIP Conf. Proc. No. 99 (American Institute of Physics, New York, 1983).
[4]J. Bachall, Phys. Rev. 124, 495 (1961).