Generation and monitoring of directed neutrino beams using electron-capture β-decay sources

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Analysis shows that directed neutrino beams could be generated by using electron-capture β-decay sources, and the requirements for the magnetic field and temperature are discussed. The recoil forces produced by ^{119}Sb and ^{57}Co sources are estimated, and it is shown that the neutrino emissions from a ^{119}Sb source could be detected using an atomic force microscope.

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I. INTRODUCTION

Experiments on the nature and properties of neutrinos have strongly suggested that neutrinos are massive and that they oscillate between flavors [1]. The next generation of experiments is being planned and developed [2], and substantial improvements in experimental signal-to-noise ratios could be realized if new directional sources of neutrinos are produced [3]. Such neutrino beam sources could help resolve several fundamental questions (e.g., neutrino mass, neutrino oscillations, and details of the electroweak interaction) [4]. The analysis presented in this paper suggests that a directed, essentially monoenergetic neutrino beam can be generated from a radioactive substance, which decays through electron-capture β decay, without the use of an accelerator. We also show that the recoil force produced by the neutrino emissions of a radioactive substance could be detected by an atomic force microscope (AFM), which allows new approaches to neutrino experiments to be contemplated. For example, if the recoil forces produced by neutrinos can be directly compared experimentally to those produced by photons of similar energy, new approaches to the neutrino mass problem may be developed. Recent reports [5] of the detection of superluminal neutrinos would suggest that alternative approaches to large source neutrino experiments might also fruitfully be explored.

II. THEORETICAL CONSIDERATIONS

Our basic idea is the following. Assume that we have a diamagnetic substance that contains nuclei that decay by electron-capture β decay. For clarity, let the only allowed decay be a Gamow-Teller transition with a decrease in the nuclear spin I of one unit: $I \rightarrow I-1$. Also, assume that the radioactive nuclei are highly polarized by an external magnetic field at low temperatures. In this case, the z component of nuclear spin before decay is $I_z = I$, and the z component of the total angular momentum of the system is $F_z = I_z$. The electron-capture β decay produces an unpaired electron in the daughter atom (ignoring shake ups and shake offs) with spin $S = \frac{1}{2}$ and a neutrino with spin $V = \frac{1}{2}$. The only combination of the three spins that satisfies the conservation of the z component of the total angular momentum would be as follows: $I_z = I - 1$, $S_z = \frac{1}{2}$, and $V_z = \frac{1}{2}$ (see Fig. 1). By taking the helicity requirement that the emitted neutrino's linear momentum is opposite to the direction of its spin into consideration, we come to the conclusion that, in this case, electron-capture decay generates a directed neutrino beam that propagates in the negative z direction (opposite to the applied magnetic field).

The directionality of the beam is then determined by the degree of polarization of the parent nuclei, which depends on the strength and homogeneity of the magnetic field at the nuclei, the nuclear magnetic moment, and the temperature. Because the final state usually contains only the neutrino and the recoiling daughter system, such sources produce relatively narrow line emissions [6]. In real systems, there may be competing branches and secondary processes that would interfere somewhat with the desirable characteristics of such sources, but compared to energetically broad omnidirectional reactor sources, the expected improvements are significant.

A good source can easily be modulated, and there is a simple and direct way to monitor the intensity and direction of the beam. With neutrino sources, these issues are extreme because detecting the neutrinos themselves is so very difficult. For the beam sources being considered, the beams can be steered using the applied magnetic field, and source characteristics can be modified by using temperature and, potentially, rf pumping. The proposed electron-capture sources also have another significant feature, namely, the directed recoils that may allow real-time monitoring of the neutrino beam intensity and its directionality.

A directed neutrino beam generates an average recoil force $\boldsymbol{F} = \dot{P}$, where $\dot{P}$ is the average rate of generation of neutrino momentum. For a massless neutrino, $\dot{P} = \dot{E}/c$, where $\dot{\mathrm{E}}$ is the power of the neutrino radiation. The value of $\dot{\mathrm{E}}$ can be expressed in terms of the number N of radioactive atoms present $\dot{E} = \alpha E_\nu = \ln(2) N E_\nu T_{1/2}$, where E_ν is the energy of an individual neutrino, α is the decay rate (activity) of the source, and $\ln(2)/T_{1/2}$ is the decay constant in terms of the half-life $T_{1/2}$. The magnitude of the average recoil force F then is given by

$$F = \frac{\ln(2)}{T_{1/2}} \frac{E_\nu}{c} N, \tag{1}$$

And by using expression (1), we can find the number of radioactive atoms that produce a particular average force F.

To complete the basic considerations, we examine the opportunities to relax the requirements for very large external magnetic fields. Large internal magnetic fields at the atomic nuclei are known to occur in many systems due to hyperfine

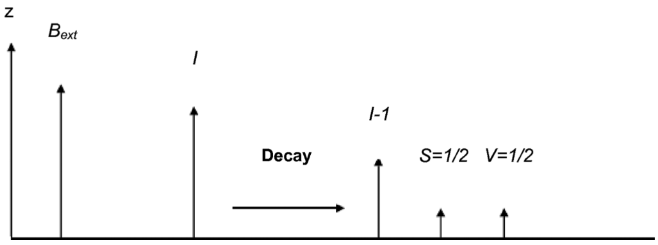

FIG. 1. Direction of the external magnetic field $\mathbf{B}_{\mathrm{ext}}$ and spins before and after decay. I, S, and V are the nuclear, electron, and neutrino spins, respectively. The nuclear magnetic moment was assumed to be positive.

interactions. In paramagnetic and, especially, ferromagnetic systems, a relatively small external field can then orient the electronic moments and through the associated hyperfine fields, can orient the nuclear moments as well, producing large nuclear polarizations and hyperfine splitting [7]. If the temperature of the system is not low compared to the hyperfine splitting, the nuclei would only be partially polarized. To account for this, we will count all possible basis spin states before and after decay. As an example, for the initial state $I_z = I - 1$, there are three final states ("channels"), which satisfy conservation of the z component of the total angular momentum:

$$\begin{aligned} &(1) \quad I_z = I-1, \quad S_z = 1/2, \quad V_z = -1/2 \\ &(2) \quad I_z = I-1, \quad S_z = -1/2, \quad V_z = 1/2 \\ &(3) \quad I_z = I-2, \quad S_z = 1/2, \quad V_z = 1/2 \end{aligned} \tag{2}$$

By taking all possible channels into consideration, we can compute the probability of the neutrino spin excess $\Delta P = P\uparrow - P\downarrow$ after the decay where

$$\begin{aligned} P\uparrow &= \sum_m P_m X_m\uparrow / X_m, \\ P\downarrow &= \sum_m P_m X_m\downarrow / X_m, \quad -I \leqslant m \leqslant I. \end{aligned} \tag{3}$$

In this equation, we use the notation $m = I_z$, P_m is the occupation probability for the nuclear spin state $|m\rangle$ before decay,

$$P_m = e^{m\mu B/Ik_BT} \Big/ \sum_m e^{m\mu B/Ik_BT}. \tag{4}$$

$X_m\uparrow$ ($X_m\downarrow$) is the number of decay channels from the initial state $|m\rangle$ to the final state with the neutrino spin $V_z = \frac{1}{2}$ ($V_z = -\frac{1}{2}$), X_m is the total number of decay channels from state $|m\rangle$, B is the magnitude of the magnetic field at the nuclei, μ is the nuclear magnetic moment, k_B is the Boltzmann constant, and T is the temperature. For example, in the initial state $|m\rangle = |I-1\rangle$, it follows from formulas (2): $X_m\uparrow = 2$, $X_m\downarrow = 1$, $X_m = 3$. In Eqs. (3), we assume equal probability for all the channels that correspond to a given value of m. Also, we assume that the initial z component of the atomic electron spin associated with the outer shells does not change in the process of decay. Finally, for partially polarized nuclei, the magnitude of the recoil force can be estimated as $F = ln(2) N E_\nu \Delta P / c T_{1/2}$.

III. EXPERIMENTAL CONSIDERATIONS

Table I shows the characteristics of some electron-capture isotopes of interest, i.e., those where the nuclear spin decreases by one unit for at least one major branch. X-ray and γ-ray energies and intensity information are from Ref. [8], K-shell energies are from Ref. [9], and the magnetic moments are from Ref. [10]. Sources for internal hyperfine field values are indicated in the table. The K-capture neutrino energy corresponds to the rest of the mass energy difference between the neutral parent and the daughter atoms, less the K-shell binding energy and any nuclear excitation in the daughter. The selection includes four representative examples with principal neutrino emission energies between 320 and 1343 keV.

Consider a sample of ferromagnetic cobalt enriched with ^{57}Co, a widely used isotope. A weak external magnetic field (less than 1 T) saturates the ferromagnetic sample. The hyperfine field at the cobalt nuclei is about 22.5 T and points in the direction opposite the electronic magnetization $\mathbf{M}$ (see, for example, Ref. [11]). The magnetic moment of ^{57}Co is 2.38×10^{-26} J/T [10], and the hyperfine splitting is, approximately, 11 mK. The isotope ^{57}Co decays to ^{57}Fe with a decrease in the nuclear spin from 7/2 to 5/2 [8]. The directions of the spins before and after decay are shown in Fig. 2. Note that, in Fig. 2, the external magnetic field points in the negative z direction, whereas, the nuclear spin is polarized in the positive z direction. In this case, the neutrino beam propagates in the direction of the external magnetic field. The half-life of ^{57}Co is 272 days, and the primary neutrino energy is 692 keV [8,9].

Another example is a sample enriched with ^{119}Sb, which has a magnetic moment $\mu = 1.74 \times 10^{-26}$ J/T [10]. It decays to ^{119}Sn with a decrease in the nuclear spin from 5/2 to 3/2 [8]. The decay half-life is 38.2 h, and the emitted neutrino energy is 538 keV for the primary K-capture branch [8,9]. Antinomy has been found to have quite large internal hyperfine fields, including values as high as 70.6 T [13], so a hyperfine splitting of, approximately, 36 mK may be achievable.

The history of small force measurement is rich and includes such classics as the Coulomb and the Cavendish balances and the more recently developed optical tweezers and AFM. To gain an appreciation for the sensitivity of AFM devices, it is informative to first consider the possibility of detecting the

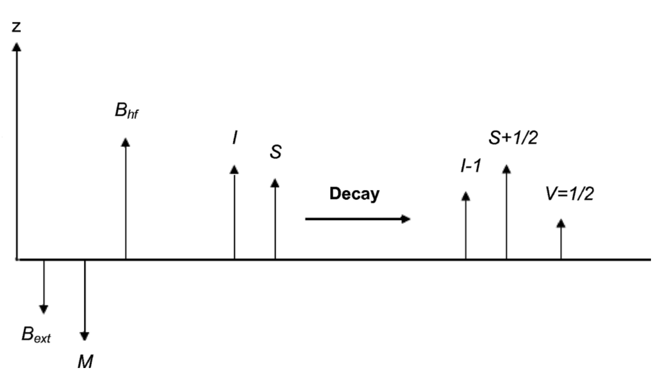

FIG. 2. Direction of the external magnetic field $\mathbf{B}_{\mathrm{ext}}$, electron magnetization $\mathbf{M}$, hyperfine field $\mathbf{B}_{\mathrm{hf}}$, and nuclear, neutrino, and atomic electron spins before and after decay.

TABLE I. Characteristics of some electron-capture isotopes.

Isotope	Half-life (d)	Parent state	Daughter state	K-capture neutrino energy (keV)	Branching fraction (%)	γ-ray energy (keV)	γ-ray intensity (%)	Daughter K-shell energy (keV)	Daughter x-ray energy (keV)	Daughter x-ray intensity (%)	Magnetic moment (nm)	Hyperfine field (T)	Level splitting (mK)
^{57}Co	272	7/2 −	5/2 −	692	99.8	136.5	10.7	7.11	7.1	5.9	4.720	22.5 [11]	11
						122.1	85.6		6.4	49.5			
						14.4	9.2		0.7	1.5			
^{65}Zn	244	5/2 −	3/2 −	1343	48.5	0		8.98	8.9	4.1	0.7690	18.785 [12]	2
				188*	1.4	511.0	2.8		8.0	34.2			
			5/2 −	228	50.0	1115.5	50.0		0.9	1.2			
^{119}Sb	1.59	5/2 +	3/2 +	538	100	23.9	16.5	29.20	29.1	1.9	3.45	70.6 [13]	36
									28.5	6.8			
									28.4	3.5			
									25.3	38.9			
									25.0	21.0			
									3.4	11.8			
^{131}Cs	9.69	5/2 +	3/2 +	320	100	0		34.56	34.4	2.1	3.543	33.3 [14]	17
									33.6	10.7			
									29.8	38.9			
									29.5	21.1			
									4.1	8.6			

*Mean-neutrino energy from the $\beta+$ component.

recoil due to the neutrino emitted in a single electron-capture β-decay event. As is customary, we treat the cantilever of the AFM as a simple harmonic oscillator [15].

To be directly detectable, the recoil energy deposited in the AFM cantilever by the neutrino emission should be larger than the average thermal energy,

$$E_R = \frac{P_\nu^2}{2m_{\mathrm{eff}}} > E_T = \frac{1}{2}k_B T = \frac{1}{2}k_c x_T^2, \tag{5}$$

where P_ν is the neutrino momentum, m_{eff} is the effective mass of the cantilever, T is the cantilever temperature, k_c is the cantilever spring constant, and x_T is the average thermal noise amplitude of the cantilever, or

$$P_\nu \geqslant \sqrt{m_{\mathrm{eff}} k_B T} = \sqrt{\frac{k_c k_B T}{\omega_c^2}}, \tag{6}$$

and ω_c is the angular frequency of the cantilever oscillations. By using the parameters for the cantilever used in the first sub-atto-Newton force measurement [16], the minimum detectable individual neutrino emission energy would be about 2 GeV. Subsequent developments [17,18] have lowered this significantly to 680 and 180 MeV, respectively. This is still 2 to 3 orders of magnitude larger than the typical energy of neutrinos emitted in electron-capture events in atoms, so direct observation of the individual recoils would be quite challenging. However, should efforts to detect individual nuclear spins be successful [17,19], detection of individual recoils would likely also be within reach.

Detecting the average deflection of a cantilever due to a beam of emitted neutrinos may, however, be more readily achievable. AFMs have been developed to study a variety of small forces, which include some devices with large structures mounted on the cantilever [20] and some with micron-sized particles attached to the cantilever [17,18]. To be considered a beam, the fluctuations in the source intensity should be small, and to be detectable, the recoil force amplitude should be larger than any noise sources. For such an essentially static measurement, we will assume a source activity of at least 1 MBq and a conservative dc sensitivity for the AFM of 1 pN [21].

Assume that a sample containing ^{119}Sb or ^{57}Co is attached securely to an AFM tip. From expression (1), we obtain the number of unstable ^{119}Sb nuclei needed to produce a 1-pN force to be $N = 6.9 \times 10^{14}$. The corresponding activity $\alpha = 3.5$ GBq and the mass of the antimony atoms would be about 1.4×10^{-10} kg. For ^{57}Co, the number of atoms required to produce a 1-pN force would be $N = 9.2 \times 10^{16}$. The corresponding activity would be $\alpha = 2.7$ GBq, and the mass of the cobalt atoms is 8.7×10^{-9} kg. At these relatively large activities, the statistical fluctuations in the decay rate during a sampling time on the order of seconds would be expected to be negligible. To illustrate the expected temperature dependence, we show the spin excess ΔP and the number of radioactive antinomy atoms required to produce a 1-pN recoil force as a function of temperature in Fig. 3.

The actual mass of AFM tips is another consideration. From the dimensions of the silicon tip of the Tap190-G series made by Ted Pella, Inc. [22], we obtain a tip volume of about 6×10^{-14} m^3. By multiplying by the silicon density of 2330 kg/m^3, we find the tip mass is 1.4×10^{-10} kg. Assume that the temperature of a sample that contains ^{119}Sb is 25 mK [23]. From formulas (3) and (4), we find the neutrino spin excess $\Delta P = 0.82$. Then, the mass of the antimony atoms needed for a measurement is 1.7×10^{-10} kg, which is on the same order of magnitude as the mass of an AFM tip. This comparison suggests that neutrino emission from an antinomy source could

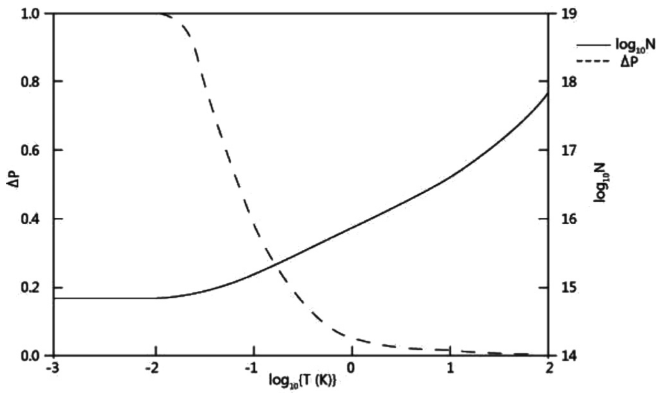

FIG. 3. The spin excess ΔP and the number of radioactive antinomy atoms required to produce a 1-pN recoil force for a ferromagnetic sample containing the isotope ^{119}Sb.

be detected by using conventional AFM techniques, provided the sample can be made cold enough.

Perhaps the most significant remaining concern is the heat load due to the radioactivity. For ^{119}Sb, the worst-case heat load would be the sum of the daughter nuclear state excitation of 23.9 keV and the maximum K-capture electronic excitation of 29.2 keV, which netts a maximum of 53.1 keV per decay [8,9]. However, the data in Ref. [8] indicate that a 23.9-keV γ ray is emitted in 16.5% of decays and that K x rays with energies between 25.0 and 29.1 keV are emitted in 72.1% of decays. With careful design and materials selection, most of these x and γ rays could be allowed to escape the cold region, so we will assume a total average heat load of $(1 - 0.165) \times 23.9 + (1 - 0.721) \times 29.2 + 0.721 \times 4.2 = 31$ keV per decay. This corresponds to a heat load for a 3.5-GBq source of some 17 μW. Commercial refrigerators can provide several hundred microwatts of cooling power at 100 mK [24], but the cooling power of these devices drops with decreasing temperature. At a temperature of 25 mK, the cooling power of a 300-μW dilution refrigerator will be about 20 μW, which is greater than the estimated heat load [25]. Thus, developing and monitoring beam source components with this magnitude of activity seems practical and worth pursuing. To scale up further, an array of sources would likely be needed with the configuration chosen to match the intended detector. As with the detection of individual neutrino emission events, large source experiments would be very challenging, even with an array of thousands of directional β-decay sources.

In conclusion, we suggest the generation of directional neutrino beams by using electron-capture β-decay sources, estimate the corresponding recoil forces, demonstrate the opportunity for detection of the neutrino emissions using atomic force microscopy, and suggest that directional electron-capture sources might be produced whose properties might rival or might surpass, in some respects, those based on reactor or accelerator sources.

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