Possible electron neutrino sources with a modulated monochromatic component

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Introduction

Developing new types of neutrino beams is essential for prospective neutrino experiments. Promising types of beams are β- and EC-beams (see [1, 2, 3]).The main features of these beams are the following:

- **Source of neutrinos.** β-decaying (β-beams) or electron capturing (EC-beams) nuclei/ions are used.
- **Neutrino flavor.** The beam contains only ν_e (for β^+/EC-decaying nuclei) or $\bar{\nu}_e$ (for β^--decaying nuclei).
- **Collimation.** The ions are boosted to $\gamma \gg 1$, so in the laboratory frame, half of the neutrinos are emitted in the forward direction within a cone with the opening angle $\theta \simeq 1/\gamma$ (see fig. 1).
- **Spectrum.** β-decay and EC-spectra in the ion rest frame are known and can be easily recalculated in the laboratory frame.
- **Monochromaticity.** For EC-beams, in the ion rest frame the neutrino energy is definite. So in the laboratory frame at $\gamma \gg 1$ the beam is monochromatic.
- **Modulation.** With specific choice of source nuclei, one can modulate EC-beams [4].
- **Controllability.** One can control the neutrino spectrum and beam collimation by varying γ.
- **Intensity.** Intensity of beams from pure electron-capturing nuclei is suppressed because the lifetimes of such nuclei are high.

Combined β^+/EC-beams [5, 6] are of particular interest, because of they have a monochromatic neutrino line and their intensity is significantly higher than that of pure EC-beams. In this work we show that, under certain conditions, one can modulate monochromatic lines of such beams and these modulated monochromatic component could be made intense. The requirements for sources of such beams are stated and the most promising isotopes are selected.

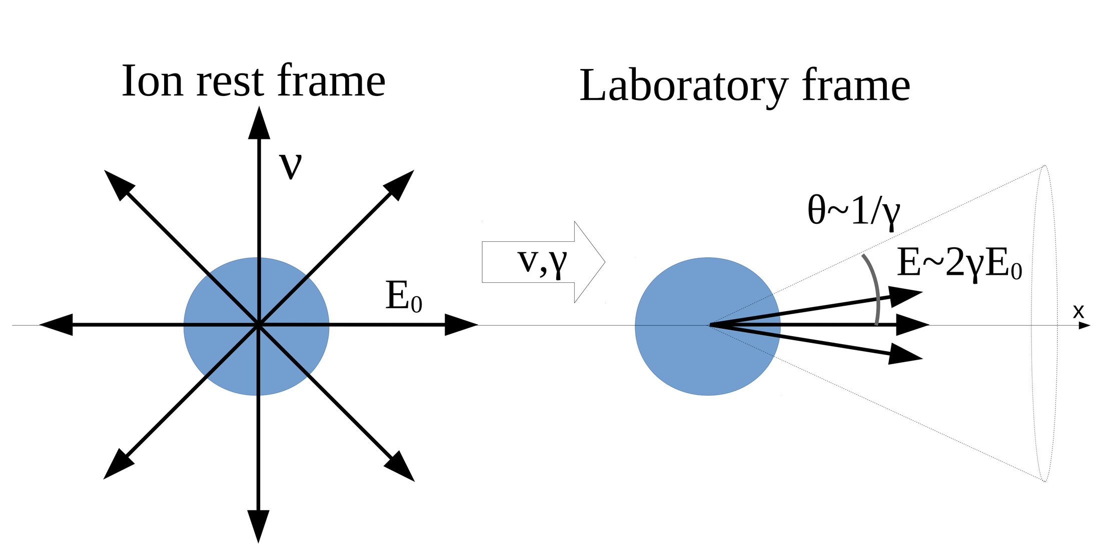

Figure 1: Beta beam generation principle

Beam modulation

The monochromatic neutrino component of a combined β^+/EC-beam can be modulated if the following conditions are satisfied:

1. Hydrogen-like (H-like) ions are used as neutrino sources
2. The nuclei in these ions have non-zero nuclear spin I
3. The decay is due to a pure Gamow–Teller transition:

$$I^{\pi} \to I'^{\pi},\ I' = I \pm 1,$$

Under these conditions, the $1s$-state of the ion is split into two hyperfine components with total angular momenta $F = I \pm 1/2$ (see fig. 2).

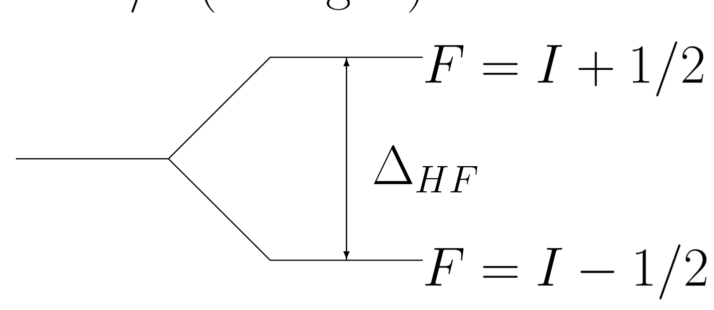

Figure 2: Hyperfine splitting of the $1s$-state (nuclear magnetic moment is positive $\mu > 0$)

The total angular momentum of the final state consists of the nuclear spin I' and the neutrino spin $1/2$. Due to total angular momentum conservation the following condition must be satisfied:

$$F = I' \pm 1/2.$$

This means that the mother nucleus can capture electrons from only one of the hyperfine states. Fig. 3 represents one of the possible decay scenarios.

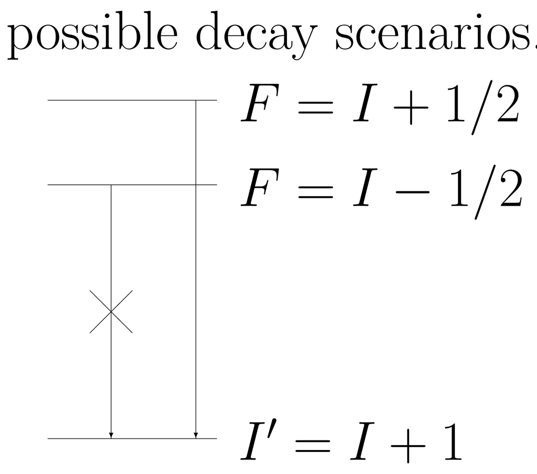

Figure 3: Decay scheme for the case of $\mu > 0$, $I' = I + 1$

Inducing transitions between the hyperfine states (e.g. with lasers), one can impact the capture rate, and, therefore, modulate the corresponding neutrino emission. A detailed description of the modulation process is given in [4].

Intensity of modulated monochromatic beam component

Considering a beam of high-energy neutrinos ($\gamma \gg 1$) and a cylindrical detector of radius $R = L/\gamma$ and depth l at distance L from the source, a simple estimate for the event rate (per second) can be made [7]:

$$\dot{N}_e \simeq \frac{3\ln 2\,\alpha N_i n_N \sigma_0 l}{4},\ \alpha \equiv \frac{P E_{\nu}^{0}[\mathrm{MeV}]}{T_{1/2}[\mathrm{s}]}.$$

Here N_i is the number of decaying ions, n_N is the number density of nuclei in the detector, $\sigma_0 = 7 \times 10^{-42}$ cm^2, P is the electron capture branching ratio, E_{ν}^{0} is the neutrino energy in the ion rest frame, $T_{1/2}$ is the half-life of the ion. Note that our result does not depend on L or γ The parameter α incorporates all the relevant nuclear properties and, thus, can be used to choose the nuclei that will produce the most intense modulated monochromatic component of the neutrino beam.

Requirements for source nuclei

As was stated above, to produce a combined β^+/EC-beam with modulated monochromatic component of the neutrino beam, one needs isotopes with non-zero nuclear spin I decaying via pure Gamow–Teller transition $I^{\pi} \to I \pm 1$. Decay channels of these must include electron capture (we selected isotopes with branching ratio $P > 0.01$). Production of source ions takes time of order of 1 s, so beam production will be effective if $T_{1/2} > 1$ s. To narrow down the list of source isotopes, we also set an upper limit on the half-life:$T_{1/2} < 30$ s. For the intensity criterion we demand $\alpha > 0.01$.

Table 1: Source nuclei and their properties

${}^{A}X \to {}^{A}X'$	$T_{1/2}$, s	$I^{\pi} \to I'^{\pi'}$	E_{ν}^{0}, MeV	P	α
${}^{140}\mathrm{Eu} \to {}^{140}\mathrm{Sm}$	1.51	$1^+ \to 0^+$	8.470	0.031	0.174
		$1^+ \to 2^+$	7.939	0.011	0.058
${}^{142}\mathrm{Eu} \to {}^{142}\mathrm{Sm}$	2.34	$1^+ \to 0^+$	7.670	0.051	0.167
		$1^+ \to 2^+$	6.902	0.003	0.009
${}^{144}\mathrm{Eu} \to {}^{144}\mathrm{Sm}$	10.2	$1^+ \to 0^+$	6.315	0.098	0.061
		$1^+ \to 2^+$	4.655	0.021	0.010
${}^{153}\mathrm{Yb} \to {}^{153}\mathrm{Tm}$	4.2	$7/2^- \to (9/2^-)$	6.286	0.021	0.031
${}^{179}\mathrm{Pt} \to {}^{179}\mathrm{Ir}$	21.2	$1/2^- \to (3/2^-)$	5.621	0.15	0.040
${}^{150}\mathrm{Er} \to {}^{150}\mathrm{Ho}$	18.5	$0^+ \to 1^+$	3.639	0.569	0.112
${}^{152}\mathrm{Yb} \to {}^{152}\mathrm{Tm}$	3.03	$0^+ \to 1^+$	4.968	0.290	0.475
${}^{156}\mathrm{Yb} \to {}^{156}\mathrm{Tm}$	26.1	$0^+ \to 1^+$	3.459	0.420	0.056

Results

The selected source nuclei and their parameters are presented in table 1. For illustration, we also included zero-spin nuclei ^{150}Er, ^{152}Yb and ^{156}Yb that were selected in [5, 6] as sources of intense β^+/EC-beams (with these nuclei, the monochromatic component is intense, but it cannot be modulated). Comparing the intensity parameter α between these two groups of nuclei shows that the intensities in both cases are comparable. Thus, β^+/EC-beams with a modulated monochromatic component are of interest for practical applications.

Summary

We proposed a variation of a β^+/EC-beam that has a modulated monochromatic component. The requirements for the modulation were discussed. Requirements for sources of such beams were stated. We selected nuclei that satisfy these requirements.

References

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