Project 8: Waveguide CRES Measurements of Tritium Spectrum and ^{83m}Kr Conversion Electrons

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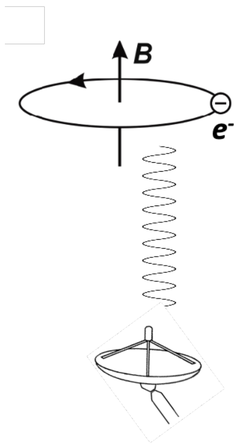
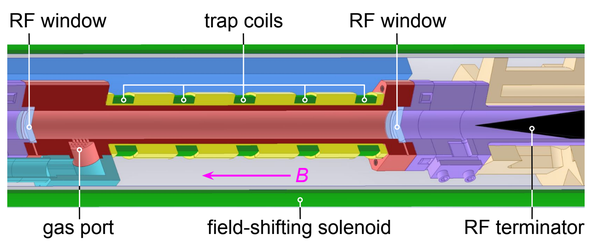
Waveguide CRES Apparatus

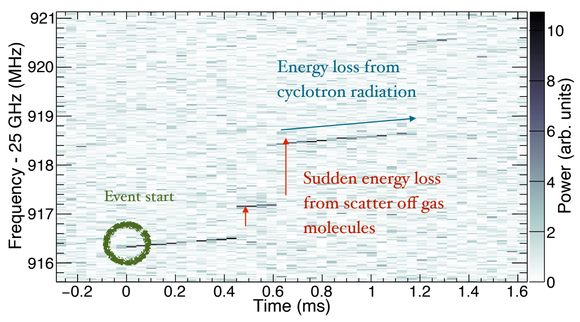
Cyclotron Radiation Emission Spectroscopy (CRES) leverages the relativistic shift in cyclotron frequency to make a frequency-based measurement of electron energy

$$f_c = \frac{f_{c,0}}{\gamma} = \frac{1}{2\pi}\frac{eB}{m_e + E_{\mathrm{kin}}/c^2}$$





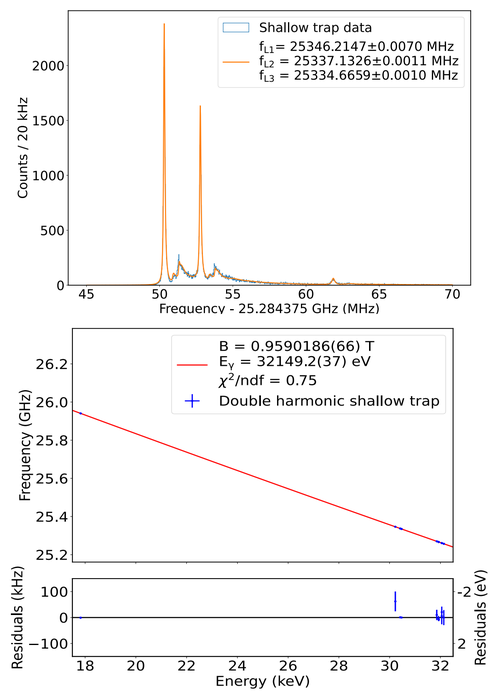
Cutaway of the cryogenic CRES cell, where electrons from radioactive decays are magnetically trapped and measured

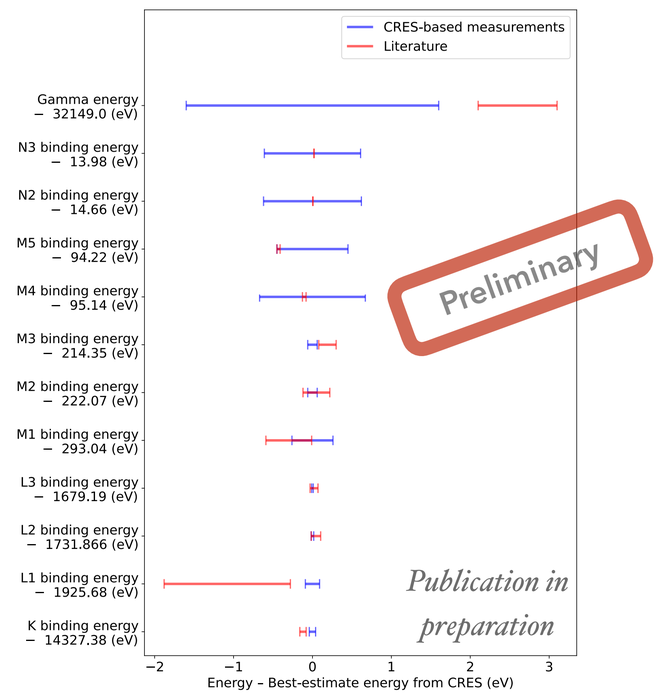


- Magnetically trapped electrons from tritium β-decay or ^{83m}Kr isomeric transitions emit cyclotron radiation signals inside a cell made with cylindrical microwave guide.
- Amplification ⟶ Mixing ⟶ Digitization ⟶ Short-time Fourier transform ⟶ Track identification.
- Event start frequency encodes the detected initial energy of the electrons from decay.

High-Resolution Spectroscopy of ^{83m}Kr Conversion Electrons

High-resolution CRES spectra were recorded of ^{83m}Kr conversion electrons produced in the 32-keV isomeric transitions.

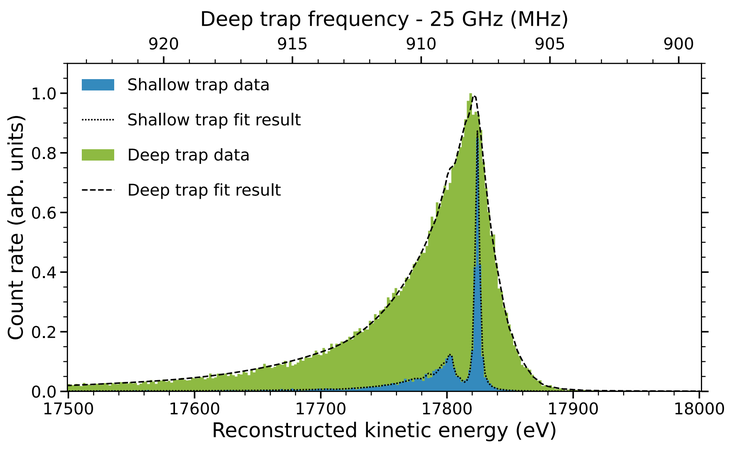




- Frequency positions of the conversion peaks were extracted by combined fit of multiple frequency peaks.
- CRES frequency-energy relation demonstrated over wide energy range.
- Measurements of the 32-keV gamma energy and Kr shell electron binding energies are deduced based on the CRES frequency-energy relation.
- Precision is improved in six Kr shell electron binding energies compared to literature.

Systematics and Detector Effects

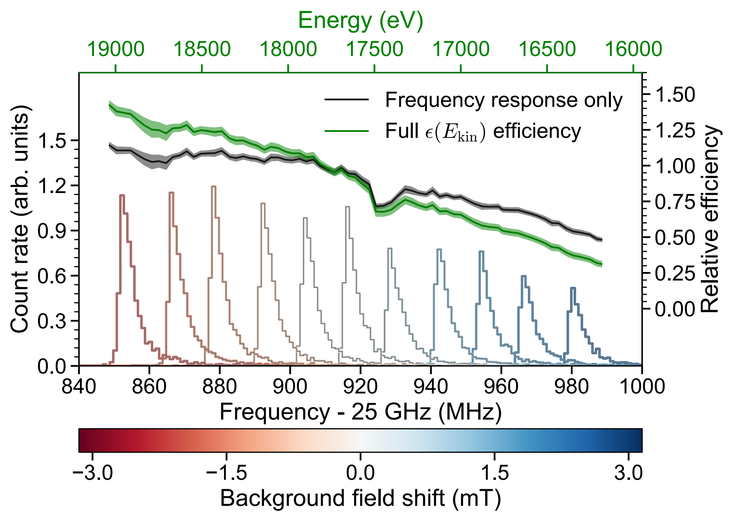
Data and fits of the 17.8 keV ^{83m}Kr conversion electron K-line measured in shallow (high-resolution) and deep (high-statistics) electron trapping configurations.



- The shallow trap exhibits an instrumental resolution of 1.66 ± 0.19 eV.
- The deep trap provides direct calibration of the tritium data-taking conditions.

Frequency-dependent effects studied using the 17.8 keV ^{83m}Kr conversion electron line under varying magnetic background fields.

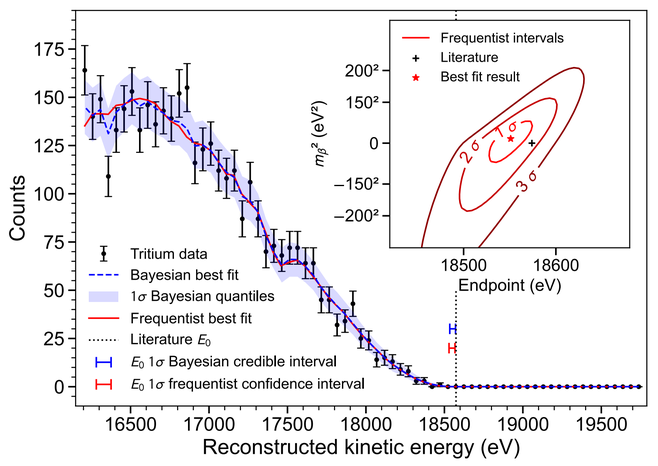
- Gray curve: frequency variation of detection efficiency extracted from data.
- Green curve: corrected analytically for energy dependence of cyclotron radiation power.



Analysis details in Phys. Rev. C **109** (2024) 035503 (also arXiv:2303.12055)

- Editor's Suggestion

First CRES Tritium Spectrum and Neutrino Mass Limit



Results published in Phys. Rev. Lett. **131** (2023) 102502 (also arXiv:2212.05048)

- Editor's Suggestion and featured in APS Physics

- Measured tritium endpoint spectrum with Bayesian and frequentist fits.
- Tritium endpoint results (1 σ): Bayesian 18553^{+18}_{-19} eV, Frequentist 18548^{+19}_{-19} eV.
- Neutrino mass limit (90% CL): Bayesian < 155 eV, Frequentist < 152 eV.
- No events detected above the tritium endpoint ⟶ Background rate: 3×10^{-10}/eV/s (90% CL).

Conclusions

- In Project 8 Phase II, the first CRES tritium β-spectrum was recorded with no background observed beyond the endpoint and an upper limit of 155(152) eV (90% CL) for neutrino mass was reported in a Bayesian (frequentist) analysis.
- Preliminary measurements of the 32-keV gamma energy and Kr shell electron binding energies were obtained based on high-resolution ^{83m}Kr conversion electron spectra. Six binding energies having improved precision compared with literature values.
- This work paves the way for future CRES neutrino mass measurement and ^{83m}Kr conversion electron spectroscopy.

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