Project 8: Single electron spectroscopy with relativistic cyclotron radiation

Martin Fertl

Center for Experimental Nuclear Physics and Astrophysics
University of Washington

On behalf of the Project 8 collaboration

August 25, 2014

CENPA
Center for Experimental Nuclear Physics and Astrophysics

Thanks...

... to the organizers of PANIC 2014 for the invitation to talk about Project 8.

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... to Janet and Alex for rescheduling this session on short notice (last Friday night, Boston time).

Janet's talk will be tomorrow, Tuesday, 15.30, same location!, Main Building, Hörsaal M

Overview

The Project 8 collaboration

http://project8.github.io

D. M. Asner, J. L. Fernandes, E. C. Finn, A. M. Jones, J. R. Tedeschi, B. A. VanDevender
Pacific Northwest National Laboratory, Richland, WA

P. J. Doe, M. Fertl, J. N. Kofron, E. L. McBride, M. L. Miller, R. G. H. Robertson, L. J. Rosenberg, G. Rybka, M. G. Sternberg, N. L. Woods
University of Washington, Seattle, WA

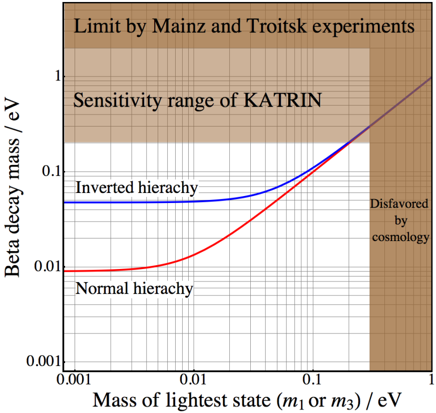
L. de Viveiros, B. H. LaRoque, M. Leber, B. Monreal
University of California, Santa Barbara, CA

J. A. Formaggio, D. Furse, P. Mohanmurthy, N. S. Oblath, D. Rysewyk
Massachusetts Institute of Technology, Cambridge, MA

R. Bradley
National Radio Astronomy Observatory, Green Bank, WV

T. Thümmler
Karlsruher Institut für Technologie, Karlsruhe, Germany

Motivation



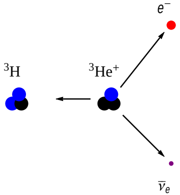
Unknown neutrino masses:

lower bound:

neutrino oscillations

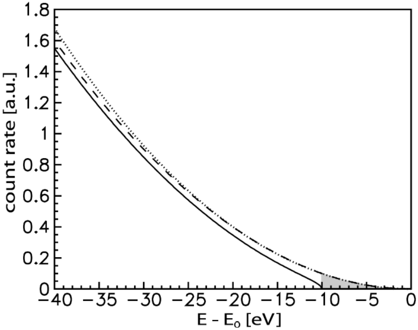
upper bound:

tritium decay



Motivation

Modification of β decay spectrum by a finite neutrino mass



Fraction of e^- in ROI for $^3\mathrm{H}$:

10 eV: 2×10^{-10}

1 eV: 2×10^{-13}

Need high count rate, high resolution measurement

Kraus *et al.* Eur. Phys. J. C **40**, 447, 2005

Motivation

Depending on the result of the KATRIN experiment we want to

- establish a precision confirmation measurement with different systematic effects.
- or provide a technique that can be scaled beyond MAC-E-type spectrometer sensitivity.

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- establish a precision confirmation measurement with different systematic effects.
- or provide a technique that can be scaled beyond MAC-E-type spectrometer sensitivity.

Both goals requires a new approach:

"Never measure anything but frequency" A. Schawlow

Most precisely measured quantities are all derived from frequency measurements (R_∞, $(g-2)$,...).

The cyclotron frequency

Determine the neutrino mass from the shape of the tritium β-decay spectrum at the maximum kinetic energy of the electron.

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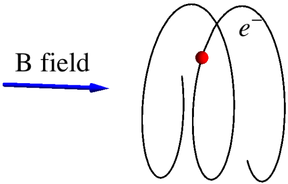
Cyclotron motion:

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

$$f_c = 27\,992.491\,10(6)\,\mathrm{MHz\,T^{-1}}$$



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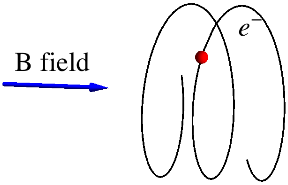

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Constant f_γ for $\gamma \approx 1$

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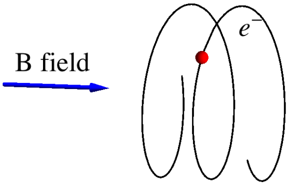
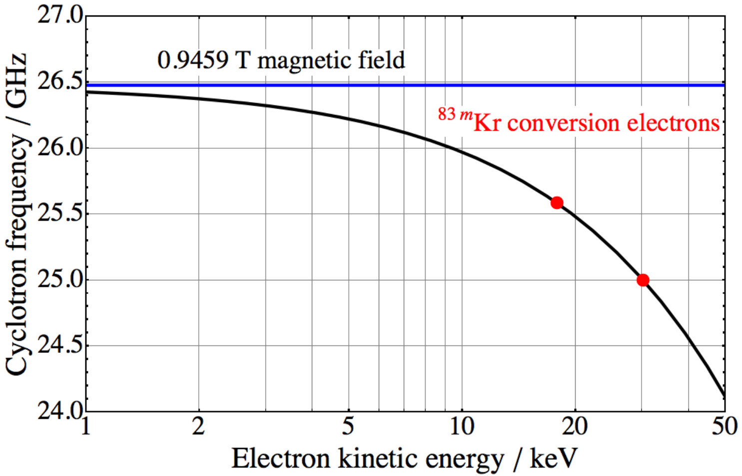


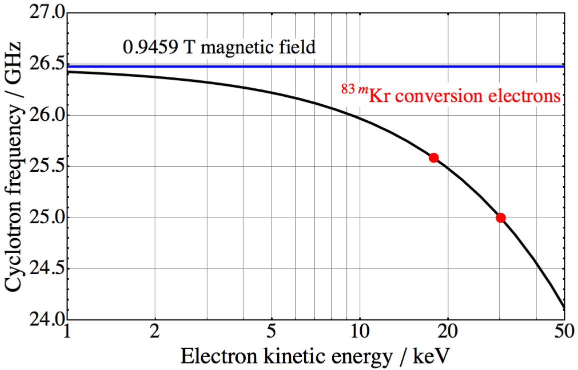
$f_\mathrm{c} = 27\,992.491\,10(6)\,\mathrm{MHz\,T^{-1}}$

Constant f_γ for $\gamma \approx 1$, but depends on the kinetic energy.

The cyclotron frequency



The cyclotron frequency



For future reference: $B = 0.9459\,\mathrm{T}$

$\Delta f_\gamma = 891\,\mathrm{MHz}$ for $17.8\,\mathrm{keV}\ e^-$ $\Delta f_\gamma = 1477\,\mathrm{MHz}$ for $30.2\,\mathrm{keV}\ e^-$

The cyclotron radiation

Proposal of a new spectroscopy technique:

Measure cyclotron radiation emission as a precise measure of the kinetic energy of single electrons!

Formaggio and Monreal, Phys. Rev. D **80**, 051301(R), 2009

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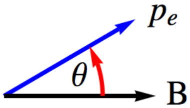
Larmor formula for emitted power

$$P(\gamma,\theta) = \frac{1}{4\pi\epsilon_0}\frac{2}{3}\frac{e^4}{m_\mathrm{e}^2 c}B^2\left(\gamma^2-1\right)\sin^2\theta,$$



with $\gamma = \left(1+\frac{E_\mathrm{kin}}{m_\mathrm{e} c^2}\right)$ and θ the pitch angle.

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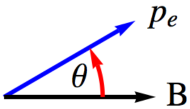


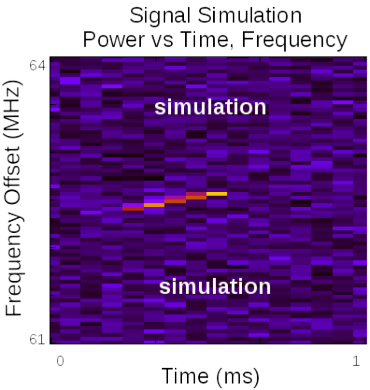
with $\gamma = \left(1+\frac{E_{\mathrm{kin}}}{m_{\mathrm{e}}c^2}\right)$ and θ the pitch angle.

$P(90^\circ) = 1.0\,\mathrm{fW}$ for $17.8\,\mathrm{keV}$ e^-

$P(90^\circ) = 1.7\,\mathrm{fW}$ for $30.2\,\mathrm{keV}$ e^-

A simulated signal

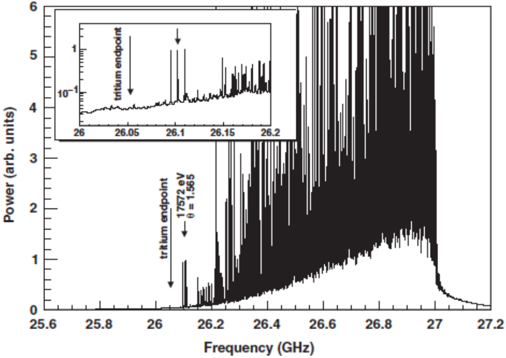
What would a electron signal look like?



In time-frequency space:

- Sudden onset of narrow band microwave power.
- Slowly rising frequency due to radiation losses.
- Ends after collision with rest gas.

A simulated tritium spectrum



Formaggio and Monreal, Phys. Rev. D **80**, 051301(R), 2009

Frequency resolution

Energy resolution connected to the frequency resolution via cyclotron frequency:

$$\frac{\Delta E_{\mathrm{kin}}}{E_{\mathrm{kin}}} = \left(1 + \frac{m_{\mathrm{e}} c^2}{E_{\mathrm{kin}}}\right) \frac{\Delta \nu_{\mathrm{c}}}{\nu_{\mathrm{c}}}$$

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$\Delta E_{\mathrm{kin}} \approx 0.2\,\mathrm{eV} \rightarrow \frac{\Delta \nu_{\mathrm{c}}}{\nu_{\mathrm{c}}} \approx 4 \times 10^{-7}$
$\nu_{\mathrm{c}} \approx 27\,\mathrm{GHz} \rightarrow \Delta \nu_{\mathrm{c}} \approx 10\,\mathrm{kHz}$

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$\Delta \nu_{\mathrm{c}} \times \Delta t_{\mathrm{obs}} \gtrapprox \frac{1}{2\pi} \rightarrow \Delta t_{\mathrm{obs}} > 16\,\mu\mathrm{s}$
But for a $\theta = 89°$ pitch angle

$$\beta t_{\mathrm{obs}} \cos\theta = 22\,\mathrm{m} \quad \text{for a } 17.8\,\mathrm{keV} \text{ electron}$$

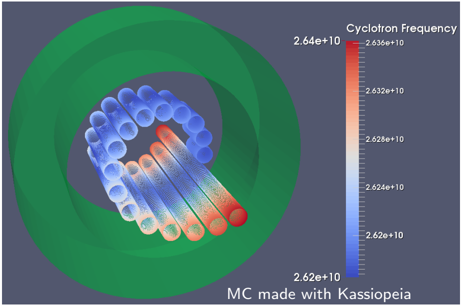
The magnetic trap

Need a magnetic trap!

The magnetic trap

Introduce a harmonic magnetic trap in the main field
→ Magnetic bottle (up to $-8.5\,\mathrm{mT}$):

$$\sin\theta_{\min} = \sqrt{\frac{B_{\min}}{B_{\max}}} \rightarrow \theta_{\min} = 85^\circ$$



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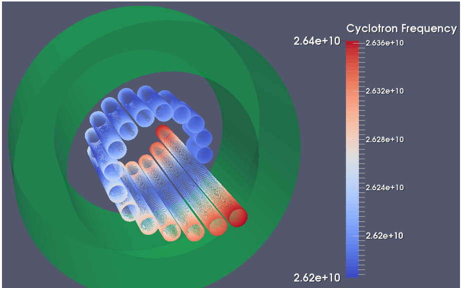

MC made with Kassiopeia

Pitch angle dependence:

$$f_\gamma(\theta, \gamma) \approx \frac{f_c}{\gamma}\left(1 + \frac{\cos^2\theta}{2\sin^2\theta}\right)$$

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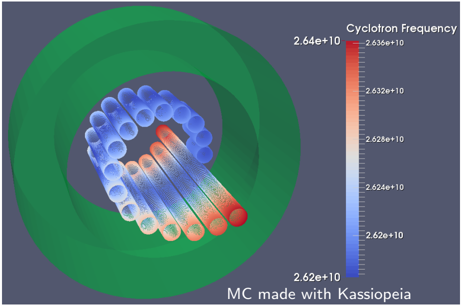
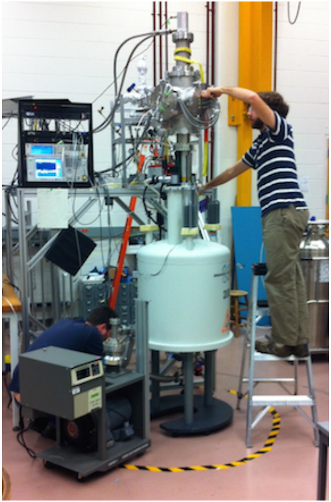


Pitch angle dependence:

$$f_\gamma(\theta,\gamma) \approx \frac{f_c}{\gamma}\left(1 + \frac{\cos^2\theta}{2\sin^2\theta}\right)$$

Trapping potential will dominate frequency distribution.

The apparatus: the outside



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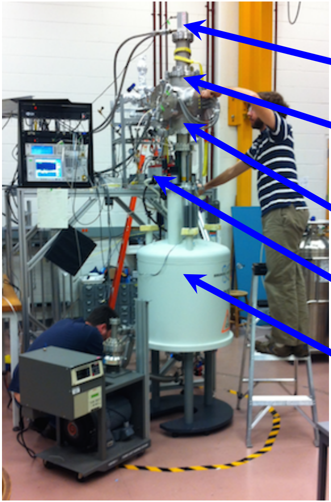


50 K cold head

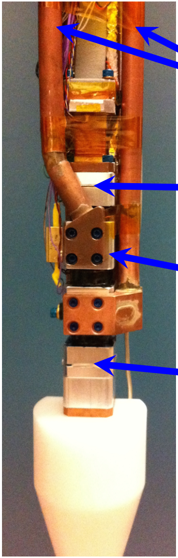
Cryogenic low-noise microwave amplifiers

Isolation vacuum system

$^{83}\mathrm{Rb}/^{83\mathrm{m}}\mathrm{Kr}$ gas system

superconducting magnet
1 T, 52 mm warm bore

The apparatus: the inside



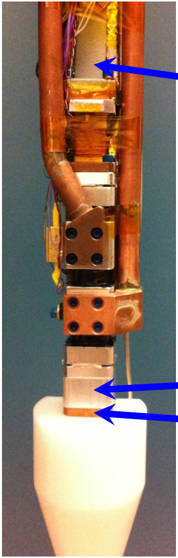
$^{83m}\mathrm{Kr}$ supply lines

Upper kapton window

Gas volume

Lower kapton window

The apparatus: the inside

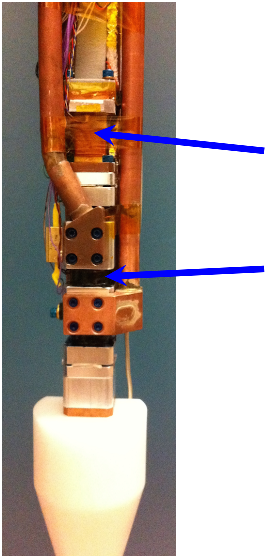


WR42 wave guide

Tickler port

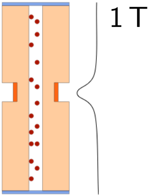
Waveguide short

The apparatus: the inside



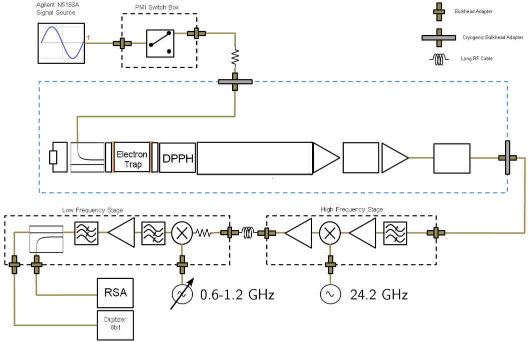
ESR magnetic field measurement (DPPH)

Harmonic trap coil



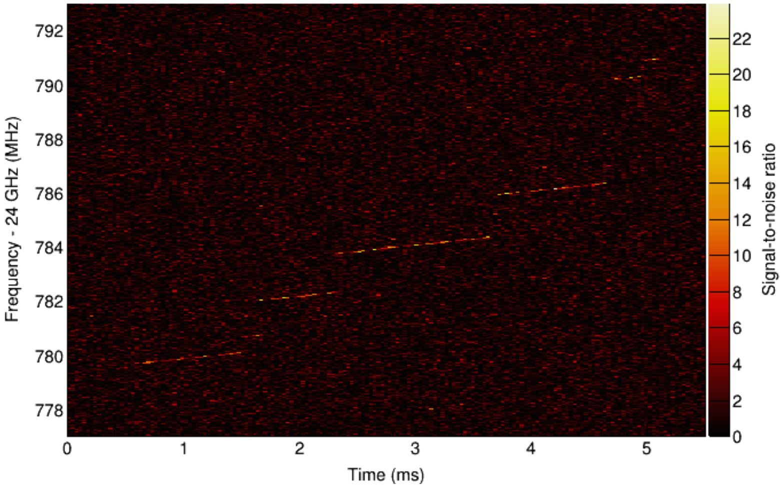
The microwave detector

- Cryogenic preamplifiers
- Double stage frequency mixing (24.2 GHz, 0.6 GHz to 1.2 GHz.)



The first light

First observation of single electron cyclotron radiation
arxiv: 1408.5362



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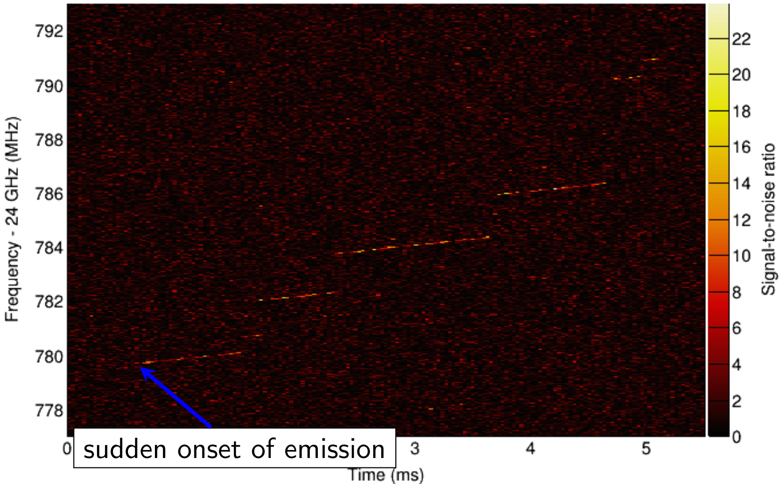

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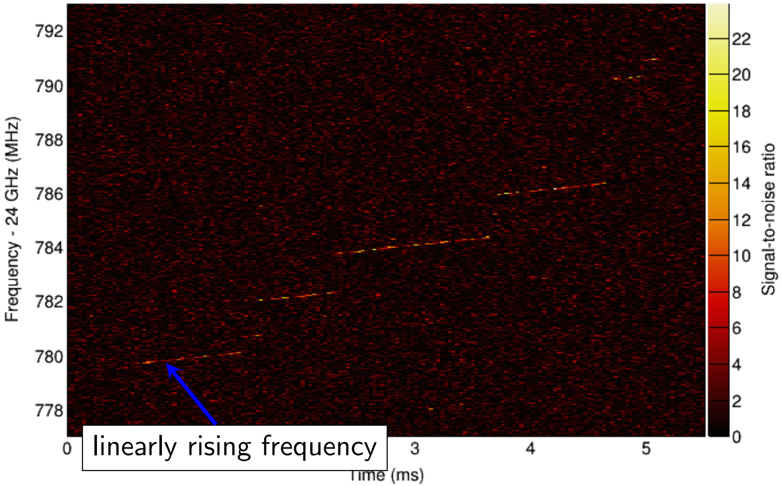

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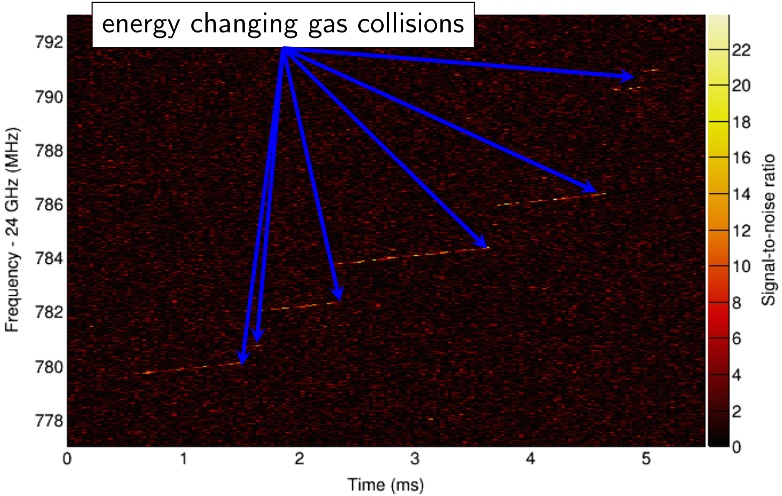
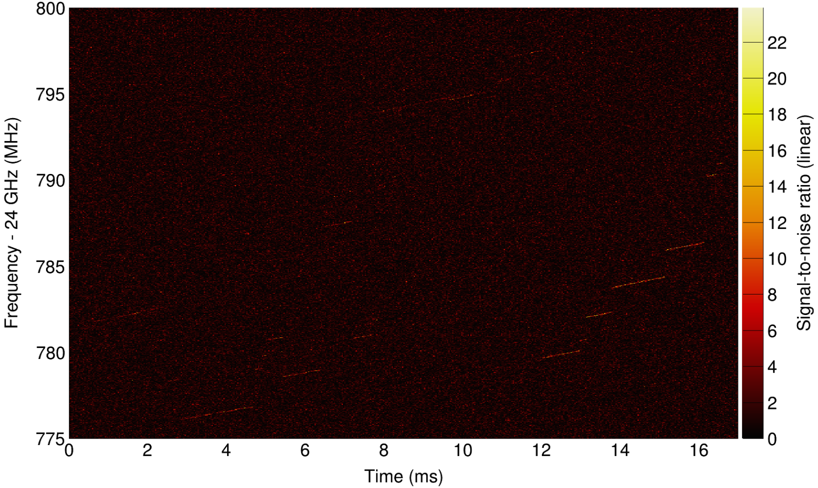


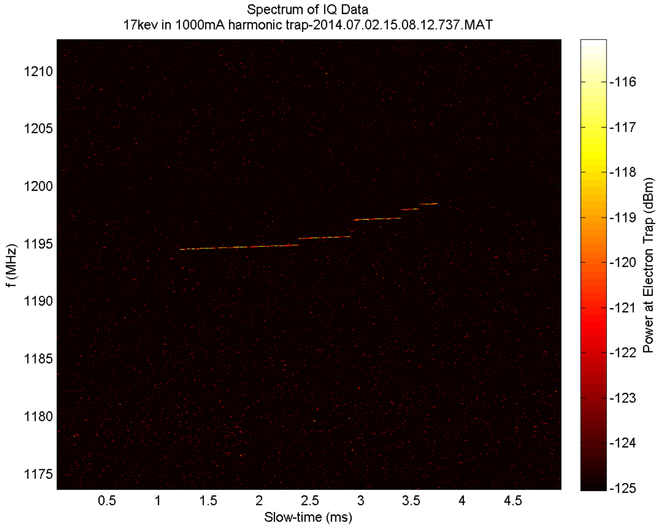
The first light

Many more well defined tracks in this 30 keV dataset:



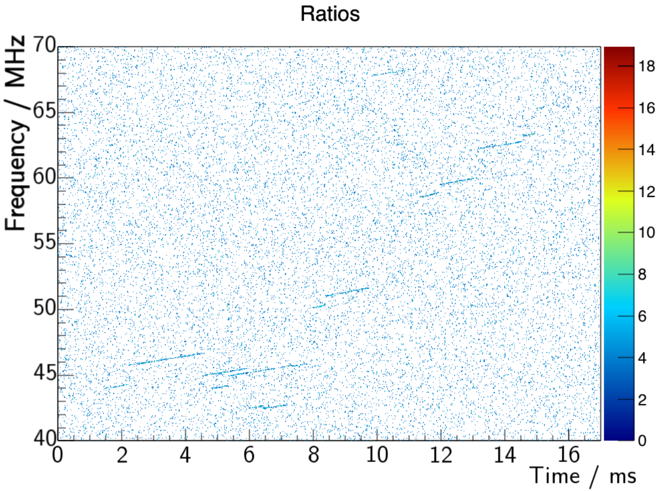
The first light

A 17 keV electron scatters in the trap.



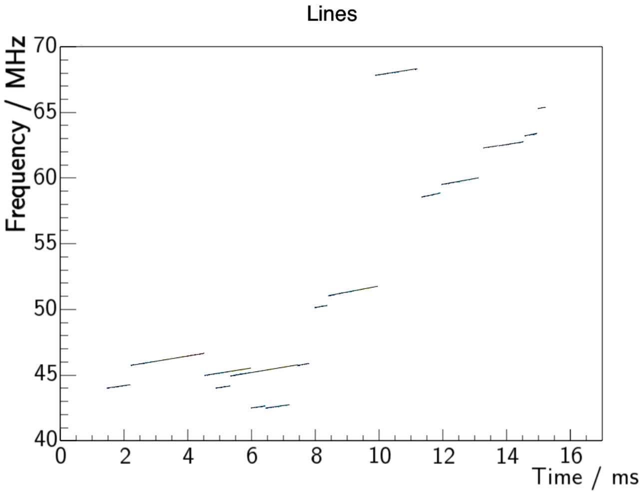
The analysis procedure

Short Time Fourier Transform (32.8 μs,30.52 kHz),
Power cut 8.12 dB above noise floor



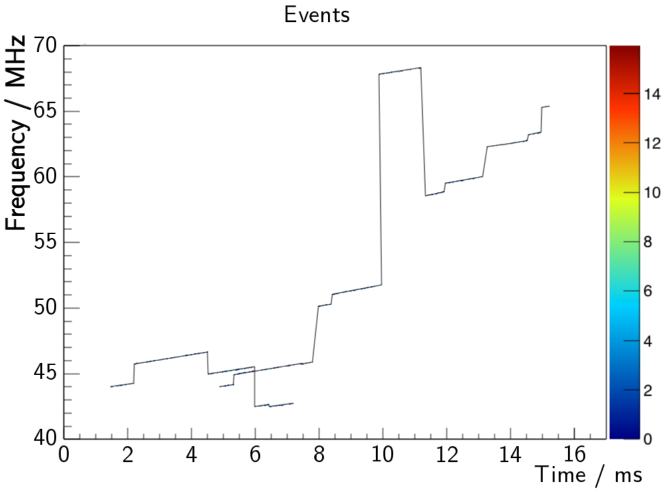
The analysis procedure

Identify short linear tracks in time-frequency plane:



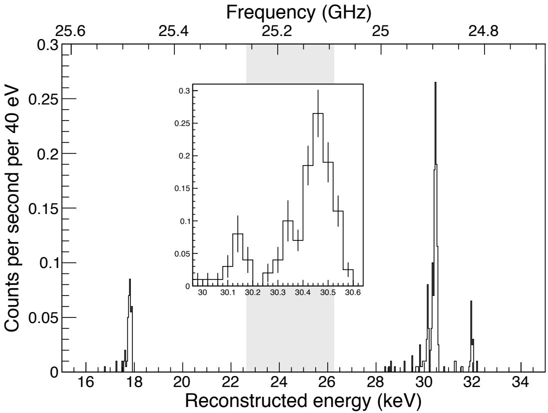
The analysis procedure

Group the short tracks to electron tracks:

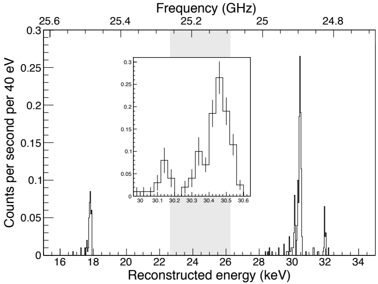


Cyclotron Radiation Emission Spectroscopy

Cyclotron Radiation Emission Spectroscopy (CRES) with ^{83m}Kr



Cyclotron Radiation Emission Spectroscopy Details



Applied data cuts:

- Event within digitizer band-width.
- Event longer than 0.5 ms.

Weighted peak frequency ratio:

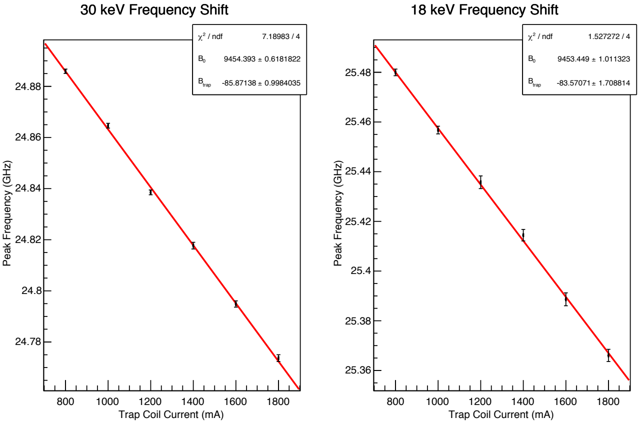
- 1.023 870(60) measured
- 1.023 875(2) expected

FWHM (skewed Gaussian)

- 130 eV for 17.8 keV e^-
- 140 eV for 30 keV e^-

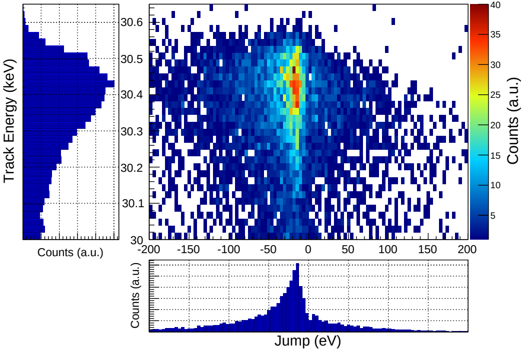
The magnetic trapping field

Influence of the trapping field: linear shift of peak frequency



The jump size distribution

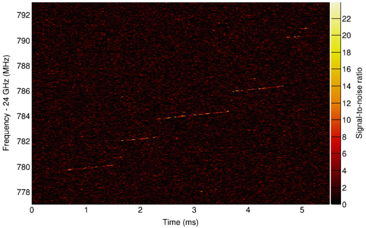
Extract the frequency shift for each scattering event e.g. 30 keV

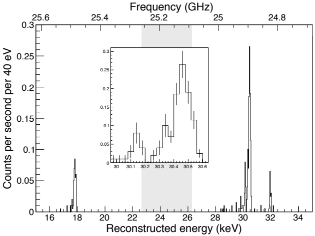


Jump size peaks around 14 eV.

Summary

- Successfully detected single electron cyclotron radiation.
- Cyclotron Radiation Emission Spectroscopy provides a new spectroscopy technique based on frequency.
- First step towards a frequency based measurement of the neutrino mass.





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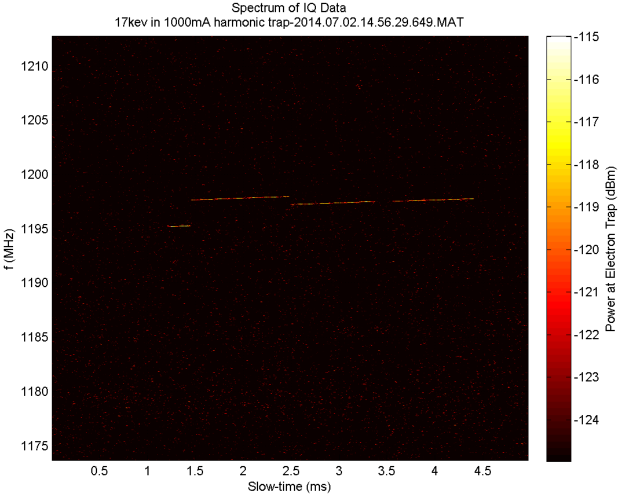
Funding agencies

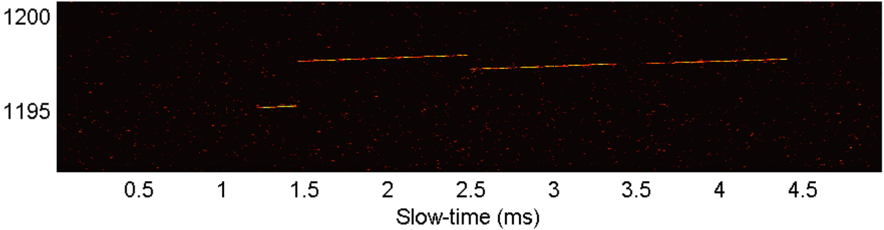
The Project 8 collaboration is supported by:

- U.S. Department of Energy, Office of Science, Office of Nuclear Physics
- National Science Foundation
- Institutional Computing at Pacific Northwest National Laboratory
- University of Washington Royalty Research Foundation
- Massachusetts Institute of Technology Wade Fellowship
- Laboratory Directed Research and Development Program at Pacific Northwest National Laboratory

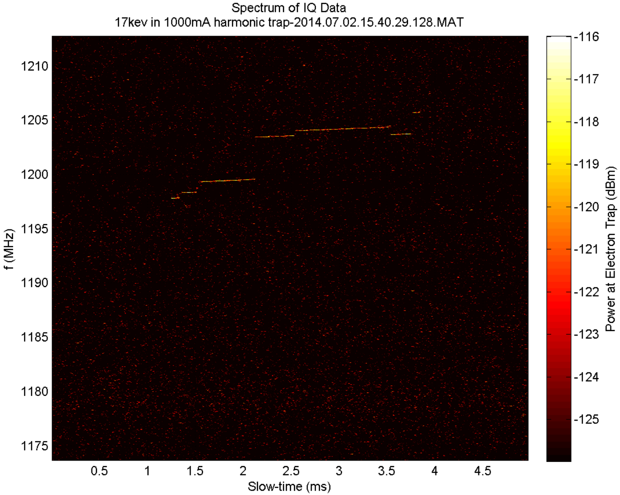
More events


Spectrum of IQ Data
17kev in 1000mA harmonic trap-2014.07.02.14.56.29.649.MAT
f (MHz)
1210
1205
1200
1195
1190
1185
1180
1175
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Slow-time (ms)
-115
-116
-117
-118
-119
-120
-121
-122
-123
-124
Power at Electron Trap (dBm)

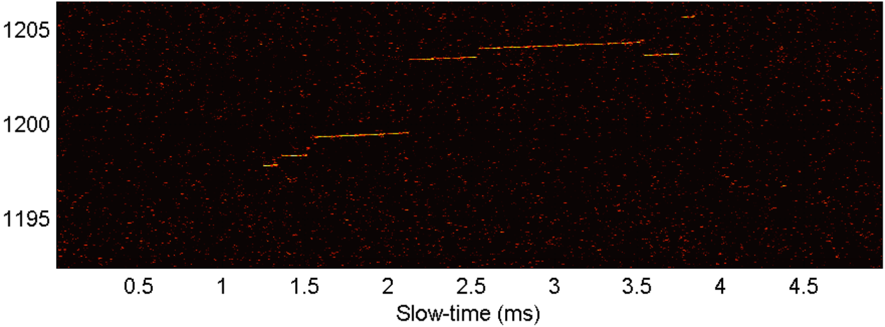
More events



More events


Spectrum of IQ Data
17kev in 1000mA harmonic trap-2014.07.02.15.40.29.128.MAT
f (MHz)
1210
1205
1200
1195
1190
1185
1180
1175
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Slow-time (ms)
-116
-117
-118
-119
-120
-121
-122
-123
-124
-125
Power at Electron Trap (dBm)

More events



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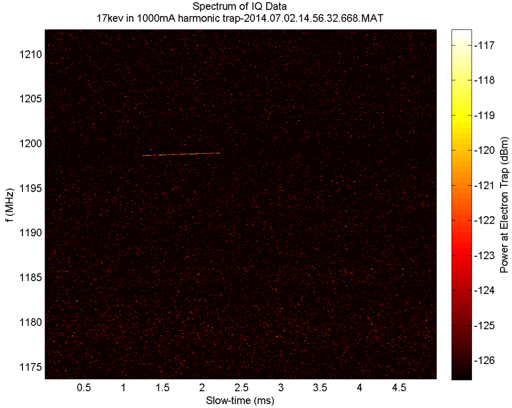
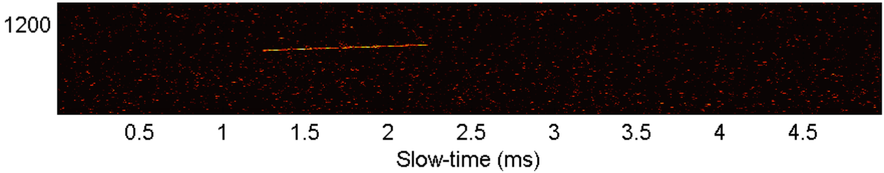
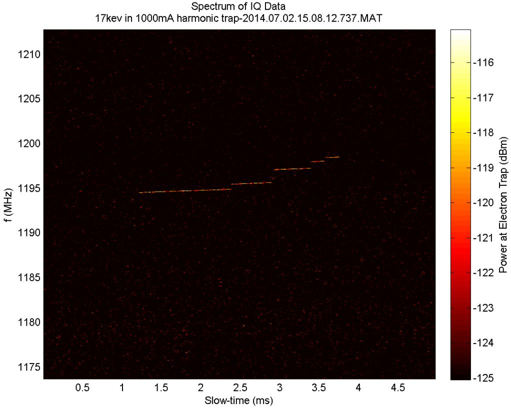

Spectrum of IQ Data
17kev in 1000mA harmonic trap-2014.07.02.14.56.32.668.MAT
f (MHz)
1210
1205
1200
1195
1190
1185
1180
1175
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Slow-time (ms)
-117
-118
-119
-120
-121
-122
-123
-124
-125
-126
Power at Electron Trap (dBm)

More events



More events


Spectrum of IQ Data
17kev in 1000mA harmonic trap-2014.07.02.15.08.12.737.MAT
f (MHz)
1210
1205
1200
1195
1190
1185
1180
1175
0.5
1
1.5
2
2.5
3
3.5
4
4.5
Slow-time (ms)
-116
-117
-118
-119
-120
-121
-122
-123
-124
-125
Power at Electron Trap (dBm)