Electromagnetic modulation of monochromatic neutrino beams

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Outline

1. β-beams
2. Hyperfine effect
3. Nuclei selection
4. Summary

Neutrino beam applications

Problems

- Oscillation experiments
- Search for neutrino magnetic moment
- Refining of the weak interaction constants
- Coherent scattering off nuclei
- Elastic/inelastic scattering of ν on nucleons and nuclei

Requirements

- ν of single flavor
- Precise knoweledge of spectrum
- Precise knoweledge of intensity

β-beams

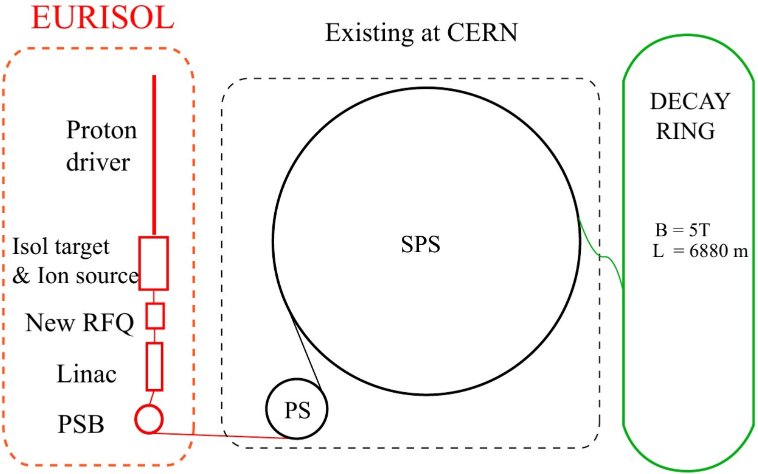
The idea of β-beams (P. Zucchelli, Phys.Lett.B, 2002)

Source β-radioactive nuclei/ions in a storage ring
High γ $\Rightarrow$ neutrinos are emitted within angle $\theta \simeq 1/\gamma$ $\Rightarrow$ beam collimation
Neutrino energy (in lab frame) $E_\nu \simeq 2\gamma E_\nu^0 \gg E_\nu^0$

e-capture beams (J. Sato, Phys.Rev.Lett. 95, 2005; J. Bernabeu et al., JHEP, 2005)

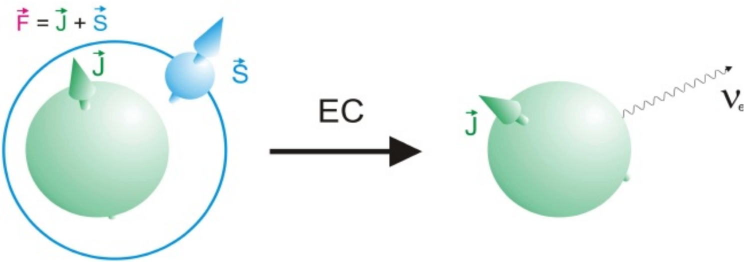
Source: ions with electron-capturing nuclei
Neutrinos are monochromatic in the ion rest frame $\Rightarrow$ if $\gamma \gg 1$ one obtains a monochromatic beam in lab frame

β-beams



Possible β-beam facility (C. Volpe, J.Phys.G, 2007)

Hyperfine effect for the K-shell of H-like ions



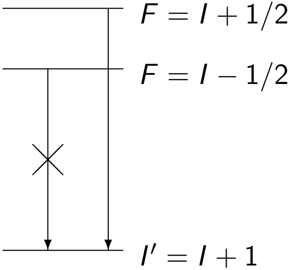
Total angular momentum conservation

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

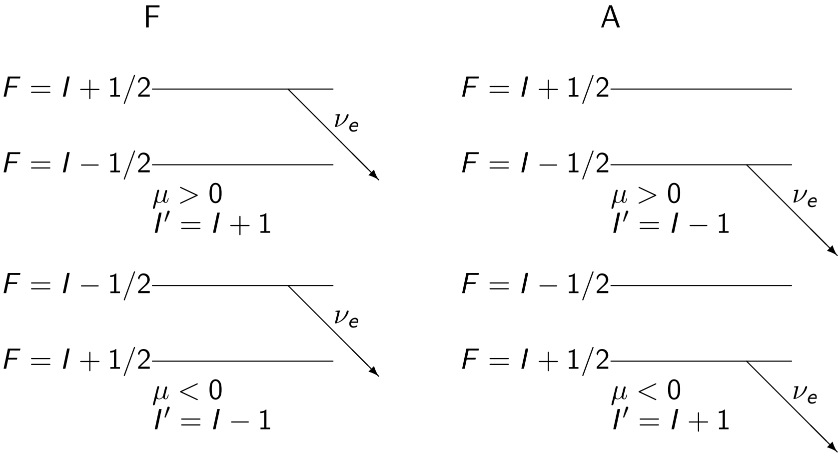
For Gamow–Teller transition $I' = I \pm 1$:

$I' = I - 1 \Rightarrow$ decay occurs from $F = I - 1/2$

$I' = I + 1 \Rightarrow$ decay occurs from $F = I + 1/2$



Ion types


F
A
$F = I + 1/2$
ν_e
$F = I - 1/2$
$\mu > 0$
$I' = I + 1$
$F = I - 1/2$
ν_e
$F = I + 1/2$
$\mu < 0$
$I' = I - 1$
$F = I + 1/2$
$F = I - 1/2$
ν_e
$\mu > 0$
$I' = I - 1$
$F = I - 1/2$
$F = I + 1/2$
ν_e
$\mu < 0$
$I' = I + 1$

Requirements for nuclei

- Spin/parity: $I \neq 0$, $I' = I \pm 1$, $\pi' = \pi$
- β^+ decay is suppressed, $Q \lesssim 2 m_e c^2$
- Transition to only one state of daughter nucleus $98 - 100\%$
- Half-life $2\ \mathrm{s} < T_{1/2} \lesssim 10^6\ \mathrm{s} \simeq 11.6$ d.

Properties of selected nuclei

${}^{A}_{Z}X$	I^{π}	$T_{1/2}$	${}_{Z-1}^{A}X'$	I'^{π}	E', keV	Q_{EC}, keV	P, %
${}^{71}_{32}$Ge	$1/2^-$	11.4 d	${}^{71}_{31}$Ga	$3/2^-$	0	232.6	100
${}^{107}_{48}$Cd	$5/2^+$	6.5 h	${}^{107}_{47}$Ag*	$7/2^+$	93.1	1323.2	99.7
${}^{118m}_{51}$Sb	8^-	5.0 h	${}^{118}_{50}$Sn*	7^-	2574.8	1332	98.3
${}^{131}_{55}$Cs	$5/2^+$	9.7 d	${}^{131}_{54}$Xe	$3/2^+$	0	354.8	100
${}^{135}_{57}$La	$5/2^+$	19.5 h	${}^{135}_{56}$Ba	$3/2^+$	0	1207	98.1
${}^{163}_{68}$Er	$5/2^-$	75 m	${}^{163}_{67}$Ho	$7/2^-$	0	1211	99.9
${}^{165}_{68}$Er	$5/2^-$	10.4 h	${}^{165}_{67}$Ho	$7/2^-$	0	378	100

Properties of ions

${}^{A}_{Z}X$	$I^{\pi} \rightarrow I'^{\pi}$	μ/μ_N	Type	$\lvert\Delta_{HF}\rvert$, eV	λ_{HF}, μm	τ_{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
${}^{118m}_{51}$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
${}^{163}_{68}$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

Summary

Results

- Usage of modulated monochromatic ν_e-beams is proposed
- The requirements for source nuclei are stated
- Possible source nuclei are selected
- The most promising nucleus is $^{163}_{68}$Er

Thank you!

Backup slides

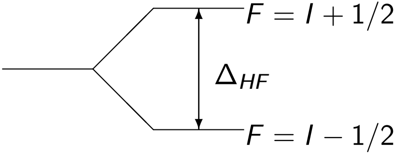
Hyperfine splitting

Splitting

$$\Delta_{HF} = \frac{4\alpha^4 Z^3}{3} \frac{\mu}{\mu_N} \frac{m_e}{m_p} \frac{2I+1}{2I} m_e c^2 A(\alpha Z)$$

Relativistic factor

$$A(\alpha Z) = \frac{1}{\left(2\sqrt{1-\alpha^2 Z^2} - 1\right)\sqrt{1-\alpha^2 Z^2}}$$



For large Z there are significant radiative and finite-size corrections $\sim 5\%$.

Spontaneous transitions

$E1$ — forbidden (by parity)
$M1$ — allowed

$M1$ transition rate

$$w_{HF}(F_2 \to F_1) = \frac{4\alpha|\Delta_{HF}|^3}{3\hbar(m_e c^2)^2} \times$$
$$\times \frac{1}{2I+1} \cdot \begin{cases} I, & F_2 = I + 1/2 \to F_1 = I - 1/2, \\ I+1, & F_2 = I - 1/2 \to F_1 = I + 1/2. \end{cases}$$

Induced transitions

Magnetic field

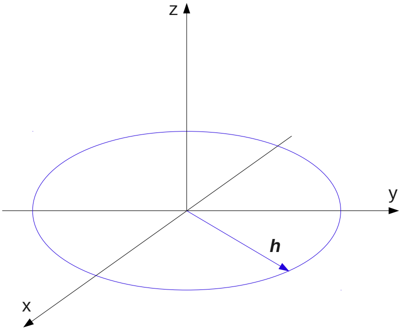
$$\mathbf{h}(t) = h_0\,(\mathbf{e}_x \cos\omega t + \mathbf{e}_y \sin\omega t)$$

Perturbation operator

$$\hat{V}(t) = -\mu_e \boldsymbol{\sigma} \mathbf{h}(t)$$

State vector

$$|\Psi(t)\rangle = \sum_{Ff} a_{Ff}(t)\,|Ff\rangle\, e^{-i\frac{E_F t}{\hbar}}$$



System of equations for amplitudes

$$\dot{a}_{Ff}(t) = -\frac{i}{\hbar} \sum_{F'f'} a_{F'f'}(t) \langle Ff|\hat{V}(t)|F'f'\rangle\, e^{i\frac{(E_F - E_{F'})t}{\hbar}} .$$

Resonance

Resonance condition

$$\omega = \frac{E_2 - E_1}{\hbar} \equiv \frac{|\Delta_{HF}|}{\hbar}$$

Dominant transitions $|F_1 f\rangle \leftrightarrow |F_2\, f+1\rangle$
System takes form

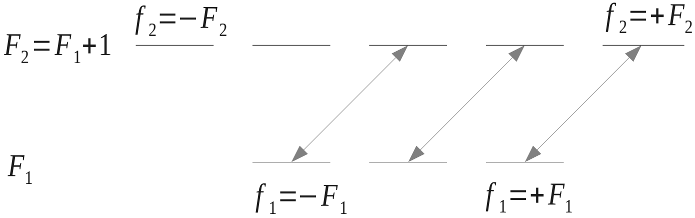
$$\begin{cases} \dot{a}_{F_2 f+1}(t) = -i\,\Omega^f_{F_1 F_2}\, a_{F_1 f}(t), \\ \dot{a}_{F_1 f}(t) = -i\,\Omega^f_{F_1 F_2}\, a_{F_2 f+1}(t). \end{cases}$$

Rabi frequency

$$\Omega^f_{F_1 F_2} = -\frac{\mu_B h_0}{\hbar}\sqrt{3(2F_1+1)}\; W(I\tfrac{1}{2}F_2 1, F_1\tfrac{1}{2})\; C^{F_2 f+1}_{F_1 f\ 1 1}\,,$$

W is Racah function, C is Clebsch–Gordan coefficient

Resonance



Simplest case:

1. $F_2 = F_1 + 1\,(\mu > 0)$;
2. all unexcited ions are in $f = F_1$ state

$\Rightarrow$ transitions $|F_1 F_1\rangle \leftrightarrow |F_2 F_2\rangle$ with

$$\Omega_{F_1 F_2}^{F_1} = \frac{\mu_B h_0}{\hbar}\sqrt{\frac{2I}{2I+1}}.$$

Typical period $T_0 = 2\pi\hbar/\mu_B h_0$

For radiation intensity $S = ch_0^2/(4\pi) \simeq 1$ W/cm^2 one obtains $T_0 \simeq 1.1 \cdot 10^{-5}$ s.