Partially monochromatic modulated neutrino beams

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Outline

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

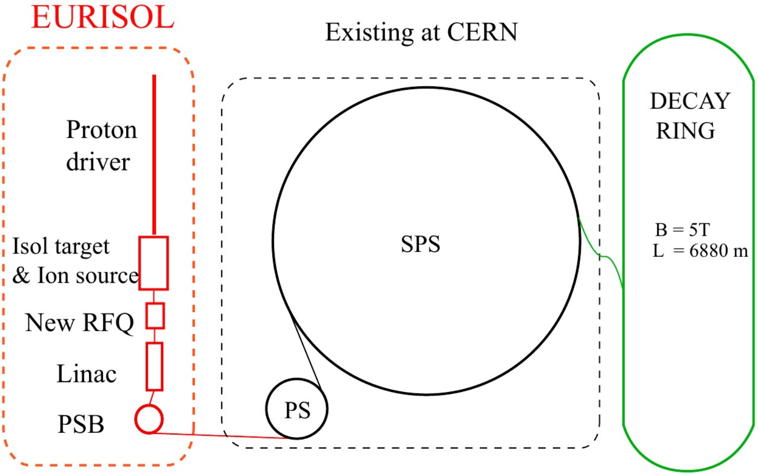
The idea of β-beams (P. Zucchelli, Phys.Lett.B, 2002)

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)

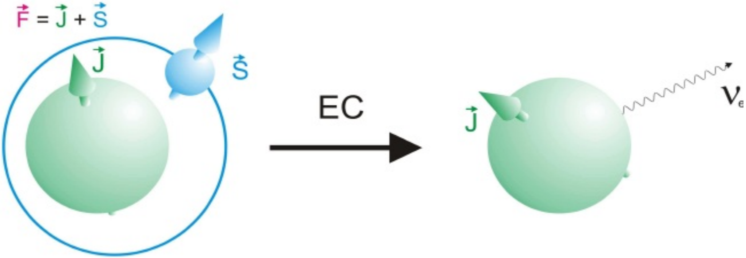
Source: ions with electron-capturing nuclei
Neutrinos are monochromatic in the ion rest frame $\Rightarrow$ if $\gamma \gg 1$ one obtains a monochromatic beam in lab frame

β-beams



Scheme of a β-beam facility (*C.Volpe, J.Phys.G, 2007*)

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



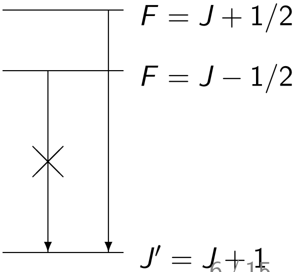
Total angular momentum conservation

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

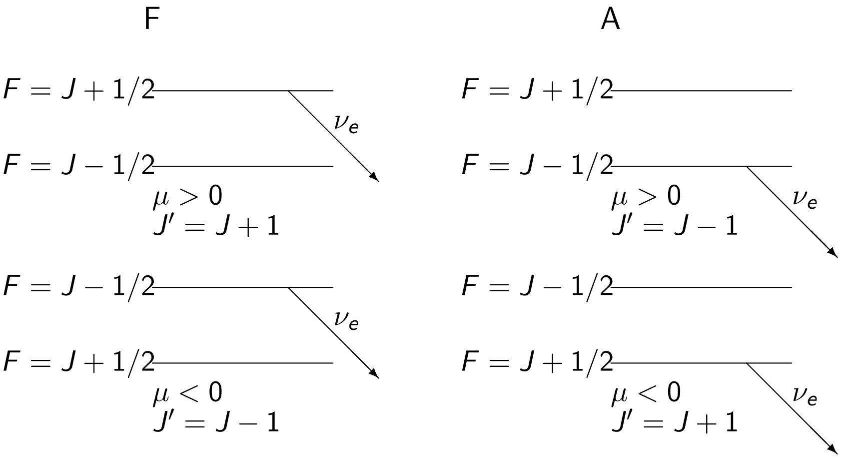
For Gamow–Teller transition $J' = J \pm 1$:

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

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



Ion types


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

EC-beam intensity

Consider a "maximal" cylindrical detector of radius $R = L/\gamma$ and height l

Number of events (per time unit) is

$$N_{event} = \frac{0.7 \cdot \eta \cdot N_{ions} \cdot \rho \cdot l \cdot E_\nu^0(\mathrm{GeV}) \cdot 10^{-38}\ \mathrm{cm}^2}{\tau m_0},$$

η is the monochromaticity, E_ν^0 is the neutrino energy in the rest frame, τ is the ion lifetime, m_0 the is atomic mass unit

Estimates:

- Number of ions in a storage ring $N_{ions} \sim 10^{11}$
- Density $\rho \simeq 1\ \mathrm{g/cm}^3$
- $l \simeq 10$ m

Number of events per year

$$N_e^y \simeq 1 \cdot 10^7 \cdot \frac{\eta\, E_\nu^0(\mathrm{GeV})}{\tau(\mathrm{s})}$$

Modulated monochromatic neutrino beams

Requirements for nuclei:

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

Properties of selected nuclei

${}^{A}_{Z}X$	J^{π}	$T_{1/2}$	${}_{Z-1}^{A}X'$	J'^{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
${}^{119}_{51}$Sb	$5/2^+$	38.2 h	${}^{118}_{50}$Sn	$3/2^+$	23.9	590.8	100
${}^{131}_{55}$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

${}^A_Z X$	$J^\pi \to J'^\pi$	μ/μ_N	Type	$\lvert\Delta_{HF}\rvert$, eV	λ_{HF}, μm	τ_{HF}, s
${}^{71}_{32}$Ge	$1/2^- \to 3/2^-$	$+0.55$	F	0.041	30.2	1024
${}^{107}_{48}$Cd	$5/2^+ \to 7/2^+$	-0.615	A	0.105	11.8	26.3
${}^{118m}_{51}$Sb	$8^- \to 7^-$	2.32		0.433	2.86	$0.46+$, $0.41-$
${}^{119}_{51}$Sb	$5/2^+ \to 3/2^+$	$+3.45$	A	0.725	1.71	0.11
${}^{131}_{55}$Cs	$5/2^+ \to 3/2^+$	$+3.54$	A	0.973	1.27	0.046
${}^{135}_{57}$La	$5/2^+ \to 3/2^+$	$+3.70$	A	1.162	1.06	0.027
${}^{163}_{68}$Er	$5/2^- \to 7/2^-$	$+0.56$	F	0.346	3.58	1.03
${}^{165}_{68}$Er	$5/2^- \to 7/2^-$	$+0.64$	F	0.399	3.10	0.67

Intense β-beams with modulation

Requirements for nuclei:

- Spin/parity: $J \neq 0$, $J' = J \pm 1$, $\pi' = \pi$
- Half-life $1\ \mathrm{s} < T_{1/2} \lesssim 30\ \mathrm{s}$
- EC branching $\geq 1\%$
- $\alpha = \eta(\%) E_\nu^0(keV)/T_{1/2}(s) \geq 10^3$

Properties of selected nuclei

Nuclear properties

${}^{A}_{Z}X$	$T_{1/2}$, s	μ/μ_N	$J^\pi \to J'^{\pi'}$	E', keV	Q, keV	η, %	$\alpha = \frac{\eta E_\nu^0}{T_{1/2}}$
${}^{140}_{63}$Eu	1.51	+1.37	$1^+ \to 0^+$	0	8470	3.1	17400
${}^{140}_{63}$Eu			$1^+ \to 2^+$	531	7940	1.1	5780
${}^{140}_{63}$Eu			$1^+ \to 2^+$	1600	6870	0.29	1320
${}^{142}_{63}$Eu	2.34	+1.54	$1^+ \to 0^+$	0	7670	5.12	16800
${}^{144}_{63}$Eu	10.2	+1.89	$1^+ \to 0^+$	0	6320	9.75	6040

Ion properties

${}^{A}_{Z}X$	μ/μ_N	$J^\pi \to J'^{\pi}$	E', keV	Type	$\lvert\Delta_{HF}\rvert$, eV	λ_{HF}, μm	τ_{HF}, s
${}^{140}_{63}$Eu	+1.37	$1^+ \to 0^+$	0	A	0.522	2.38	0.375
${}^{140}_{63}$Eu	+1.37	$1^+ \to 2^+$	531	F	0.522	2.38	0.375
${}^{140}_{63}$Eu	+1.37	$1^+ \to 2^+$	1600	F	0.522	2.38	0.375
${}^{142}_{63}$Eu	+1.54	$1^+ \to 0^+$	0	A	0.586	2.12	0.264
${}^{144}_{63}$Eu	+1.89	$1^+ \to 0^+$	0	A	0.720	1.72	0.143

Summary

Results

- Idea of modulated EC-beam is discussed
- Intensity of EC-beams is estimated
- Sources for entirely monochromatic modulated EC-beams are selected
- Sources for intense modulated partially monochromatic beams are selected

Thank you!