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Neutrino induced electron capture using bound-beta beams

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Resonant antineutrino induced electron capture with low energy bound beta beams

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arXiv:0905.1029

Resonant neutrino processes

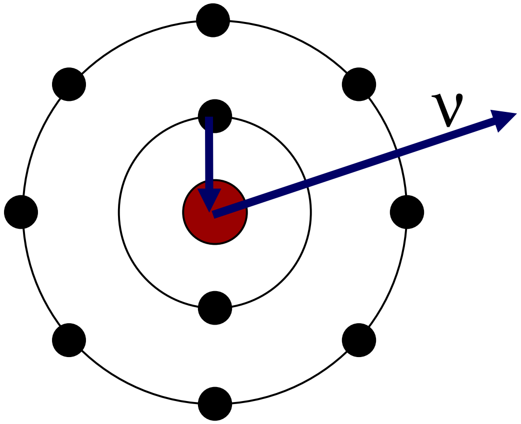
- Neutrino cross-sections for continuous processes are small
  $\sigma \propto \frac{G_F^2}{\pi} Q^2$ ≈10^{-44} cm^2 at $1\mathrm{MeV}^2$, ≈$10^{-38}\mathrm{cm}^2$ at $1\ \mathrm{GeV}^2$
- With resonant intermediate state, cross-section can in principle be much larger:

$$\sigma_{peak} \propto \frac{4\pi}{Q^2} Br\left(Res \rightarrow initial \quad state\right)$$

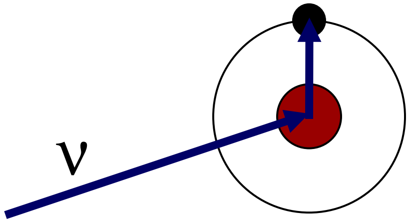
- Well known example: absorption of UHE ν from scattering on (massive) cosmic background ν
  $\sigma(\nu\bar{\nu} \rightarrow Z^0) = 5\mathrm{x}10^{-31}\mathrm{cm}^2$

Electron capture and bound-beta decay

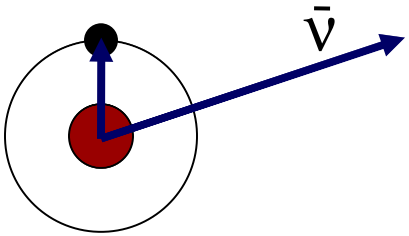
Electron capture



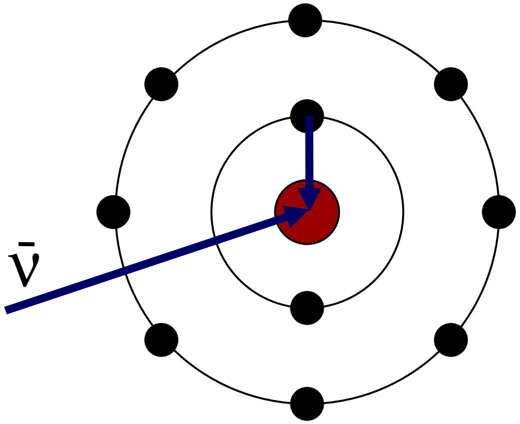
Inverse electron capture
(bound state neutrino absorption)



Bound-beta decay



Inverse bound-beta decay
(antineutrino induced electron capture)



Studies of νEC

- 1950 Fermi mentions in book “Nuclear Physics”

- 1959 W.M. Visscher proposes Mossbauer neutrinos
  - *W.M. Visscher Phys Rev 116, 1581-1582 (1959)*

- 1968 Mikaelyan et al study its rate integrating over continuous reactor spectrum
  - *For Z>60 νEC cross-section exceeds inverse beta decay*

  Mikaelyan et al Sovj.J.Nucl.Phys. 6. 254 (1968)

- 1983 Kells, Schiffer propose Mossbauer antineutrinos
  - *W.P. Kells, J.P. Schiffer, Phys.Rev.C28:2162-2164,1983*

- 2005 R.S. Raghavan proposes Mossbauer in ^{3}H ↔ ^{3}He system
  - *hep-ph/0511191*

- 2009 A.G. Cocco et al consider νEC for CBν detection
  - *arXiv:0903.1217*

Antineutrino induced electron capture (νEC)

$$\bar{\nu}_e + {}^{A}_{Z+1}Y \rightarrow {}^{A}_{Z}X^*,$$

The new atom has a vacancy in an inner shell

Dominant decay: radiative de-excitation
proportional to square of binding energy B: $\Gamma = \alpha \frac{B^2}{m_e},$

Twofold experimental signature:

- *photons from de-excitation*
- *Radioactive decay of daughter nucleus*

The cross-section is resonant:

$$\sigma_{\bar{\nu}\mathrm{EC}}(Q) = S\frac{4\pi}{Q^2}\left[\frac{\Gamma^2/4}{(Q-Q_t)^2+\Gamma^2/4}\right]\frac{\Gamma_{b\beta}}{\Gamma}$$

S is a spin-factor of order 1

Bound beta decay

Probability of beta minus to be emitted in orbit:

$$\frac{\Gamma_{b\beta}}{\Gamma_{c\beta}} = n_f \pi \left(\frac{\alpha}{n}\right)^3 \frac{(Z+1)^{2.87+6.2\cdot 10^{-3}(Z+1)}}{f(Z+1, Q_{c\beta})} \left(\frac{Q_{b\beta}}{m_e}\right)^2$$

Mikaelyan et al Sovj.J.Nucl.Phys. 6. 254 (1968)

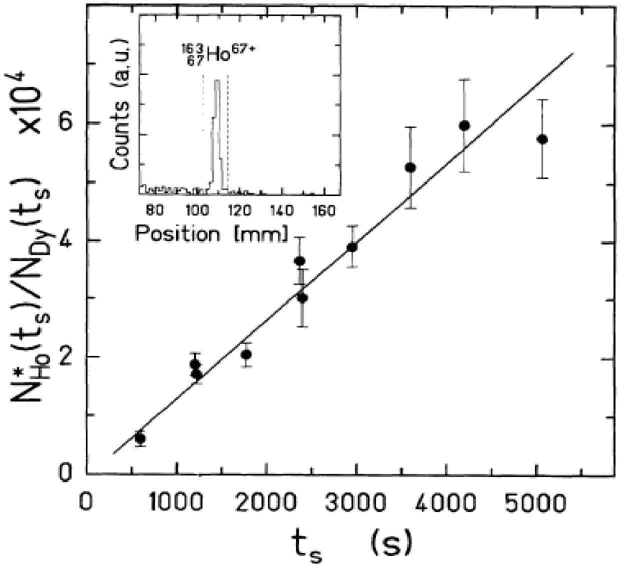
Non-zero only for L=0 oribitals (ns)

Largest probability for:

- 1s oribital (n=1)
- high-Z nuclei
- small Q-value
- highly ionized atoms

First observation 1992 GSI

M.Jung et.al. PRL 69:2164-2167,1992

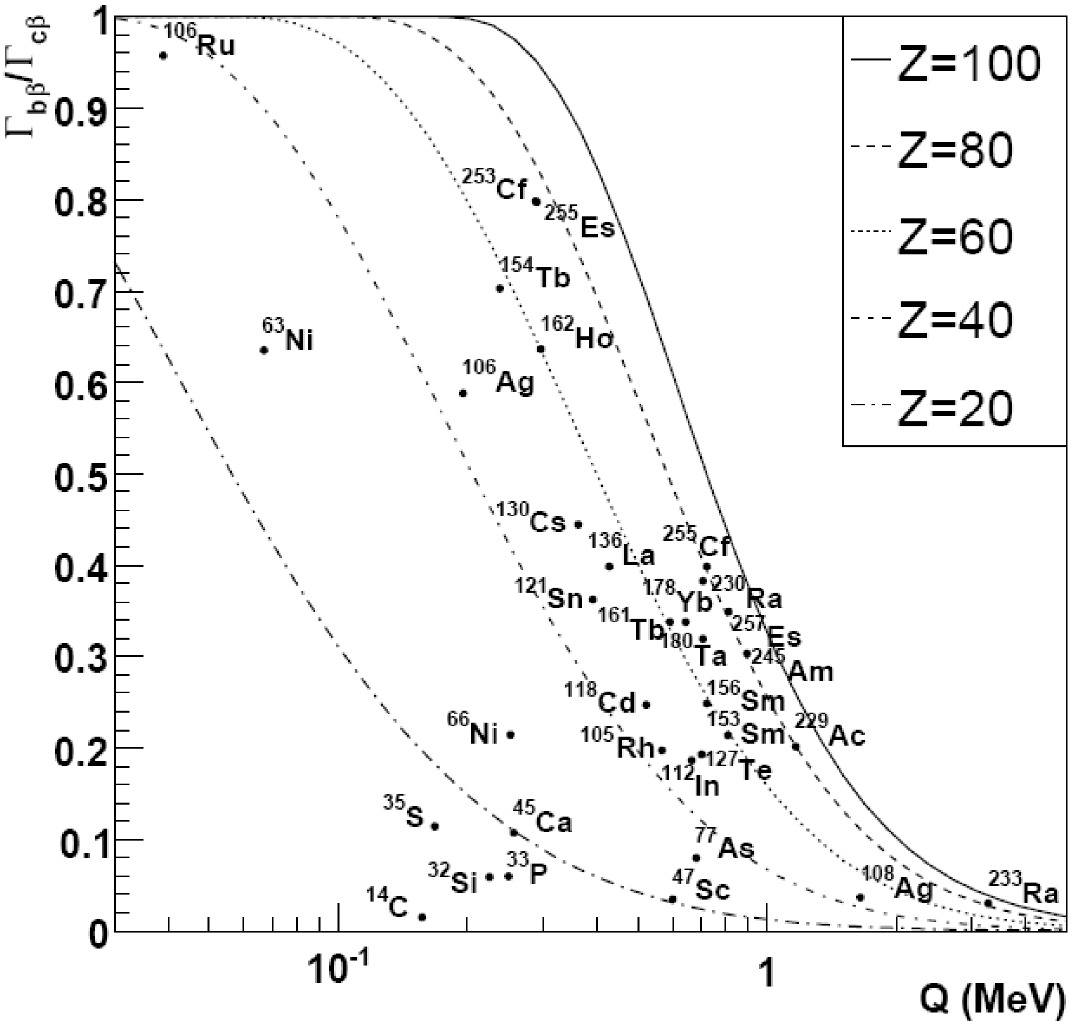


Bound beta decay probability

Fully ionized atoms to 1s orbital

8x smaller for 2s orbital

Only consider allowed transistions ($\Delta P=0$, $\Delta J\leq 1$)

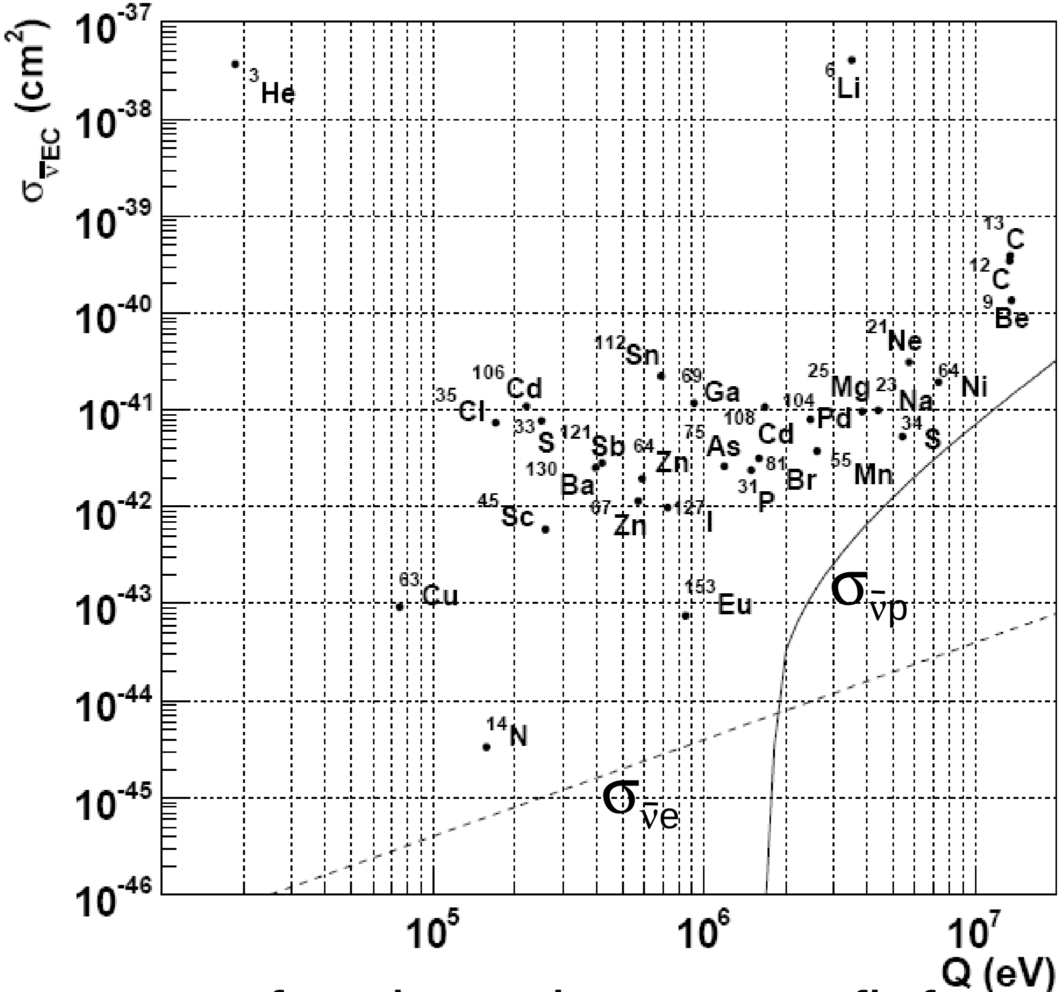


νEC peak cross-sections

Several orders of magnitude larger than neutrino-electron or neutrino proton scattering

Only valid in very narrow energy range:
1meV for ^{12}C,
11eV for ^{112}Sn

νEC from 2s orbital
2x larger cross-section
but 8x smaller width



Need monochromatic source of antineutrinos to profit from large cross-section!

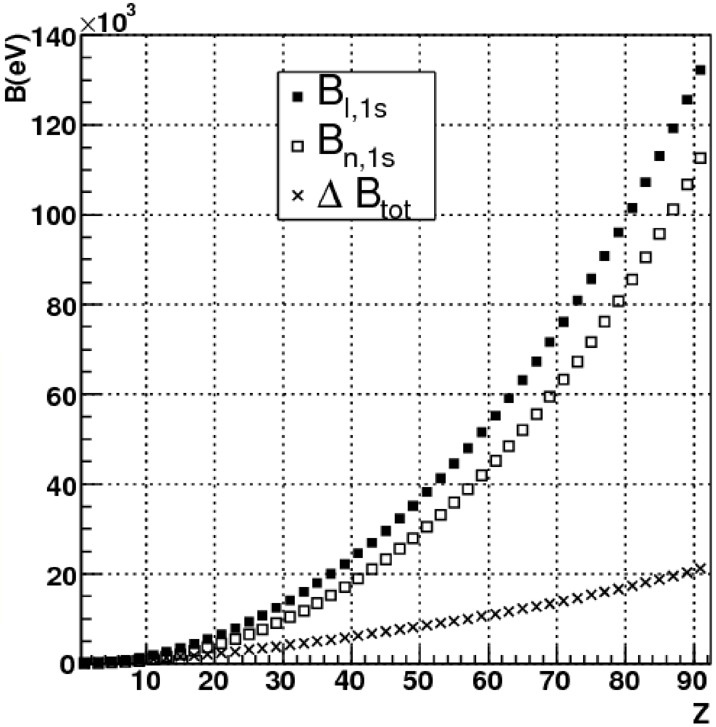
Neutrino energy in bβ and νEC

ν emitted in bβ does not match Q value of νEC:

- nuclear recoil: $Q^2/2m$ 'lost' in both source and target
  - *<1eV for ^{35}Cl to 22keV for ^{9}Be*
- Differences in binding energy:
  - $Q_{c\beta,n}=\Delta m$
  - $Q_{c\beta,i}=\Delta m-\Delta B_{tot}$
  - $Q_{b\beta,i}=\Delta m-\Delta B_{tot}+B_I$
  - $Q_{\nu EC,n}=\Delta m+B_n$

$$Q_{\nu EC}-Q_{b\beta,i} \approx 15\text{eV}*Z$$

Δm	mass difference between the neutral atoms
ΔB_{tot}	difference in total binding energy atom Z,Z+1
B_i	binding energy of 1s electron in ionized atom)
B_n	binding energy of 1s electron in neutral atom)



Bound beta beams

- Stripped atoms in a storage ring with straight sections
- Antineutrinos emitted monochromatic in CMS frame
- Neutrino energy can be tuned with Lorentz boost:

$$E_{\bar{\nu}} = E_{\bar{\nu}s}\gamma(1 + \beta\cos\theta')$$

- Neutrino energy depends on emission angle
- Tune beam speed such that at $\theta=0$ $E_\nu = E_{\nu t} + x\Gamma$
- Monochromatic (within $x\Gamma$) up to angles of

$$\cos\theta = 1 - \frac{2x\Gamma}{E_{\bar{\nu}s}\beta\gamma}.$$

- Best monochromaticity for non-relativistic beams!

Beam monochromaticity

How monochromatic does the beam need to be?

$$E_{\bar{\nu}} = E_{\bar{\nu}s}\gamma(1+\beta\cos\theta')$$

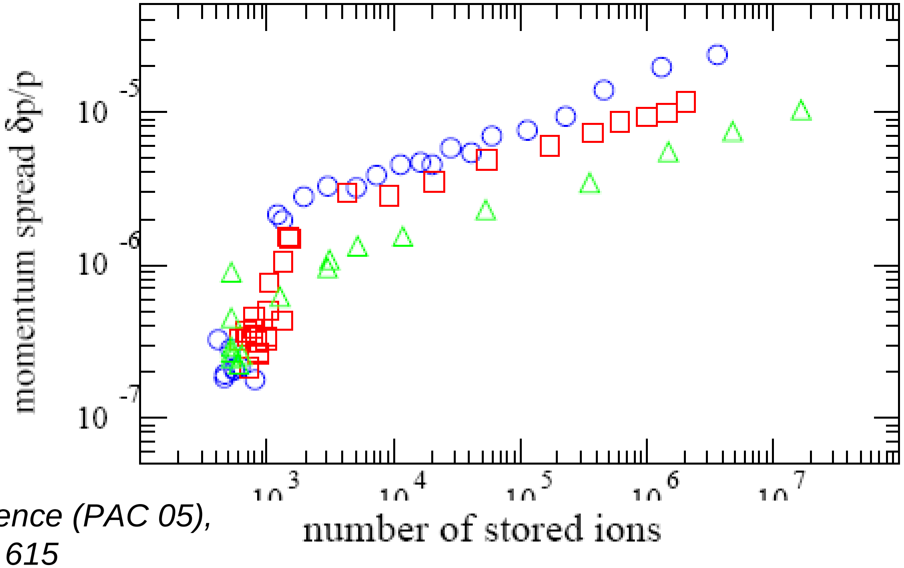
For non-relativistic beams (β<<1) p_ν spread much smaller than beam momentum spread!

Requirement on beam monochromaticity:

$$\frac{\Delta p}{p} \leq \frac{\Gamma}{|\beta| E_\nu}$$

ESR@GSI:

$\Delta p/p \approx 2\times10^{-7}$ achieved:

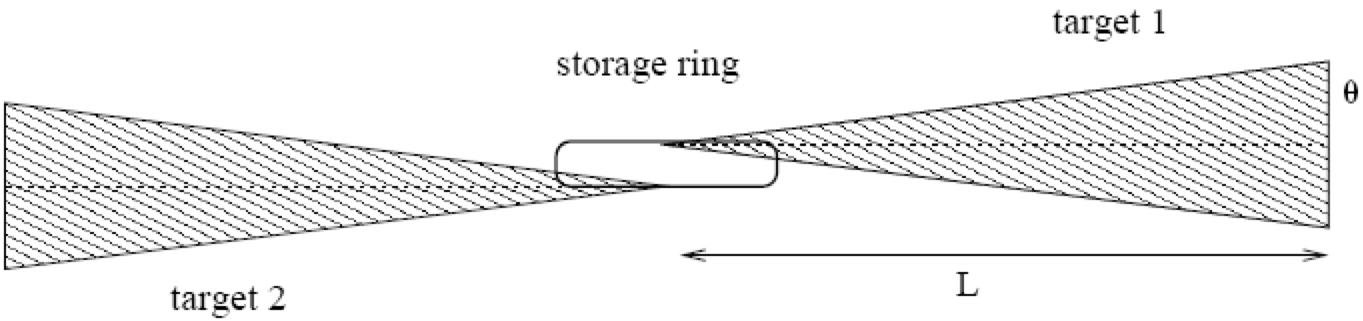


Proceedings of Particle Accelerator Conference (PAC 05), Knoxville, Tennessee, 16-20 May 2005, pp 615

Possible experimental setup

Conical targets as close as possible to storage ring

(demonstration experiment)



Expected number of interactions per decaying atom:

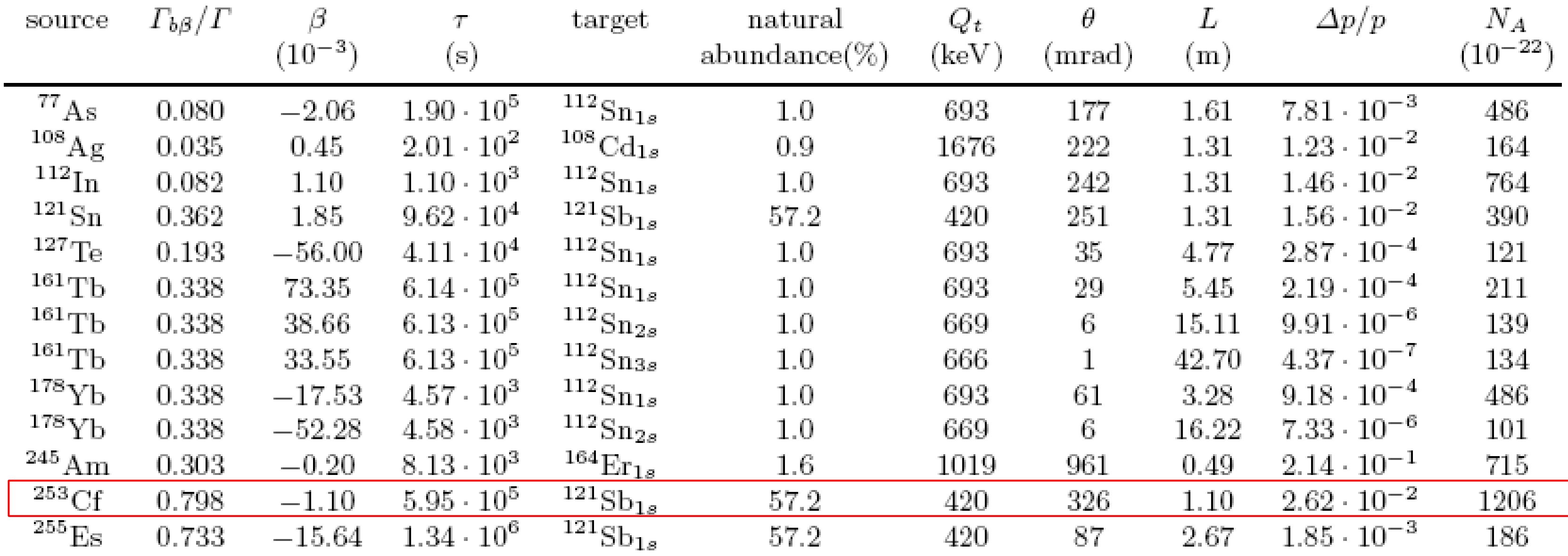
$$N_A = \frac{\Gamma_{b\beta}}{\Gamma} \frac{1-\cos\theta'}{2} \varepsilon_{BW} \sigma_{peak} L \frac{\rho}{m}$$

Highly idealized:

- *neglected losses in curved sections*
- *neglected size of straight sections*
- *neglected momentum spread*
- *assumed target 100% pure isotope*

Expected rates

for a target of 10^3 kg pure isotope:



source	$\Gamma_{b\beta}/\Gamma$	β (10^{-3})	τ (s)	target	natural abundance(%)	Q_t (keV)	θ (mrad)	L (m)	$\Delta p/p$	N_A (10^{-22})
^{77}As	0.080	−2.06	$1.90 \cdot 10^5$	^{112}Sn$_{1s}$	1.0	693	177	1.61	$7.81 \cdot 10^{-3}$	486
^{108}Ag	0.035	0.45	$2.01 \cdot 10^2$	^{108}Cd$_{1s}$	0.9	1676	222	1.31	$1.23 \cdot 10^{-2}$	164
^{112}In	0.082	1.10	$1.10 \cdot 10^3$	^{112}Sn$_{1s}$	1.0	693	242	1.31	$1.46 \cdot 10^{-2}$	764
^{121}Sn	0.362	1.85	$9.62 \cdot 10^4$	^{121}Sb$_{1s}$	57.2	420	251	1.31	$1.56 \cdot 10^{-2}$	390
^{127}Te	0.193	−56.00	$4.11 \cdot 10^4$	^{112}Sn$_{1s}$	1.0	693	35	4.77	$2.87 \cdot 10^{-4}$	121
^{161}Tb	0.338	73.35	$6.14 \cdot 10^5$	^{112}Sn$_{1s}$	1.0	693	29	5.45	$2.19 \cdot 10^{-4}$	211
^{161}Tb	0.338	38.66	$6.13 \cdot 10^5$	^{112}Sn$_{2s}$	1.0	669	6	15.11	$9.91 \cdot 10^{-6}$	139
^{161}Tb	0.338	33.55	$6.13 \cdot 10^5$	^{112}Sn$_{3s}$	1.0	666	1	42.70	$4.37 \cdot 10^{-7}$	134
^{178}Yb	0.338	−17.53	$4.57 \cdot 10^3$	^{112}Sn$_{1s}$	1.0	693	61	3.28	$9.18 \cdot 10^{-4}$	486
^{178}Yb	0.338	−52.28	$4.58 \cdot 10^3$	^{112}Sn$_{2s}$	1.0	669	6	16.22	$7.33 \cdot 10^{-6}$	101
^{245}Am	0.303	−0.20	$8.13 \cdot 10^3$	^{164}Er$_{1s}$	1.6	1019	961	0.49	$2.14 \cdot 10^{-1}$	715
^{253}Cf	0.798	−1.10	$5.95 \cdot 10^5$	^{121}Sb$_{1s}$	57.2	420	326	1.10	$2.62 \cdot 10^{-2}$	1206
^{255}Es	0.733	−15.64	$1.34 \cdot 10^6$	^{121}Sb$_{1s}$	57.2	420	87	2.67	$1.85 \cdot 10^{-3}$	186

Additional requirements

>10^{-20} interactions per stored atom per year

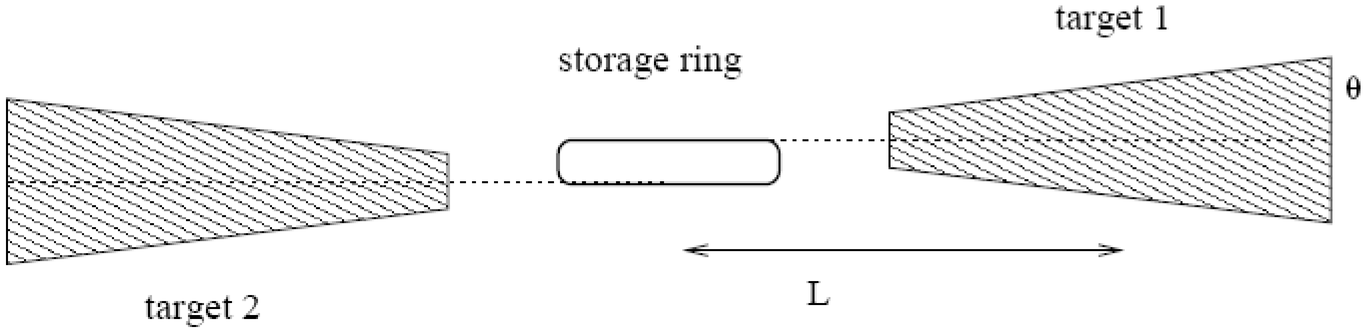
>10^{-10} interactions per joule (stripping and accelerating)

Most favourable outcome:

need 8×10^{18} decays for one interaction

Oscillation experiment

Targets at the atmospheric oscillation maximum $L = \frac{2\pi E_\nu}{\Delta m^2_{32}}$



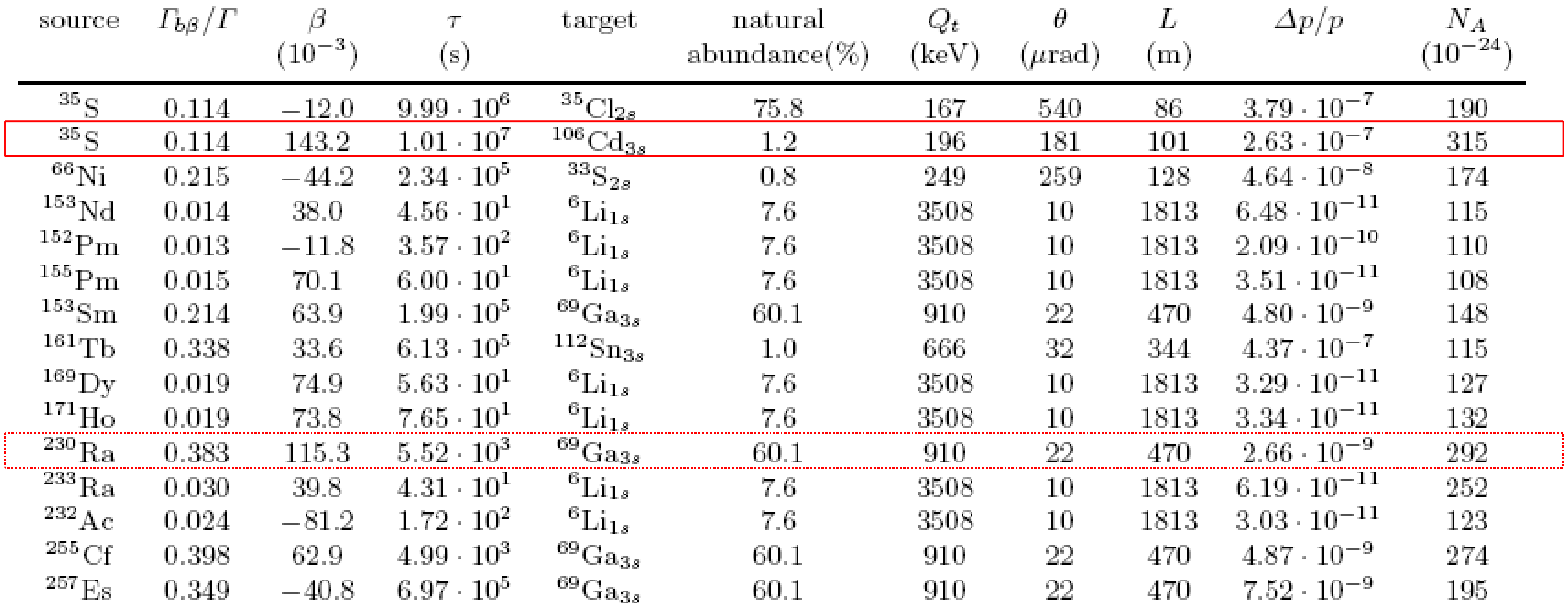
Target volume limited by monochomaticity

but fits 10^3 kg for all cases studied

Potential for measuring θ_{13} from neutrino disappearance

Rates for oscillation experiment

for a target of 10^3 kg pure isotope:



source	$\Gamma_{b\beta}/\Gamma$	β (10^{-3})	τ (s)	target	natural abundance(%)	Q_t (keV)	θ (μrad)	L (m)	$\Delta p/p$	N_A (10^{-24})
^{35}S	0.114	-12.0	$9.99 \cdot 10^6$	^{35}Cl$_{2s}$	75.8	167	540	86	$3.79 \cdot 10^{-7}$	190
^{35}S	0.114	143.2	$1.01 \cdot 10^7$	^{106}Cd$_{3s}$	1.2	196	181	101	$2.63 \cdot 10^{-7}$	315
^{66}Ni	0.215	-44.2	$2.34 \cdot 10^5$	^{33}S$_{2s}$	0.8	249	259	128	$4.64 \cdot 10^{-8}$	174
^{153}Nd	0.014	38.0	$4.56 \cdot 10^1$	^{6}Li$_{1s}$	7.6	3508	10	1813	$6.48 \cdot 10^{-11}$	115
^{152}Pm	0.013	-11.8	$3.57 \cdot 10^2$	^{6}Li$_{1s}$	7.6	3508	10	1813	$2.09 \cdot 10^{-10}$	110
^{155}Pm	0.015	70.1	$6.00 \cdot 10^1$	^{6}Li$_{1s}$	7.6	3508	10	1813	$3.51 \cdot 10^{-11}$	108
^{153}Sm	0.214	63.9	$1.99 \cdot 10^5$	^{69}Ga$_{3s}$	60.1	910	22	470	$4.80 \cdot 10^{-9}$	148
^{161}Tb	0.338	33.6	$6.13 \cdot 10^5$	^{112}Sn$_{3s}$	1.0	666	32	344	$4.37 \cdot 10^{-7}$	115
^{169}Dy	0.019	74.9	$5.63 \cdot 10^1$	^{6}Li$_{1s}$	7.6	3508	10	1813	$3.29 \cdot 10^{-11}$	127
^{171}Ho	0.019	73.8	$7.65 \cdot 10^1$	^{6}Li$_{1s}$	7.6	3508	10	1813	$3.34 \cdot 10^{-11}$	132
^{230}Ra	0.383	115.3	$5.52 \cdot 10^3$	^{69}Ga$_{3s}$	60.1	910	22	470	$2.66 \cdot 10^{-9}$	292
^{233}Ra	0.030	39.8	$4.31 \cdot 10^1$	^{6}Li$_{1s}$	7.6	3508	10	1813	$6.19 \cdot 10^{-11}$	252
^{232}Ac	0.024	-81.2	$1.72 \cdot 10^2$	^{6}Li$_{1s}$	7.6	3508	10	1813	$3.03 \cdot 10^{-11}$	123
^{255}Cf	0.398	62.9	$4.99 \cdot 10^3$	^{69}Ga$_{3s}$	60.1	910	22	470	$4.87 \cdot 10^{-9}$	274
^{257}Es	0.349	-40.8	$6.97 \cdot 10^5$	^{69}Ga$_{3s}$	60.1	910	22	470	$7.52 \cdot 10^{-9}$	195

Additional requirements

$>10^{-22}$ interactions per stored atom per year

$>10^{-12}$ interactions per joule (stripping and accelerating)

Most favourable outcome:

need $3\text{x}10^{21}$ decays for one interaction

Comparison

Interaction rate $3x10^{21}$ decays for one interaction rate seems a lot.

Compare with nuclear reactor

3 MeV reactor neutrinos: oscillation maximum at 1500 m

$\sigma_{eff}=5.8x10^{-43}cm^2$/fission = $8.1x10^{23}$ fissions per interaction

νEC interaction rate more than 2 orders of magnitude more favourable than reactor neutrinos

But

- *3GW reactor = 10^{20} fission/s,*
- *most optimistic radioactive beams 10^{13} decays/second*
- *Loose 7 orders of magnitude in beam power...*

Conclusions

Several nuclear processes lend themselves for resonant neutrino scattering with potentially large cross-sections

Neutrino-induced electron capture has peak cross-sections several orders of magnitude larger than continuoum cross-sections

many below the 1.8 MeV antineutrino-proton threshold

Stripped ions undergoing bound-beta decay are possible source of monochromatic antineutrinos

small Lorentz boost $10^{-3}<\beta<10^{-1}$ *sufficient*

$8\mathrm{x}10^{18}$ decays per interaction in a 1 ton target seems too low to be practical in near future

BACKUP

Rates from reactor experiments

- Oscillation maximum at 3Mev: $L = \frac{2\pi E_\nu}{\Delta m^2_{32}}$ =1500m
- number of interactions per fission for 1 ton of protons
  - *7tons of* $(CH_2)_n$

∀ $\sigma_{eff}=(5.75\pm0.08)\times10^{-43}$cm/fission *Phys.Lett.B338:383-389,1994*

- M/m=number of protons in 10^3kg=6.0×10^{29}

$$N = \frac{\sigma}{4\pi L^2}\frac{M}{m} = 1.23\times10^{-24}$$

- Require 8.1×10^{23} fissions per interaction

Oscillation maximum

oscillation probability:

$$P_{\alpha\to\beta} = \sin^2(2\theta)\sin^2\left(\frac{\Delta m^2 L}{4E}\right)$$

oscillation maximum

$$\frac{\Delta m^2 L}{4E} = \frac{1}{2}\pi \to L = \frac{2\pi E}{\Delta m^2}$$

Radiative width of excited atoms

We use $\Gamma=\alpha B^2/m_e$

For K-shell $B=(1/2)\alpha^2 m_e Z_2 \text{->} \Gamma_K=(1/4)\alpha^5 m_e Z^4=2.64\text{x}10^{-6}Z^4\text{eV}$

Bransden&Joachain: Eq 9.119: $\Gamma_K=1.73\text{x}10^{-6}Z^{3.93}\text{eV}$

(includes Auger transistions)

Hydrogen 2p->1s

We use $\Gamma=\alpha B^2/m_e$

Bransden&Joachain:

electric dipole transition (E1)

$\Gamma=(4/3)\alpha E_\gamma^3 r^2$

$\Gamma=(2/3)^8 m_e\alpha^5=4.13\text{x}10^{-7}\text{eV}$

mine: $B=1/2\alpha^2 m_e=13.6\text{eV}$ $\Gamma=(1/4)m_e\alpha^5=2.6\text{x}10^{-6}\text{eV}$

continuum cross-sections

$$\sigma_{\bar{\nu}p} = \frac{G_F^2}{\pi} E_\nu^2 \left(g_V^2 + 3g_A^2\right)\left(1 - \frac{\Delta}{E_\nu}\right)\sqrt{1 - 2\frac{\Delta}{E_\nu} + \frac{\Delta^2 - m_e^2}{E_\nu^2}}$$

$$\sigma_{\bar{\nu}e} = \frac{G_F^2}{\pi} 2m_e E_\nu \left(\frac{1}{3}\left(\sin^2\theta_w + \tfrac{1}{2}\right)^2 + \left(\sin^2\theta_w\right)^2\right)$$