Direct Experimental Constraints on the Spatial Extent of a Neutrino Wavepacket from ^{7}Be Electron Capture Decay with the BeEST Experiment

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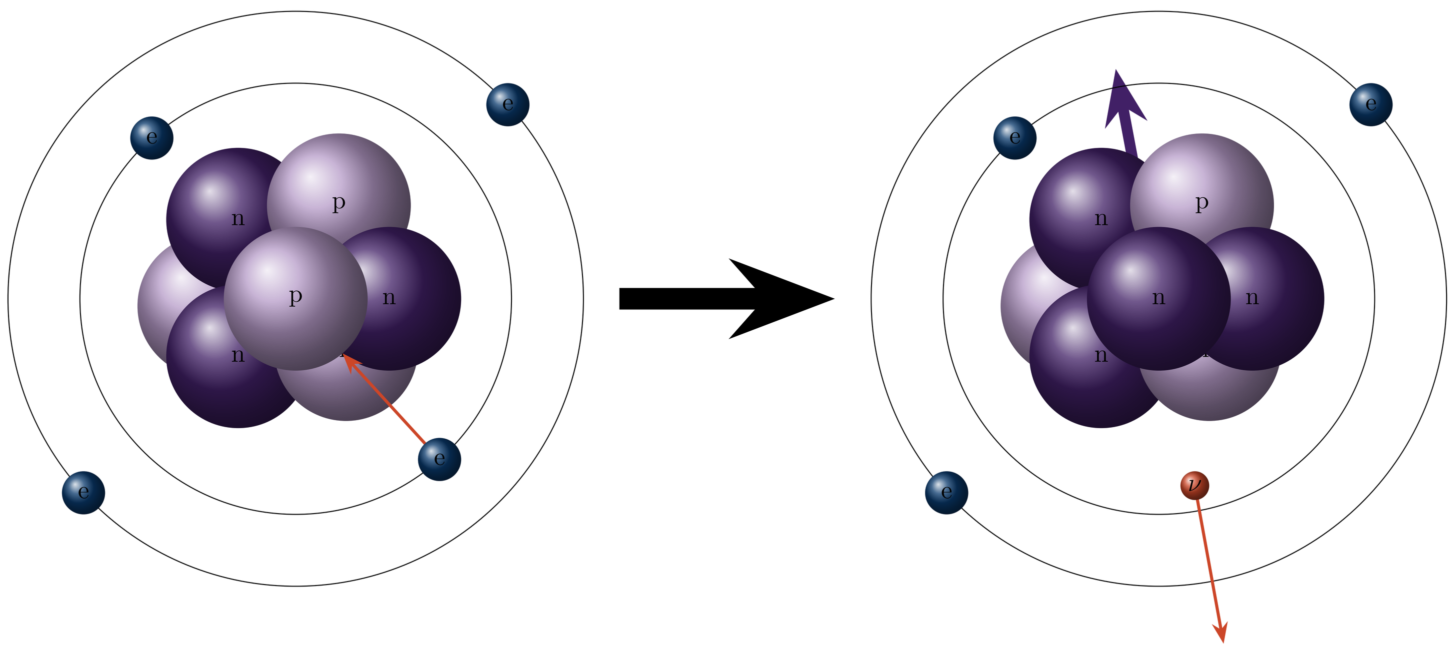
Electron Capture

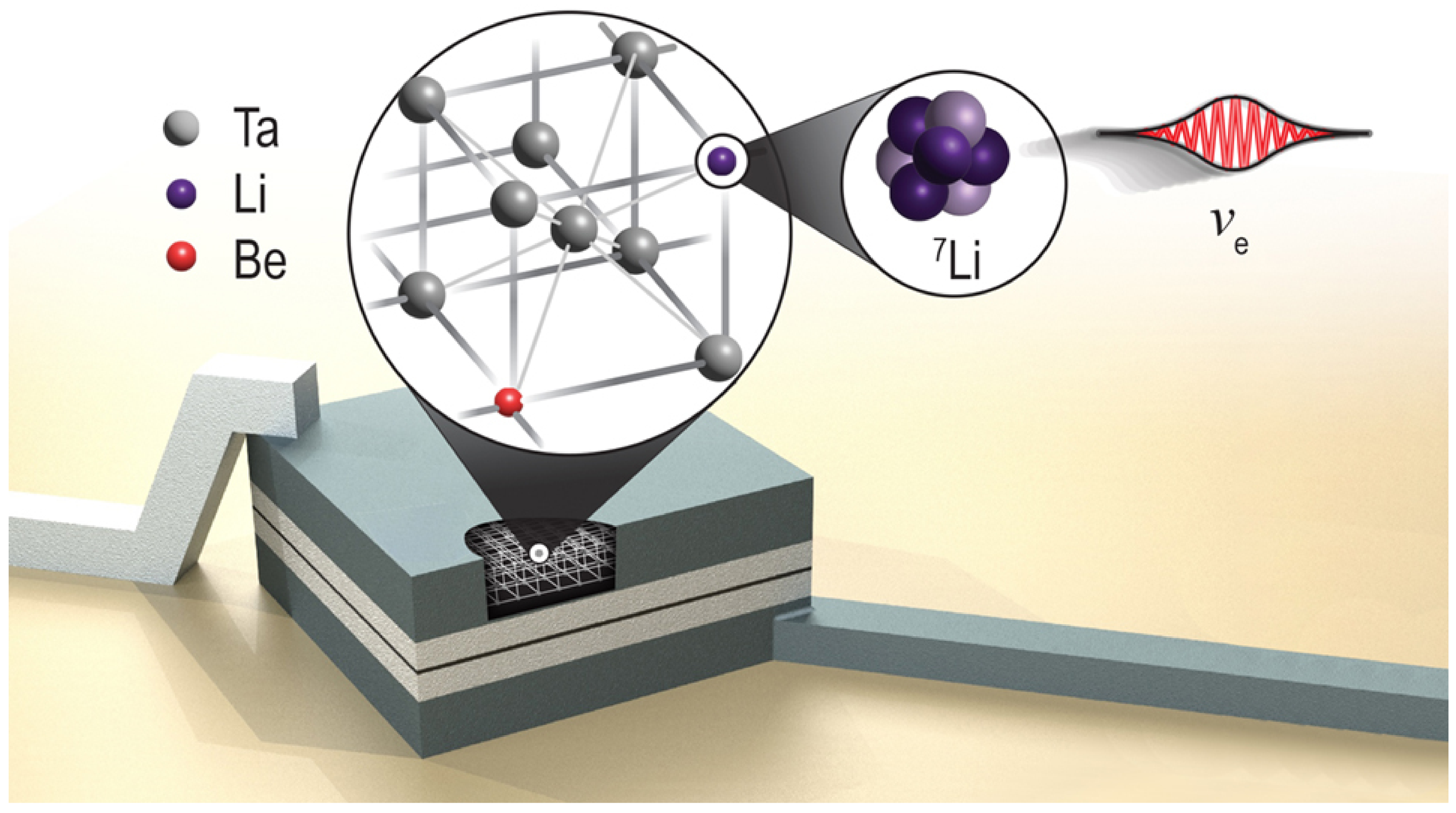
$$^7\text{Be} + e^- \longrightarrow \, ^7\text{Li} + \nu_e$$



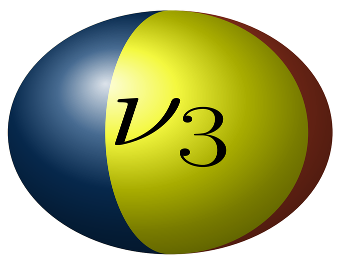
- ^{7}Be is the lightest mass pure electron capture (EC) decaying isotope
- The electron is captured either from 1s (K shell) or 2s (L shell) orbital
- The final state ^{7}Li nucleus can be in the ground state (GS) or an excited state (ES)
- The entangled $^7\text{Li} - \nu_e$ pair share inherent uncertainties in energy and momentum at their creation

The BeEST Experiment

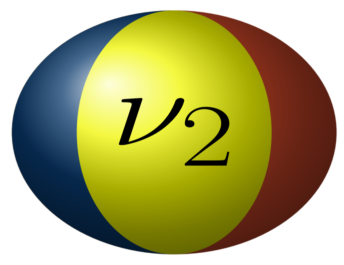
- Superconducting tunnel junctions (STJs) are implanted with ^{7}Be at TRIUMF
- STJs are cooled to ~0.1 K in an adiabatic demagetization refrigerator (ADR) for readout at LLNL
- ^{7}Be EC produces recoiling ^{7}Li which break Cooper pairs and create an energy dependent current
- Precision measurements of ^{7}Li recoil energies are used to study the entangled ν_e

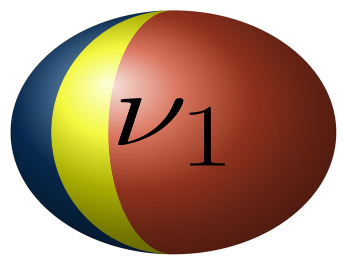


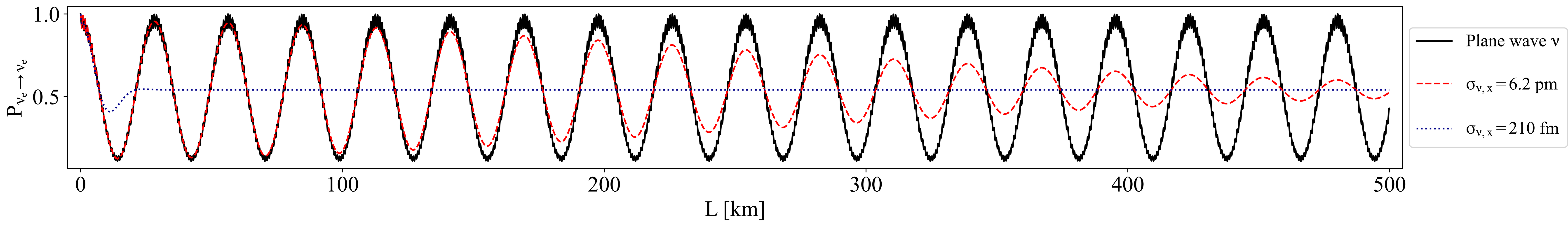
Quantum Uncertainty of Neutrinos



- Uncertainty relations between position and momentum are inherent in quantum measurements: $\sigma_x \sigma_p \geq \hbar/2$
- Environmental interactions serve as measurements of radioactive decay ν sources, resulting in ν with finite widths: $\sigma_{\nu,x}$
- The scale of localizing interactions that set this width is an open question and dampen oscillation probabilities as wavepackets separate
- By measuring ^{7}Li recoil energies from ^{7}Be EC decays in STJs, the BeEST experiment places direct limits on ^{7}Li and ν_e wavepackets







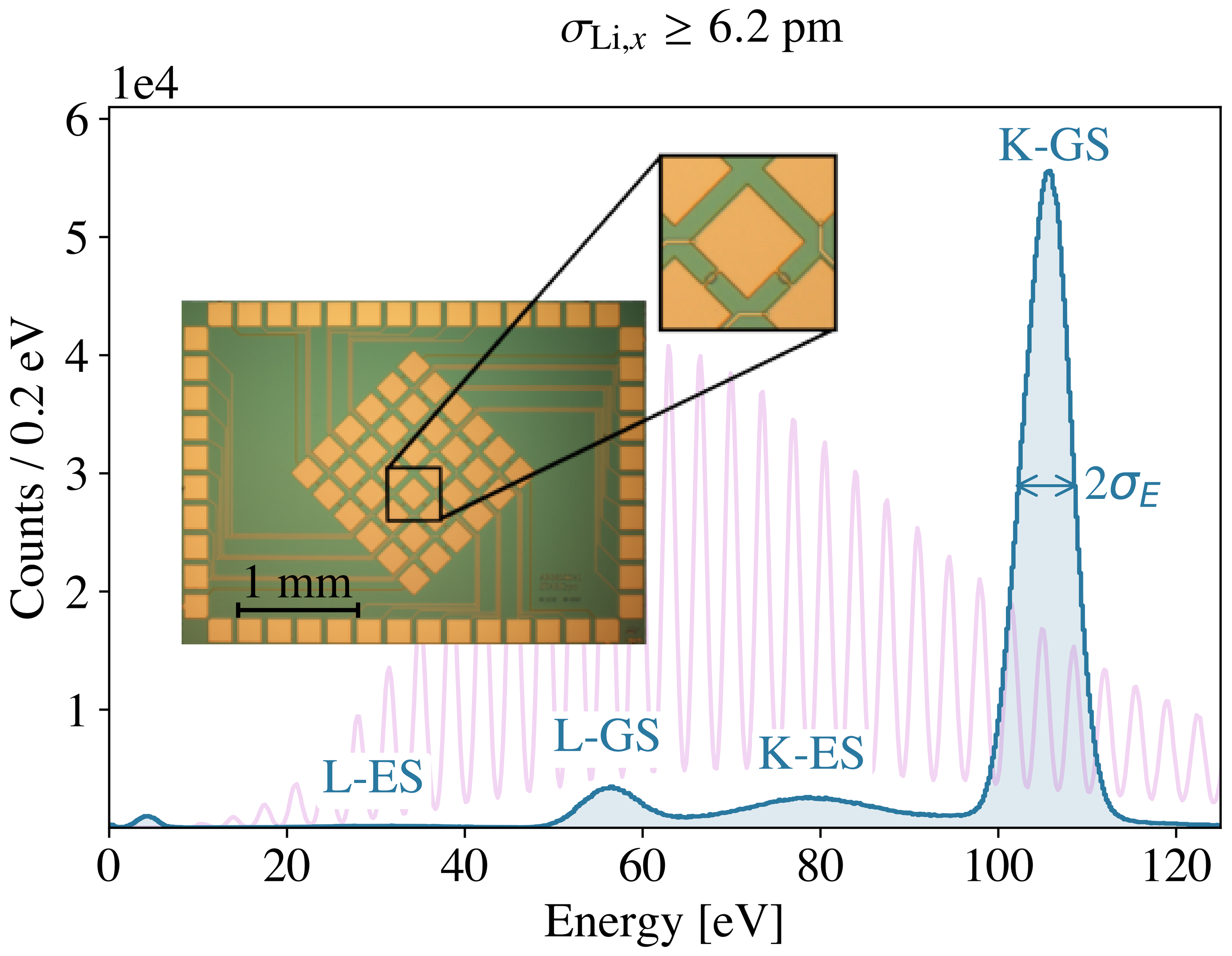
Measurement and Uncertainty

- This analysis uses ~20 hours of data from a single pixel in the 36-pixel array
- The K-GS peak width is conservatively used as an upper limit on quantum uncertainty:

$$\sigma_{\text{Li},E} \leq 2.9 \text{ eV}$$

- From this, we obtain a limit on the spatial width (localization scale) of the Li recoil:

$$\sigma_{\text{Li},x} \geq 6.2 \text{ pm}$$



Extraction of Neutrino Wavepacket Size: Two Theoretical Methods

^{7}Li–ν share energy uncertainty

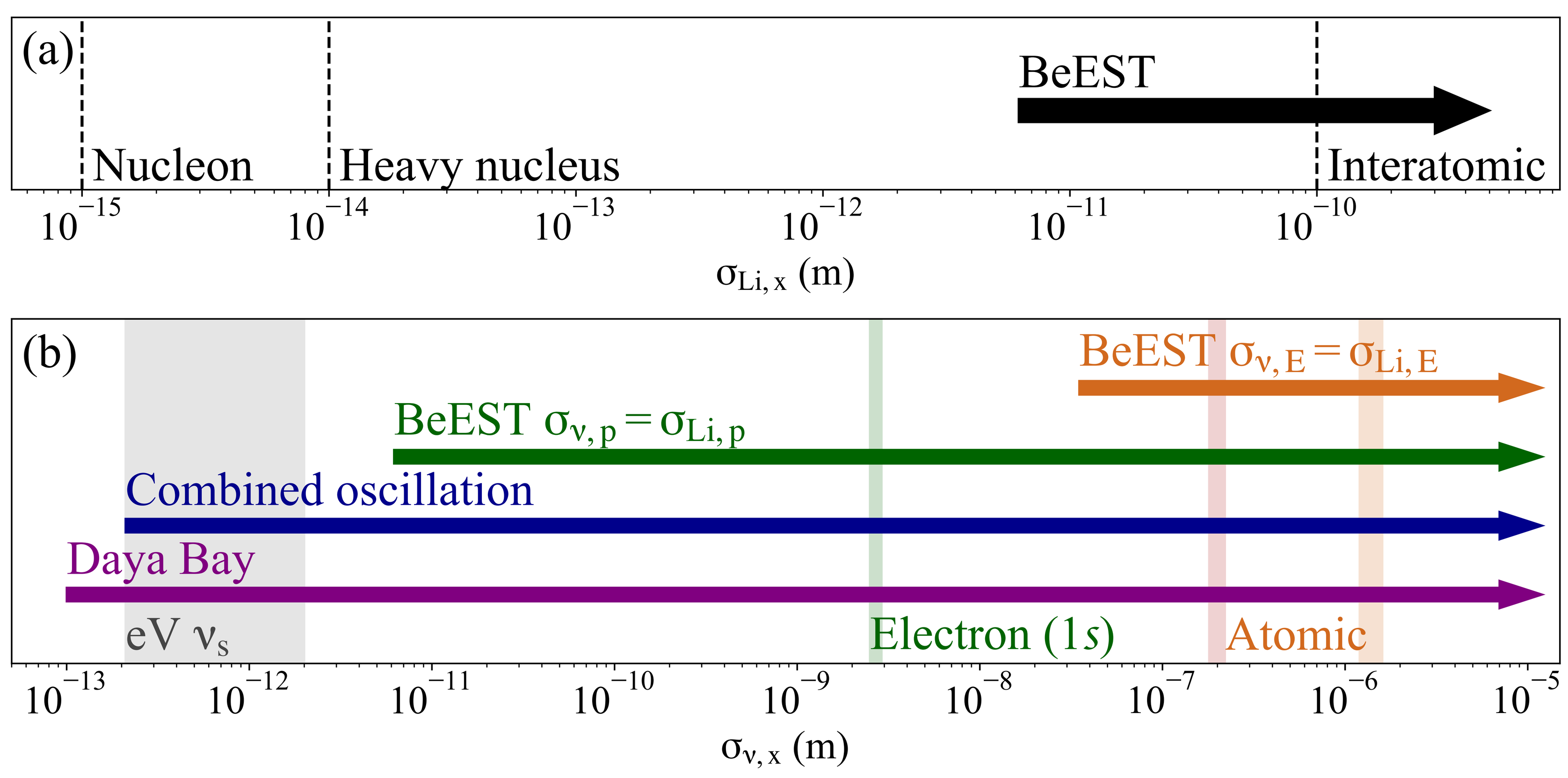
1. $\sigma_{\nu,E} = \sigma_{\text{Li},E}$
2. $\sigma_{\nu,x} \geq \frac{\hbar}{2\sigma_{\nu,p}} = \frac{\hbar c}{2\sigma_{\nu,E}}$

$$\sigma_{\nu,x} \geq 35 \text{ nm}$$

^{7}Li–ν share momentum uncertainty

1. $\sigma_{\text{Li},p} = \sqrt{m/2E}\, \sigma_{\text{Li},E}$
2. $\sigma_{\nu,x} = \sigma_{\text{Li},x} \geq \frac{\hbar}{2\sigma_{\text{Li},p}}$

$$\sigma_{\nu,x} = \sigma_{\text{Li},x} \geq 6.2 \text{ pm}$$



(a) The lower-limit on the spatial width of ^{7}Li produced in ^{7}Be EC decays in STJs, with vertical lines at approximate nuclear and atomic scales for comparison.

(b) Experimental limits on $\sigma_{\nu,x}$ using BeEST [1] and reactor data [2,3]. The 3 vertical bands on the right show predictions based on localization via atomic interactions [4,5] or sub-atomic interactions [6]. The left vertical band shows the range that can improve eV-scale ν_s model fits to data [7,8].

Summary

- New experimental paradigm to measure neutrino properties and the fundamental nature of quantum mechanics at subatomic scales
- The BeEST limit on $\sigma_{\text{Li},x}$ is the first direct limit on the scale of localization in weak decay and ν_e wavepacket size
- The limits on $\sigma_{\nu,x}$ exclude wavepacket separation as the cause of the dampening preferred by eV-scale ν_s fits to data [7,8]

References

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