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Electromagnetic modulation of monochromatic neutrino beams

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Abstract. We discuss the possibility to produce a modulated monochromatic neutrino beam. Monochromatic neutrinos can be obtained in electron capture by nuclei of atoms or ions. Hydrogen-like ions are of particular interest. It is shown that monochromatic neutrino beam from such hydrogen-like ions with nuclei of non-zero spin can be modulated because of different probabilities of electron capture from hyperfine states. Modulation arises by means of inducing of electromagnetic transitions between the hyperfine states. Requirements for the hydrogen-like ions with necessary properties are discussed. A list of the appropriate nuclei for such ions is presented.

1. Introduction
"Clean" neutrino beams (with neutrinos of single flavour) with known intensity and energy spectrum are of great interest for studying the neutrino properties and the details of neutrino-involving processes. A comprehensive list of applications for such beams is given, e.g., in [1]. In [2] it was proposed to use accelerated $\beta^+$- and $\beta^-$-decaying nuclei (or radioactive ions), held in a storage ring, as a source for such neutrino beams ($\beta$-beams). A useful modification has been advanced in [3, 4]: one can use the ions with electron-capturing nuclei as a neutrino source. The advantage of the electron capture (EC) is that in the ion rest frame the neutrino energy $E_\nu^0$ is completely definite. Thus, in the laboratory frame at $\gamma \gg 1$, one can obtain a high-energy neutrino beam, which is collimated and monochromatic (EC-beam).

We discuss another possible improvement: EC-beam could be modulated, or, in other words, transformed into a sequence of neutrino pulses. This can increase the efficiency of neutrino detection. A modulated beam causes a modulated signal in the detector which can be separated from constant or randomly fluctuating background noise (the similar advantage is pointed out in [5] for neutrinos produced by interaction of a modulated high-energy electron beam with a target).

The capture of an electron $e^-$ by the nucleus in a H-like ion (with emission of an electron neutrino $\nu_e$) is similar to the muon capture by the nucleus in a muonic atom (with emission of a muonic neutrino $\nu_\mu$). In both cases, a lepton of spin 1/2 is captured from the $|1s\rangle$-state. In more exact terms, if the nucleus has a non-zero spin $I$, then the capture occurs from the hyperfine state with definite total angular momentum $F = I \pm 1/2$. In general, the decay probability highly depends on the value of $F$. This dependence for muon capture was first found out in...
1950s and it was called ”the hyperfine effect” [6, 7]. This effect was repeatedly observed (see, e.g., [8] and references therein).

The hyperfine effect is most pronounced in pure Gamow–Teller transitions, i.e.

\[ I^\pi \rightarrow I'^\pi, \quad I' = I \pm 1, \tag{1} \]

where \( I' \) is the daughter nucleus spin. In the Gamow–Teller approximation, the total angular momentum consists of the daughter nucleus spin \( I' \) and the neutrino spin 1/2. Therefore, due to the total angular momentum conservation the following condition must be satisfied:

\[ F = I' \pm 1/2. \tag{2} \]

This means that the mother nucleus can capture \( e^- \) or \( \mu^- \) from only one of the hyperfine states: if \( I' = I - 1, \) the capture occurs from the state \( F = I - 1/2, \) while in the case of \( I' = I + 1 \) the capture occurs from the state \( F = I + 1/2. \)

It is clear that, inducing transitions between the states with ”allowed” and ”forbidden” \( F \) values, one can impact the capture rate, and, therefore, modulate the corresponding neutrino emission. The idea to use electromagnetic radiation to induce transitions between hyperfine states and change the capture probability was first stated for muonic atoms in [9]. In 1990s, the hyperfine effect for the H-like ions was rediscovered in [10] (evidently, due to the prospects for experimental studies of H-like ions with heavy \( \beta^+ \)-radioactive nuclei). The authors of [10] also noted the possibility to impact the EC rate by using electromagnetic radiation.

Our purpose was to select the appropriate \( \beta^+ \)-radioactive nuclei (in fact, H-like ions with such nuclei), that could be used as sources of modulated monochromatic neutrino beams. This report briefly summarizes our results.

2. Possible source isotopes for modulated beams

The nuclei of source ions have to satisfy several requirements. The mother nuclei must have non-zero spin. The spins of the initial and the final nuclear states have to differ by 1, their parities have to be the same. To provide high monochromaticity of the neutrino beam, \( \beta^+ \) decay must be highly suppressed and the nuclear transition through electron capture must go predominantly to only one final state (we admitted the branching larger than 98% of total decay probability). In order to produce a beam of significant intensity, the nuclei have to be rather short-living (we set the upper limit on the half-lives \( T_{1/2} < 10^6 \text{ s} \simeq 11.6 \text{ d} \)).

Table 1 shows the nuclear transitions that satisfy the requirements stated above.

3. Hyperfine structure and modulation

In the point-like nucleus approximation, the distance between two hyperfine levels is determined by the squared modulus \( |\psi_{g.s.}(0)|^2 \) of the electron wavefunction in the ion, taken at the origin (at the nucleus), and by the nuclear spin \( I \) and magnetic moment \( \mu \) (see, e.g., [11]). For ions with high \( Z \), there are significant contributions (of the order of 5%) into the hyperfine splitting from finite-size nuclear corrections and radiative corrections.

Note that the sign of the nuclear magnetic moment \( \mu \) determines the sequence of hyperfine levels in a H-like ion: when \( \mu > 0 \), the state with angular momentum \( F = I - 1/2 \) is lower, while in the case of \( \mu < 0 \) the lower state has \( F = I + 1/2 \). In Gamow–Teller transitions in H-like ions, EC decay from the lower state could be either allowed or forbidden. Accordingly, we define two types of H-like ions: A type and F type, depending on whether the EC decay is allowed or forbidden for the lower state. The type of an ion is determined, first, by the sign of the nuclear magnetic moment \( \mu \) and, second, by the relation between the initial and the final nuclear spins \( I \) and \( I' \).
Table 1. The pairs of mother and daughter nuclei, related by Gamow–Teller transition following the electron capture. Here $^{A\ Z}_{Z\ X}$ is the mother nucleus (of spin and parity $I^\pi$ and half-life $T_{1/2}$), undergoing the Gamow–Teller transition into one state of the daughter nucleus $^{Z\ A\ X'}_{Z-1\ A\ X}$ (of spin and parity $I'^\pi$ and of excitation energy $E'$) with probability $P \geq 98 \%$. $Q_{EC}$ is the energy release in the transition. The data are taken from [12].

| $^{A\ Z}_{Z\ X}$  | $I^\pi$ | $T_{1/2}$ | $^{Z\ A\ X'}_{Z-1\ A\ X}$ | $I'^\pi$ | $E'$, keV | $Q_{EC}$, keV | $P$, % |
|-------------------|---------|-----------|-----------------------------|---------|-----------|-------------|-------|
| $^{71\ Ge}_{32\ Ge}$ | $1/2^-$ | 11.4 d    | $^{71\ Ga}_{31\ Ga}$ | $3/2^-$ | 0         | 232.6       | 100   |
| $^{107\ Ag^*}_{47\ Cd}$ | $5/2^+$ | 6.5 h     | $^{107\ Ag^*}_{47\ Ag}$ | $7/2^+$ | 93.1      | 1323.2      | 99.7  |
| $^{118m\ Sn^*}_{51\ Sb}$ | $8^-$  | 5.0 h     | $^{118m\ Sn^*}_{50\ Sn}$ | $7^-$  | 2574.8    | 1332       | 98.3  |
| $^{131\ Xe}_{55\ Cs}$ | $5/2^+$ | 9.7 d     | $^{131\ Xe}_{54\ Xe}$ | $3/2^+$ | 0         | 354.8       | 100   |
| $^{135\ Ba}_{57\ La}$ | $5/2^+$ | 19.5 h    | $^{135\ Ba}_{56\ Ba}$ | $3/2^+$ | 0         | 1207       | 98.1  |
| $^{163\ Ho}_{68\ Er}$ | $5/2^-$ | 75 m      | $^{163\ Ho}_{67\ Ho}$ | $7/2^-$ | 0         | 1211       | 99.9  |
| $^{165\ Ho}_{68\ Er}$ | $5/2^-$ | 10.4 h    | $^{165\ Ho}_{67\ Ho}$ | $7/2^-$ | 0         | 378        | 100   |

The modulation methods for neutrino beams, produced by H-like ions of A and F types, are different. Indeed, for A-type ions, the transition from the lower to the upper state, induced by a resonant electromagnetic field, is accompanied by an interruption of the neutrino emission. For F-type ions, on the contrary, such transition will initiate the neutrino emission. In both cases, the reverse transition from the upper level to the lower one could be either spontaneous or induced by an external resonant electromagnetic wave.

To our opinion, H-like ions of F type are of special interest. Such ions decay predominantly or exclusively from the upper state of the hyperfine structure. Hence, their lower state is practically stable. This circumstance may be used to accumulate ions in a storage ring. Then, by electromagnetic transitions to the upper state (arranged in $\pi$-pulses), one may form neutrino pulses.

4. Results and discussion

Table 2 gives the following parameters of H-like ions: the hyperfine splitting $|\Delta_H F|$ of the ground state, the resonant wavelength $\lambda_{HF}$, the lifetime $\tau_{HF} = 1/w_{HF}$ of the upper hyperfine state with respect to spontaneous emission. For the ion with the nucleus $^{118m\ Sb}$ we give values of $\tau_{HS}$ both for positive (+) and for negative (−) magnetic moment $\mu$.

All the selected nuclei have rather large half-lives (for a nucleus, accelerated to Lorentz factor $\gamma$, lifetime increases by $\gamma$ times). This means that the total number of radioactive ions in a storage ring should be large, in order to get the neutrino beam of significant intensity. Of course, the required beam intensity, as well as its energy (and, thus, the factor $\gamma$), depends on the experimental problem.

5. Conclusion

It turns out that the list of appropriate nuclei is rather short. However, the H-like ions with these nuclei noticeably differ from each other both by the lifetime with respect to the electron
Table 2. The main properties of the H-like ions that could be used as sources of monochromatic and modulated neutrino beams. Here $\frac{A}{Z}X$ is the mother nucleus, which undergoes the Gamow–Teller transition $I^+ \rightarrow I'^+\nu$ into the final state of the daughter nucleus, $\mu$ is the magnetic moment of the mother nucleus in units of nuclear magneton $\mu_N$, A or F is the type of the H-like ion, $|\Delta_{HF}|$ is the absolute value of hyperfine splitting of the H-like ion ground state, $\lambda_{HF}$ is the resonant wavelength of hyperfine transition, $\tau_{HF}$ is the lifetime of the upper hyperfine state with respect to spontaneous emission.

| $A/Z$X | $I^+ \rightarrow I'^+$ | $\mu/\mu_N$ | Type | $|\Delta_{HF}|$, eV | $\lambda_{HF}$, $\mu$m | $\tau_{HF}$, s |
|--------|-----------------|-------------|------|-----------------|-----------------|-----------------|
| $^{71}_{32}$Ge | $1/2^- \rightarrow 3/2^-$ | $+0.55$ | F | 0.041 | 30.2 | 1024 |
| $^{107}_{48}$Cd | $5/2^+ \rightarrow 7/2^+$ | $-0.615$ | A | 0.105 | 11.8 | 26.3 |
| $^{118}_{51}$Sb | $8^- \rightarrow 7^-$ | 2.32 | 0.433 | 2.86 | 0.46(+), 0.41(−) |
| $^{131}_{55}$Cs | $5/2^+ \rightarrow 3/2^+$ | $+3.54$ | A | 0.973 | 1.27 | 0.046 |
| $^{135}_{57}$La | $5/2^+ \rightarrow 3/2^+$ | $+3.70$ | A | 1.162 | 1.06 | 0.027 |
| $^{165}_{68}$Er | $5/2^- \rightarrow 7/2^-$ | $+0.56$ | F | 0.346 | 3.58 | 1.03 |
| $^{165}_{68}$Er | $5/2^- \rightarrow 7/2^-$ | $+0.64$ | F | 0.399 | 3.10 | 0.67 |

capture as well as by the hyperfine structure of the ground states. The latter is important for the modulation method. Given a specific problem, one can choose a suitable sort of H-like ions from our list and use it as a source of modulated monochromatic neutrino beams.

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