Prospects for finding a light Z' in a table top neutrino experiment at ESS

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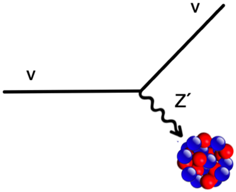
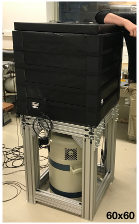
Searching for BSM physics using neutrinos at ESS

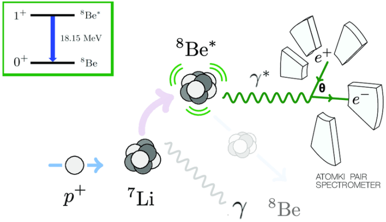


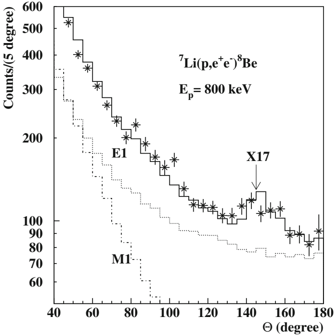
- ESS will not only be the most powerful manmade source of neutrons – but also of neutrinos
- coherent elastic scattering off the whole nucleus – gives up to A^2 enhancement in cross-section
- tabletop detector possible – $\mathcal{O}(10)$ kg
- neutrinos at low energies has very weak interactions – $\mathcal{O}(1)$ deviations still allowed
- plenty of room to search for BSM physics
- requires extremely low threshold to be sensitive – nuclear recoil energies down to $\sim$1 keV



Evidence for the X_{17} – a fifth force

- finding a fifth force would be a major breakthrough in our understanding of the universe
- $p\,^7\mathrm{Li} \to {}^8\mathrm{Be}^* \to {}^8\mathrm{Be}\; e^+e^-$ and $p\,^3\mathrm{H} \to {}^4\mathrm{He}^* \to {}^4\mathrm{He}\; e^+e^-$ data from the Atomki experiment could be explained by a light Z' with a mass of 17 MeV - the X_{17}
- supporting evidence from PADME experiment in $e^+e^- \to Z' \to e^+e^-$
- such a state could be found (or ruled out) in Coherent Elastic neutrino Nucleus Scattering at ESS





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The Z' model

Gauge sector:

- additional $U(1)'$ field which has kinetic mixing with the SM $U(1)_Y$
- there is also mass mixing between the Z and the Z'

Higgs sector:

- additional complex scalar χ which mixes with the SM Higgs field H

Fermion sector:

- SM fermions + three right handed neutrinos
- first two generations get masses from higher dim. operators with χ and H
- $U(1)'$ charges respect anomaly equations

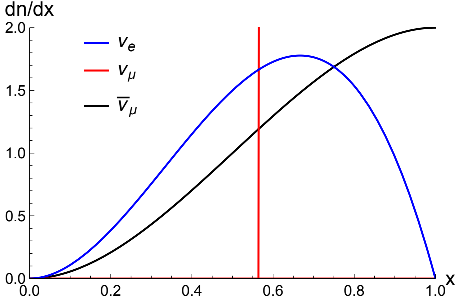
$$\mathcal{L}_{\rm NC}^{\rm Z'} = -\sum_f \bar{\psi}_f(\gamma^\mu C_V^f + \gamma^\mu\gamma^5 C_A^f)\psi_f Z'_\mu$$

axial vector couplings C_A^f constrained to explain X17 data

Neutrino flux from $\pi^+ \to \mu^+\nu_\mu \to e^+\nu_e\bar{\nu}_\mu\nu_\mu$ decay at rest

$$\frac{d\Phi_{\nu_e}}{dx} = \frac{rN_{\mathrm{POT}}}{4\pi L^2} 12x^2(1-x)$$
$$\frac{d\Phi_{\bar{\nu}_\mu}}{dx} = \frac{rN_{\mathrm{POT}}}{4\pi L^2} 2x^2(3-2x)$$
$$\frac{d\Phi_{\nu_\mu}}{dx} = \frac{rN_{\mathrm{POT}}}{4\pi L^2} \delta(x-x_0)$$

- $x = \frac{2E_\nu}{m_\mu}$, $0 < x < 1$
- r nr of π^+ per proton (r =0.08@0.8/0.3@5 MW)
- N_{POT} nr of protons on target
- L distance



$$x_0 = \frac{m_{\pi^+}^2 - m_\mu^2}{m_\mu m_{\pi^+}} \approx 0.564$$

Nuclear recoil spectrum with Z', $y = E_R/E_R^{\max}$

Dominated by vector coupling of nucleus (axial vector coupling $\propto$ nucleus spin)

$$\frac{dN_r}{dy} = \frac{rN_{\rm POT}}{4\pi L^2}\frac{1}{2\pi m_\mu^2}[N-(1-4\sin^2\theta_W)Z]^2\frac{m_{\rm target}}{M_{\rm A}}N_{\rm A}\,[F_V(y)]^2$$
$$\left\{\left(\frac{G_F m_\mu^2}{\sqrt{2}}-\frac{C_{\rm eff}^{\nu_e}}{y+m_{Z'}^2/m_\mu^2}\right)^2\frac{dn_{\nu_e}}{dy}+\left(\frac{G_F m_\mu^2}{\sqrt{2}}-\frac{C_{\rm eff}^{\nu_\mu}}{y+m_{Z'}^2/m_\mu^2}\right)^2\frac{dn_{\nu_\mu}}{dy}\right\}$$

where $G_F m_\mu^2/\sqrt{2} = 9.3\times 10^{-8}$, $m_{Z'}^2/m_\mu^2 = 0.026$ and

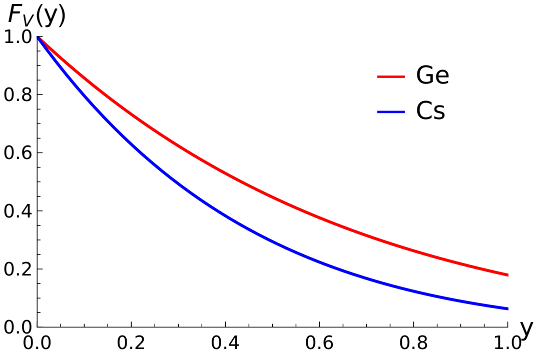
$$C_{\rm eff}^{\nu_{e/\mu}} = C_V^{\nu_{e/\mu}}\frac{N(C_V^u+2C_V^d)+Z(2C_V^u+C_V^d)}{N-(1-4\sin^2\theta_W)Z},$$
$$\frac{dn_{\nu_e}}{dy} = \frac{1}{2}-3y+4y^{3/2}-\frac{3}{2}y^2,$$
$$\frac{dn_{\nu_\mu}}{dy} = \frac{1}{2}-2y+2y^{3/2}-\frac{1}{2}y^2+\left(\frac{1}{2}-\frac{y}{2x_0^2}\right)\Theta\left(1-\frac{y}{x_0^2}\right).$$

Klein Nystrand nuclear form factor

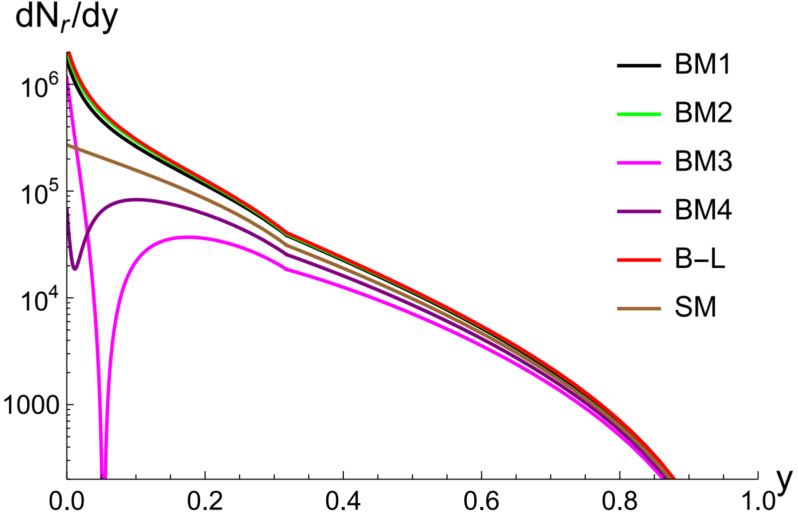
$F_{V,Z}(y)$ and $F_{V,N}(y)$ nuclear form factors for protons and neutrons

$$F_{V,Z}(Q^2) = F_{V,N}(Q^2) = \frac{3}{(QR_A)^3}\left[\sin(QR_A) - QR_A\cos(QR_A)\right]\frac{1}{1+Q^2}$$

$Q^2 = 2ME_{\mathrm{nr}} = ym_\mu^2$, $R_A = 1.2A^{1/3}$ fm, and $a = 0.7$ fm.



Recoil spectra for 20 kg Ge target, L=15 m, 5 years @ 5 MW

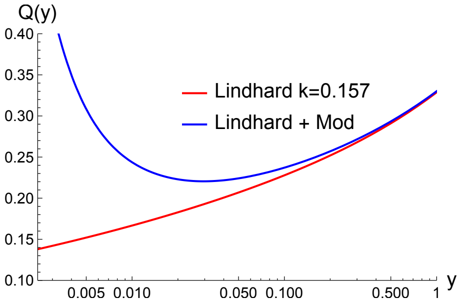


Benchmark points allowed by current data

Quenching factor and detector resolution

Quenching factor:
ionisation energy smaller than recoil energy

$$y_{\text{ion}} = Q(y)y$$

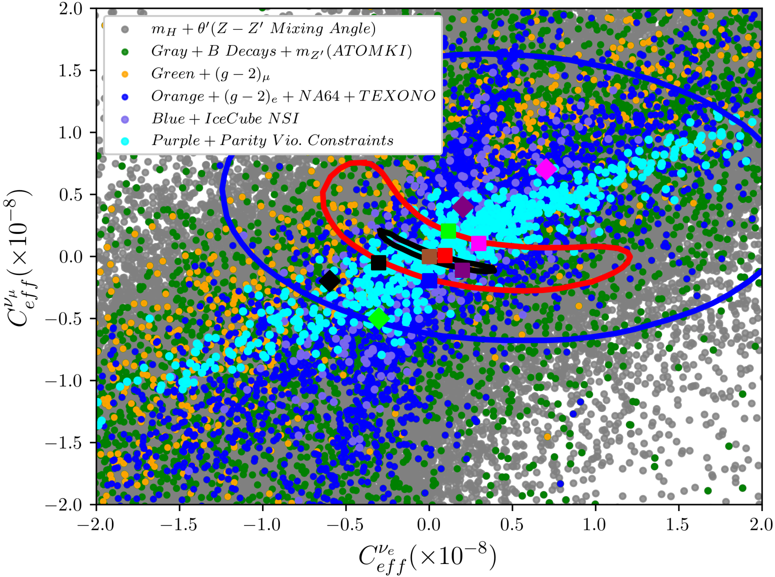


Finite detector resolution gives smearing, $\sigma \sim 0.001$

$$\frac{dN_r}{dy_{\text{rec}}} = \int_{y_{\min}}^{1} \frac{2}{1+\text{Erf}\left(\frac{Q(y)y}{\sqrt{2}\sigma}\right)} \frac{1}{\sqrt{2\pi}\sigma} \exp\left[-\frac{(y_{\text{rec}}-Q(y)y)^2}{2\sigma^2}\right] \frac{dN_r}{dy} dy$$

minimal ionisation energy $y_{\min} = 0.00034$, detector threshold $\Leftrightarrow y > 0.01$

Current and projected (at ESS) 95% exclusion contours for X_{17}



CEνNS limits

blue: current (CsI+Ar)

red: 1 year at 0.8 MW

black: 5 year at 5 MW

(current limits based on Atzori Corona et al (2202.11002))

Conclusions and outlook

CEνNS at spallation sources:

- can search for light Z' such as the X_{17}
- also sensitive to scalar exchanges
- can be used to probe dark matter models

Experimental challenges

- need better understanding of quenching factor at low nuclear recoil energies
- need to better understand neutron background
- need to measure absolute neutrino flux (uncertainty on r)

Other ways to study CEνNS:

- Reactor neutrinos: only $\bar{\nu}_e$ – very high fluxes but lower neutrino energies $\Rightarrow$ (lower)^2 recoil energies – interpretation of data obscured by quenching factor uncertainties
- Solar ^{8}B neutrinos: First evidence seen in dark matter experiments XENONnT and PandaX-4T – ν_e, ν_μ, and ν_τ all contribute – "neutrino floor" can be turned from DM background to BSM signal