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Can Recoilless Nuclear $\bar{\nu}$ Emission be Usefully Detected?

W. Kells

INTRODUCTION

The discovery of the Mössbauer effect revolutionized nuclear spectroscopy by greatly increasing sensitivity (resonantly enhanced absorption cross sections) and energy resolution ($\sim$ natural line widths). The lack of similar qualities virtually prevent any ν, $\bar{\nu}$ spectroscopy. Measuring the ν mass or its "oscillations" in conventional ν absorption experiments will be extremely difficult[1].

Here I describe the β decay analogy to the Mossbauer effect. The effect is small, but possibly quite competitive with "ν detector" type experiments. In principle much larger effects could be possible if (1) line widths much narrower than achieved in the Mössbauer field could be attained and (2) a more ideal β decay candidate existed (or could be found!).

II. Bound State Beta Decay

Attempts to measure the $\bar{\nu}$ mass from the free electron spectrum at the end point corner of phase space ($E_{\bar{\nu}} \to 0$, $E_{e^-} \to Q$) are difficult since the exact end point has zero phase space volume. In a different corner of phase space ($E_{\bar{\nu}} \to Q$, $\bar{p}_{e^-} \to 0$) the decay rate remains finite, just as K capture has a finite probability. For instance, about 1% of tritium decays are two body decays (to neutral, ground state ^{3}He plus a $\bar{\nu}$), and the possibility of using this mode for $\bar{\nu}$ mass measurements has been investigated[2]. Bahcall has considered this bound state capture process in detail[3]. His result is

$$\frac{\Gamma_{\text{bound}}}{\Gamma_{\text{continuum}}} = \frac{\pi(\alpha Z^3)}{f} \left(\frac{Q}{m_e}\right)^2 \Sigma \qquad (1)$$

where f is the usual beta decay parameter ($\sim$ continuum phase space available); and Σ is a sum over available daughter electronic states, representing their nuclear overlap. Principally we expect only ns states to be significantly populated. For nonrelativistic states Σ is of order unity for tritium decay and scales as n^{-3}.

III. Condition for Resonant Absorption

What conditions must hold for the $\bar{\nu}_{BC}$ from a bound capture decay to re-excite the daughter (ground state presumed) via inverse beta decay? Clearly the $\bar{\nu}_{BC}$ neutrinoes will be below threshold unless (1) the daughter has zero recoil momentum and (2) the daughter is formed in the ground state (i.e. no associated nuclear or atomic deexcitation). For isolated atoms of both

source (parent) and absorber (daughter) these two conditions are equivalent to exact resonant exchange between source and absorber. Of course it is just a tightly binding lattice environment which assures condition (1) so the possibility of a chemical shift of the resonance will arise[4].

From condition (2) we infer that the electronic ground state configuration of the daughter must be formed, in the bound state decay, by the addition of an electron wave function with significant nuclear overlap. Here I consider s states alone (for example ^{3}He is formed by the addition of a 1s electron to ^{3}H), which is a severe constraint on possible parent elements:

H, Li, Na, K, Rb, Cs, Fr. (2a)

He, Ne, Ar, Kr, Xe, Rn (2b)

Cr, Cu, Pd, Ag, Ir, Au (2c)

The elements in category 2c are of special interest since the added s electron is not really a valence state. Parent-daughter pairs in these cases have similar chemistry. They possibly allow negligible chemical shifts. The problem of chemical shift will be treated further below.

IV. Recoilless Emission and Absorption Fraction

I use the concrete example of $_{79}Au^{199} \rightarrow {}_{80}Hg^{199}$. The Q value ($\tilde{\approx} \bar{\nu}_{BC}$ energy) is 462 kV, the Au^{199} has a 3·2d half life, Hg^{99} is stable with a ground state formed by the addition of a 6s electron from the Au^{199} decay. The recoilless fraction, f_R, of two body decays (which themselves are a fraction $f_2 \times B_g$,

with Bg ≡ branching ratio of ground state decays, of the observed decay rate) is

$$f_R = \exp(-\text{ const. } Q^2/\Theta_D M) \qquad (3)$$

where Θ_D , the Debeye temperature, characterizes the lattice stiffness[5]. Low values of Θ_D for pure materials (eg. Hg) can typically be compensated for by using a "stiff" compound of the material. Therefore, in this discussion I will use Q^2/M as a figure of merit and scale f_R from the well known Fe^{57} case (where $Q^2/M = 3.7$, $f_R \tilde{\sim} 1.0$). We see immediately that $^3H \rightarrow {}^3He$ is a poor choice (346 kV/3 = 115) and that even $Au^{199} \rightarrow Hg^{199}$ is worse than any known Mossbauer transition. Note that for $\Theta_D \tilde{\sim}$ same in both source and absorber a factor f_R^2 enters any expression for inverse beta rates.

V. Possible Recoilless $\bar{\nu}_{BC}$ Experiments

For the previous example consider a sphere of Au^{199} surrounded by a shell of Hg^{199}. For zero chemical shift there will be resonant absorption of the antineutrinos formed by recoilless emission directly to the Hg^{199} ground state (nuclear and electronic). This results in a certain rate of formation, R, of Au^{199} atoms within the Hg^{199} absorber, which is anomolously large compared to any non resonant weak c.c. interaction (e.g. solar neutrinos). The resonant enhancement is $\sim Q/\Gamma_n$ with $\Gamma_n \equiv h/\tau_{1/2} . = 2.3 \times 10^{-21}$eV. Unfortunately, such a narrow line width would not be observed. Instead an effective, experimental, $\Gamma_e = 4 \times 10^{-11}$ eV based on the narrowest observed in Mossbauer spectroscopy could be expected[6]. The peak resonant

cross section is, then,

$$\sigma(Q) = \frac{c^2 \hbar^2}{2\pi Q^2} \quad \frac{\Gamma_n}{\Gamma_e} \tag{4}$$

We can now write an expression for R

$$R = \frac{1}{2} F \times N \times \sigma(Q) \times f_R^2 \times B_g \times f_2 \tag{5}$$

where N is the number of Absorber atoms and the $\frac{1}{2}$ comes from integrating over the source Lorentzian. $F \times B_g \times f_2$ is the flux of resonant antineutrinos at the absorber. The example $Au^{199} \rightarrow Hg^{199}$ with a high specific activity but with $f_R^2 B_{gB} f_2 \approx 10^{-9}$ has R_{sp} (per curie of source per kilogram of absorber) $\leq 7 \times 10^{-3}$/day.

I have found only one other beta transition with larger f_R satisfying the created s state condition, ${}_{46}Pd^{107} \rightarrow {}_{47}Ag^{107}$. The Q value is 35 KeV and ${}_{46}Pd^{107}$ has a 7×10^6 year half life! For this case $R_{sp} \leq 0.28$/day/curie/Kg with $f_R \sim 1$, $f_2 \sim 0.5$, and $B_g = 100\%$. The reason that R_{sp} is so low is that $\Gamma_n/\Gamma_e \approx 10^{-19}$. That is, if natural line widths could be approached, R_{sp} would be enormous! Still, the inverse beta rate is significant if thousands of curies ($\sim$ 10 cm radius sphere) and tens of kilos of Ag^{107} (most common natural Ag) were used. Strong Pd^{107} sources are possible since Pd^{106} is the most abundant stable isotope (neutron capture).

The specific source activity assumed is for <u>pure</u> Pd^{107}. One way to assure identical chemical environment for initial Pd^{107} and final (inversely produced) Pd^{107} is to have a source

of dilute Pd^{107} in Ag^{107} and a pure Ag^{107} absorber. Correct chemical preparation is also a possibility[4].

Pd^{107} also poses an acute problem in "signal" measurement. The half life is too long to count decay activity. Chemical separation after a period of counting would be extremely difficult for a few thousand Pd atoms (not to mention initial purification of the Absorber to this level)!

In this vein several other beta decays are much more favorable:

$_{97}Bk^{249}$(314d)	→ Cf^{249}(360y)	125kv
$_{88}Ra^{228}$(6.7y)	→ Ac^{228}(6·13 hr)	55kv
$_{89}Ac^{227}$(22d)	→ Th^{227}(18d)	44kv
$_{82}Pb^{210}$(21y)	→ Bi^{210}(5d)	61kv
$_{80}Hg^{203}$(47d)	→ Tl^{203}(stable)	492kv
$_{24}W^{188}$(69d)	→ Re^{188}(17h)	349kv
$_{74}W^{185}$(75d)	→ Re^{185}(stable)	429kv
$_{69}Tm^{171}$(1·9yr)	→ Yb^{171}(stable)	98kv
$_{68}Er^{169}$(9.4d)	→ Tm^{169}(stable)	340kv
$_{63}Ev^{155}$(1·8yr)	→ Gd^{155}(stable)	248kv
$_{62}Sm^{151}$(87yr)	→ Ev^{151}(stable)	76kv
$_{61}Pm^{147}$(2·6yr)	→ Sm^{147}($\sim 10^{11}$yr)	225kv
$_{34}Se^{79}$(65000yr)	→ Br^{79}(stable)	154kv
$_{28}Ni^{63}$(92yr)	→ Cu^{63}(stable)	67kv

To complete the list $_{40}Zr^{93}$(10^{6}yr) → Nb^{93}(stable) should be mentioned although it has the same drawback as Pd^{107}. Un-

fortunately, none of these decays creates a ground state s electron. Presumably some resonant ground state inverse production still occurs at a rate diminished by a much smaller nuclear overlap (with a p or d electron state). It remains to be investigated whether this can be compensated for by the more attractive features of say $_{28}Ni^{63} \rightarrow Cu^{63}$. The case of $Hg^{203} \rightarrow Tl^{203}$ is special since $B_g \lesssim 4 \times 10^{-5}$ ($5/2^- \rightarrow 1/2^+$ decay!).

In this report I do not consider the complementary processes of electron capture plus neutrino emission (recoilless) and its subsequent resonant inverse. In principal, high (valence) s state capture will lead to resonance, but this branch is small. A complete survey of this possibility is clearly needed.

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