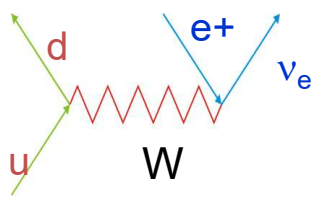
Using Cyclotron Radiation Spectroscopy to search for chirality-flipping interactions

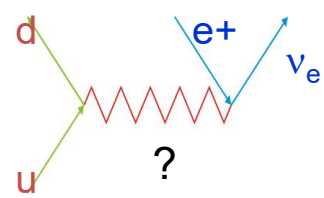
Alejandro Garcia
University of Washington

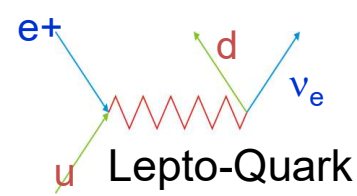
Chirality-flipping interactions

Are nuclear weak decays carried only by W's (chirality conserving)?



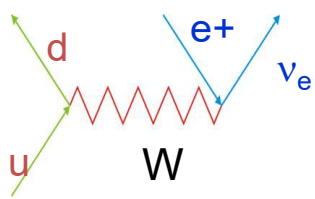
Or chirality-flipping interactions?



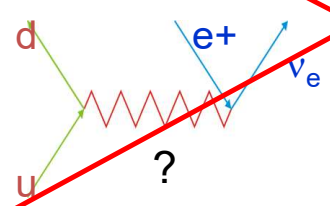


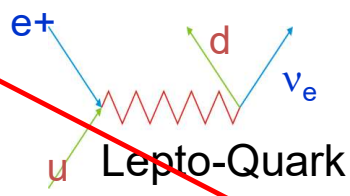
Chirality-flipping interactions

Are nuclear weak decays carried only by W's?



Or chirality-flipping interactions?





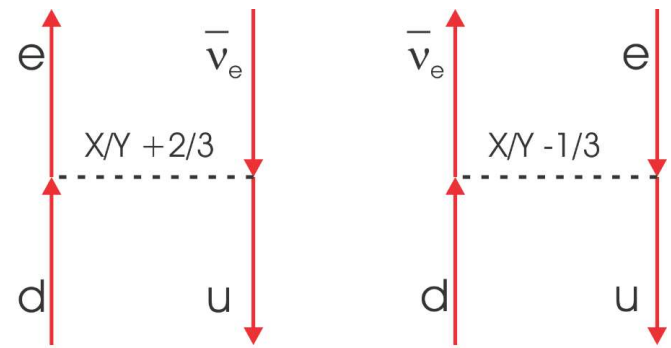
Question resolved in the late 1950's in favor of "No chirality flipping"

For nuclear beta decay:
all leptons purely left handed

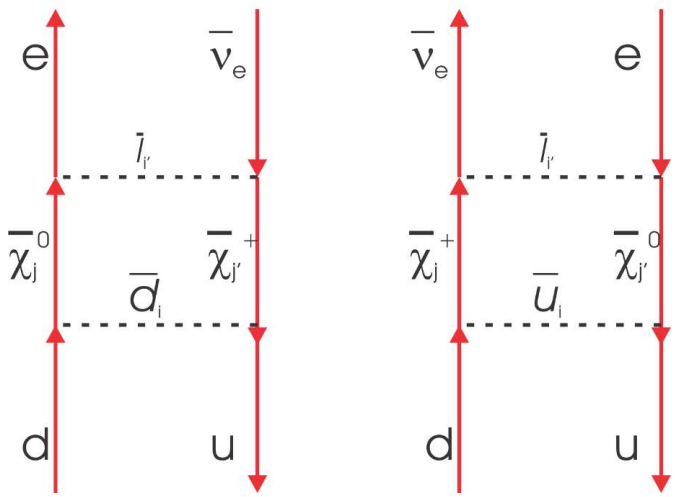
$$H = \begin{matrix} \overline{\Psi}_f \gamma^\mu \Psi_i & 2C_V \, \overline{e}^L \gamma_\mu \nu_e^L + \\ \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_i & 2C_A \, \overline{e}^L \gamma_\mu \gamma_5 \nu_e^L \end{matrix}$$

Question coming back in searching for physics beyond the Standard Model

Small contribution that could be detected with precision experiments?



Leptoquarks:
X: scalar; Y: Vector
Predicted by
Grand Unified Theories



Predicted by
Supersymmetric Theories

(with squarks, sleptons, and other supersymmetric *sparticles soverlined*) ☺

Chirality-flipping interactions to shine path beyond Standard Model?

$$H = \overline{\Psi}_f \gamma^\mu \gamma_5 \Psi_i \quad 2C_A \overline{e}^L \gamma_\mu \gamma_5 \nu_e^L +$$

Standard Model: only axial current shown

$$\overline{\Psi}_f \sigma^{\mu\nu} \Psi_i \quad \left[(C_T - C_T^{'}) \overline{e}^L \sigma_{\mu\nu} \nu_e^R + (C_T + C_T^{'}) \overline{e}^R \sigma_{\mu\nu} \nu_e^L \right]$$

New physics: tensor currents "chirality flipping".

Decay rate:

$$dw = dw_0 \left[1 + a \frac{\overrightarrow{p_e}}{E_e} \cdot \frac{\overrightarrow{p_\nu}}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right]$$

$$b \approx \pm \frac{\mathrm{Re}\left[2C_A\left(C_T + C_T^{'}\right)\right]}{2\left|C_A\right|^2 + \left|C_T\right|^2 + \left|C_T^{'}\right|^2}$$

Fierz interference

$$a \approx -\frac{1}{3} \frac{2\left|C_A\right|^2 - \left|C_T\right|^2 + \left|C_T^{'}\right|^2}{2\left|C_A\right|^2 + \left|C_T\right|^2 + \left|C_T^{'}\right|^2}$$

Electron-neutrino correlation

^{6}He β-ν angular correlation at CENPA

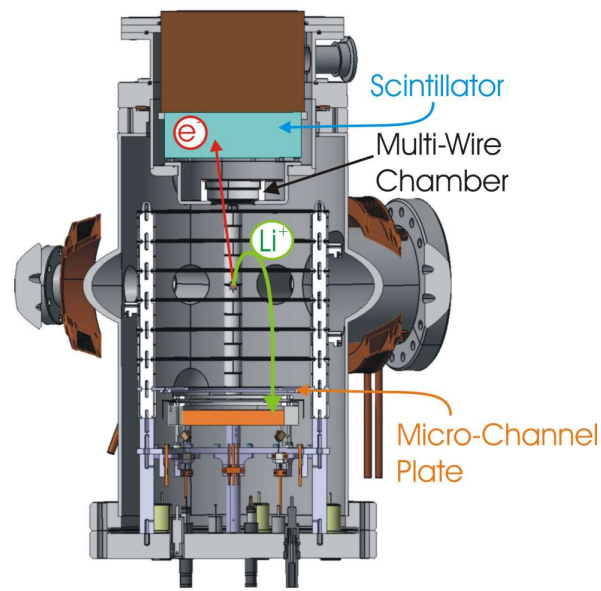
Y. Bagdasarova[1], K. Bailey[2], X. Fléchard[3], A. Garcia[1,*], R. Hong[1], A. Knecht[4], A. Leredde[2], E. Liennard[3], **P. Mueller[2,*]**, O. Naviliat-Cuncic[5], T. O'Connor[2], M. Sternberg[1], H.E. Swanson[1], F. Wauters[1]

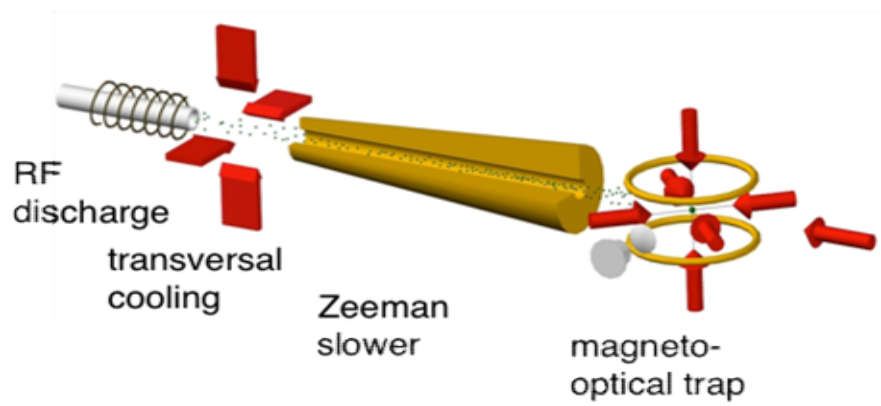
[1]*University of Washington,* [2]*Argonne National Lab,* [3]*LPC, CAEN, France,* [4]*PSI,* [5]*NSCL, Michigan State University*

[*]Spokepersons

- Goal: measure "little a" to 0.1% in ^{6}He
  - pure Gamow-Teller decay
  - sensitive to tensor couplings
  - simple nuclear and atomic structure
- Laser cooling and trapping to prepare ^{6}He source
- Detect electron and ^{6}Li in coincidence
- ΔE-E scintillator system for electron detection (energy, start of time-of-flight)
- Micro-channel plate detector for ^{6}Li detection (position, time-of-flight)

^{6}He Trap/Detector Chamber





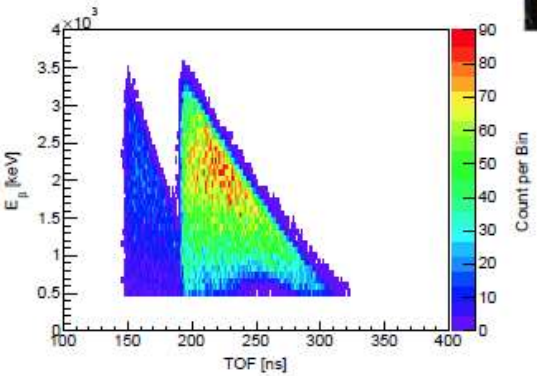
CENPA
Center for Experimental Nuclear Physics and Astrophysics

^{6}He β-ν angular correlation at CENPA

6He Source:
Reliable source of ~10^{10} ^{6}He's/s in low-background environment
A. Knecht et al. NIM A. **660**, 43 (2011)

Laser trapping:
All systems working after much development

Example of data taken recently: E_β versus TOF which yields $\Delta a/a$ =1%.



(a) Experiment

Status:

- Now efficiencies good for determination of little-a at the 1% level within 3 days (including calibrations)!
- Presently working on systematic uncertainties.
- Aiming for $\Delta a/a$ <1% in near future.

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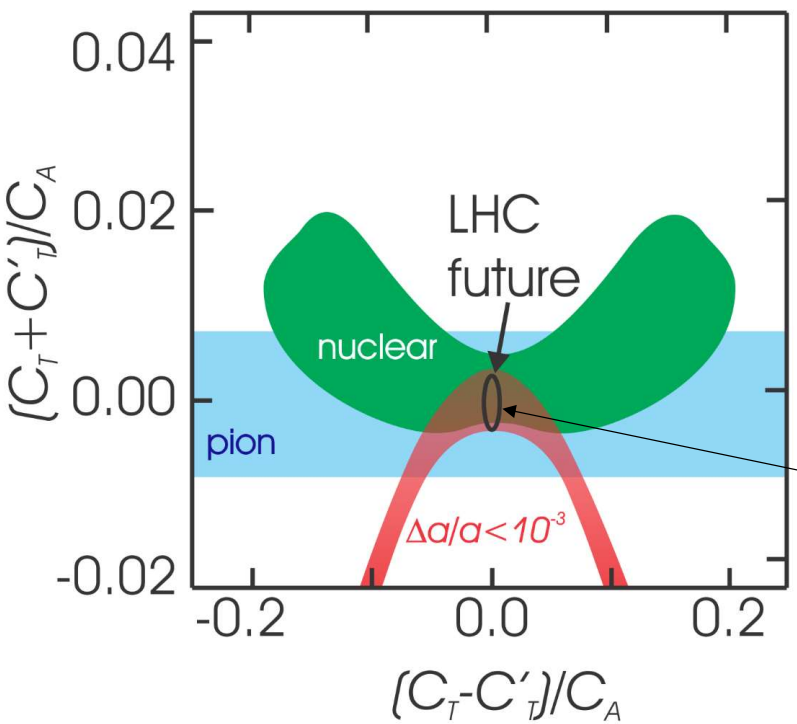
Center for Experimental Nuclear Physics and Astrophysics

Precision beta decay versus others:
Can “precision” compete with “energy”?

F. Wauters et al.
PRC **89**, 025501
(2014)

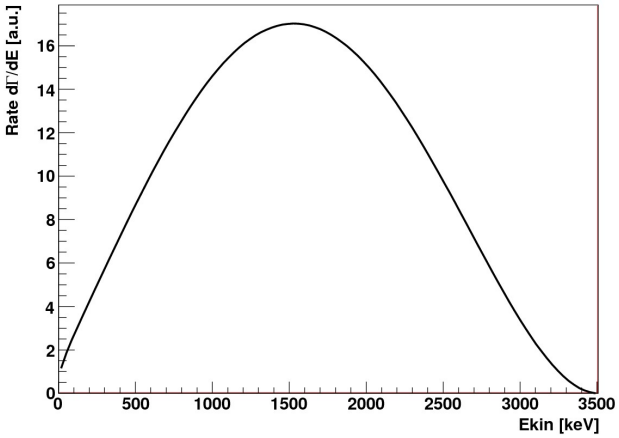


Best limits now from LHC.
Will not improve significantly with next run.
IS THIS THE END OF SEARCHING FOR THIS PROBE OF FUNDAMENTAL PHYSICS?

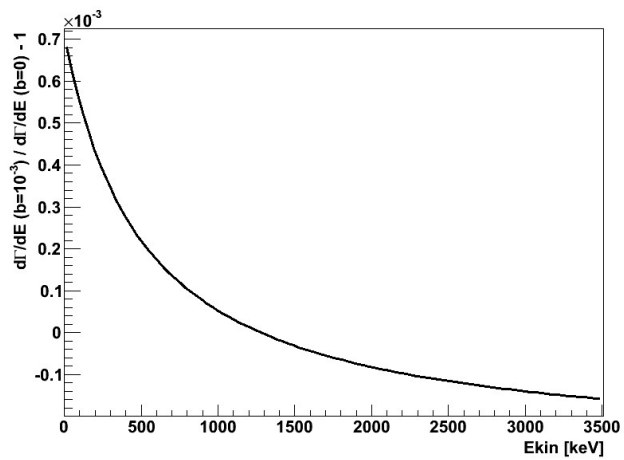
Detect little *b*

Is it possible to break the "*b* ~ 5×10^{-3} barrier" and reach into *really interesting* terrain?

Spectrum



Distortion due to b=10^{-3}



$$dw = dw_0 \left[1 + a \frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right]$$

quadratic

$$a \approx -\frac{1}{3} \frac{2|C_A|^2 - |C_T|^2 + |C_T'|^2}{2|C_A|^2 + |C_T|^2 + |C_T'|^2}$$

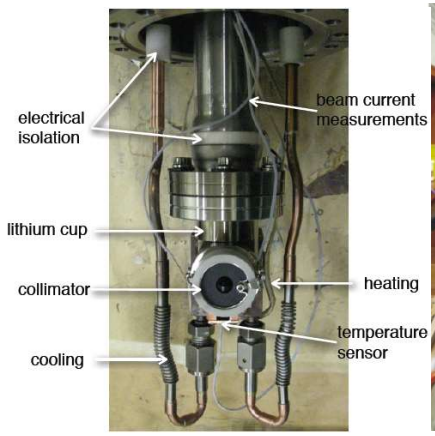
linear

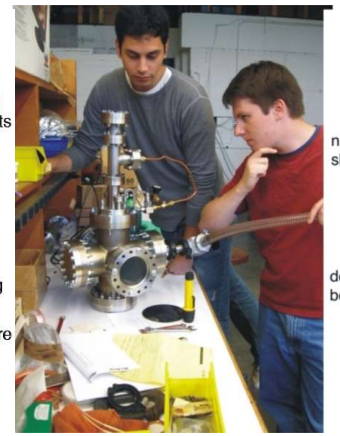
$$b \approx \pm \frac{\mathrm{Re}\left[2C_A\left(C_T + C_T'\right)\right]}{2|C_A|^2 + |C_T|^2 + |C_T'|^2}$$

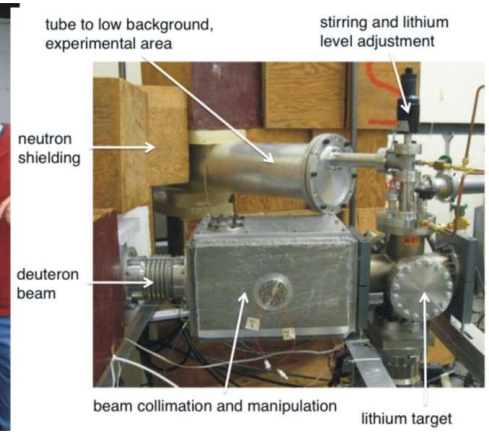
$$E_{thres} = 1\,\mathrm{keV} \qquad \Rightarrow \Delta b \approx 8/\sqrt{N}$$

$$E_{thres} = 1150\,\mathrm{keV} \Rightarrow \Delta b \approx 29/\sqrt{N}$$

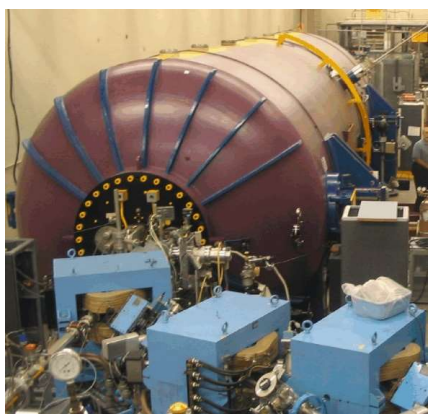
Now ~10^{10} atoms of ^{6}He/s at Seattle via ^{7}Li(d,^{3}He)^{6}He







A. Knecht et al. NIM A. **660**, 43 (2011)



Most intense source of 6He in the world at CENPA.

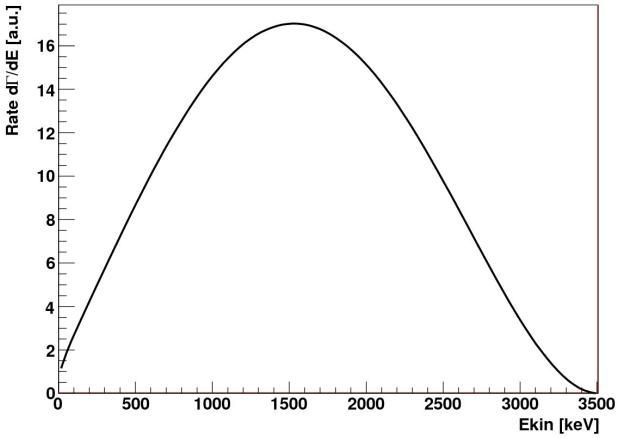
Statistics not a problem.

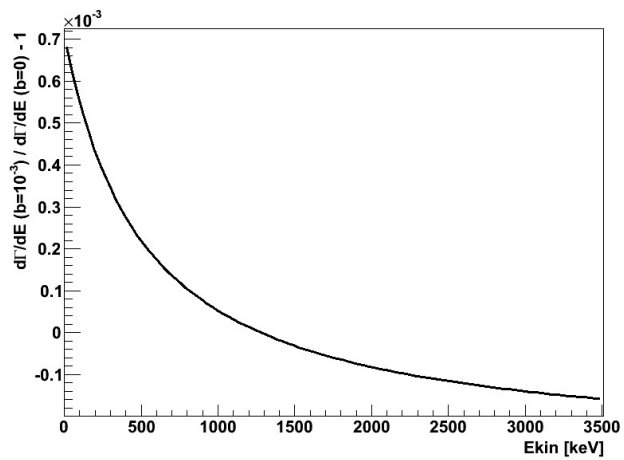
$$E_{thres} = 1\,\text{keV} \qquad \Rightarrow \Delta b \approx 8/\sqrt{N}$$

$$E_{thres} = 1150\,\text{keV} \Rightarrow \Delta b \approx 29/\sqrt{N}$$

Detect little *b*

Is it possible to break the "*b* ~ 5×10^{-3} barrier" and reach into *really interesting* terrain?





Statistics not a problem… have intense source of 6He working at UW.

Sobering number for *b* ~ 10^{-3}: need to know energy calibration gain to 10^{-4}.
Even magnetic spectrometers for E_β < 4 MeV have energy dependent response (due to scattering…)
In summary: looks ~ impossible!

PRL 114, 162501 (2015)

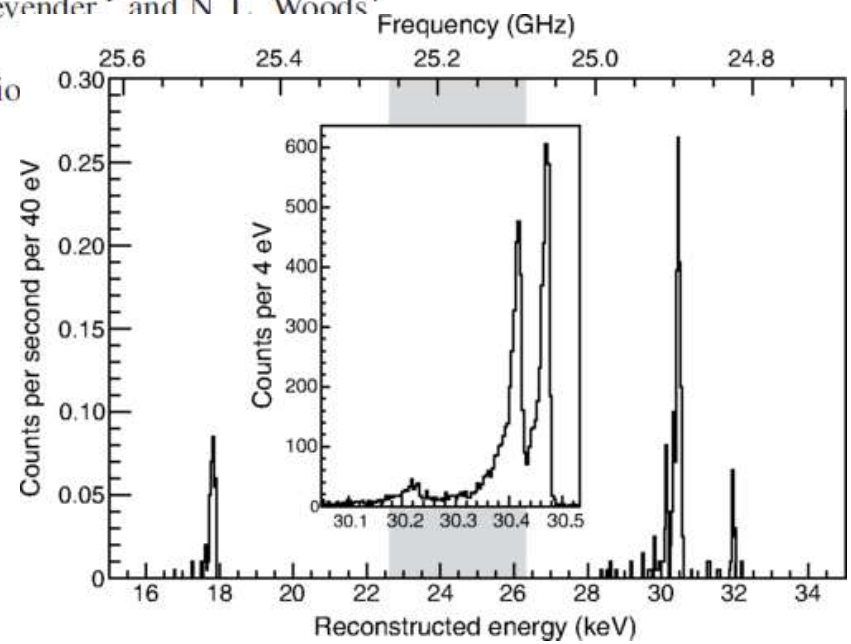
Selected for a Viewpoint in *Physics*
PHYSICAL REVIEW LETTERS

week ending
24 APRIL 2015

Single-Electron Detection and Spectroscopy via Relativistic Cyclotron Radiation

D. M. Asner,[1] R. F. Bradley,[2] L. de Viveiros,[3] P. J. Doe,[4] J. L. Fernandes,[1] M. Fertl,[4] E. C. Finn,[1] J. A. Formaggio,[5] D. Furse,[5] A. M. Jones,[1] J. N. Kofron,[4] B. H. LaRoque,[3] M. Leber,[3] E. L. McBride,[4] M. L. Miller,[4] P. Mohanmurthy,[5] B. Monreal,[3] N. S. Oblath,[5] R. G. H. Robertson,[4] L. J Rosenberg,[4] G. Rybka,[4] D. Rysewyk,[5] M. G. Stemberg,[4] J. R. Tedeschi,[1] T. Thümmler,[6] B. A. VanDevender[1] and N. L. Woods[4]

(Project 8 Collaboratio



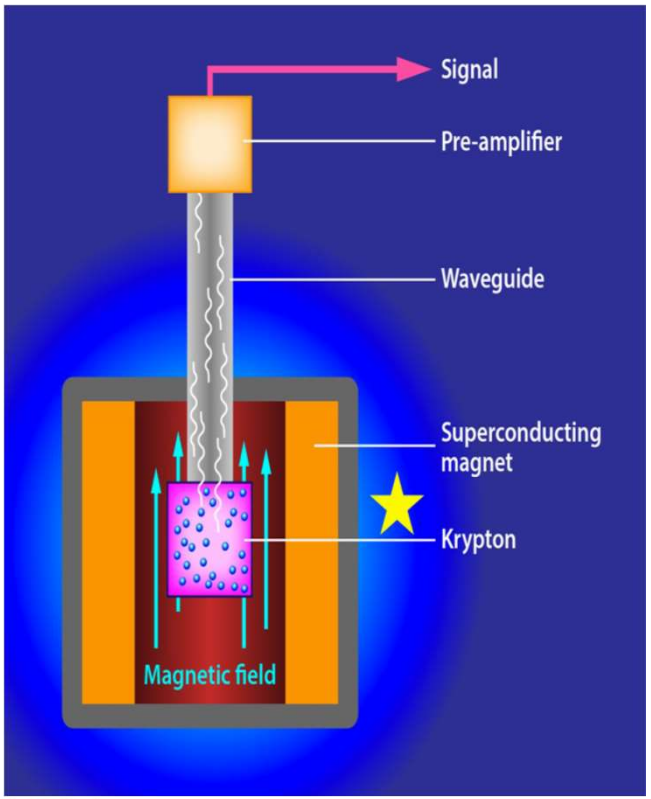
Project 8 collaboration gets FWHM/E ~ < 10^{-3} resolution for conversion electrons of 18-32 keV.

Can the technique be applied to a beta continuum with for E_β < 4 MeV ?

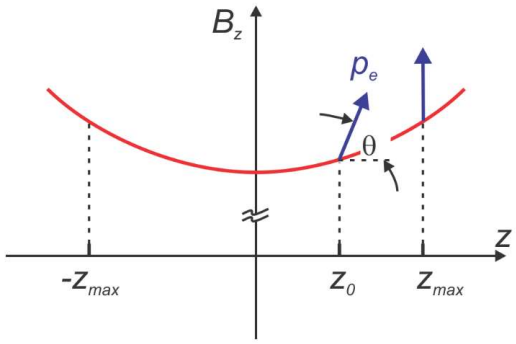
Project 8 in a nutshell

Looking at Tritium decay to get ν mass.
Electrons emitted in an RF guide within an axial *B* field. Antenna at end detects cyclotron radiation.

$$\omega = \frac{qB}{E}$$

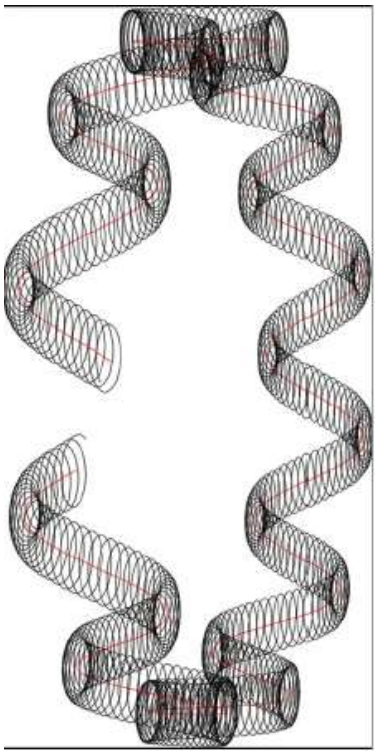


Electrons of ~ 30 keV from a gaseous source were let to decay within a 1 tesla field with an additional pair of coils to set up a *magnetic trap*:



Longitudinal comp. of momentum decreases as *B* increases up to return point, z_{max}. Axial oscillations with ω_z.

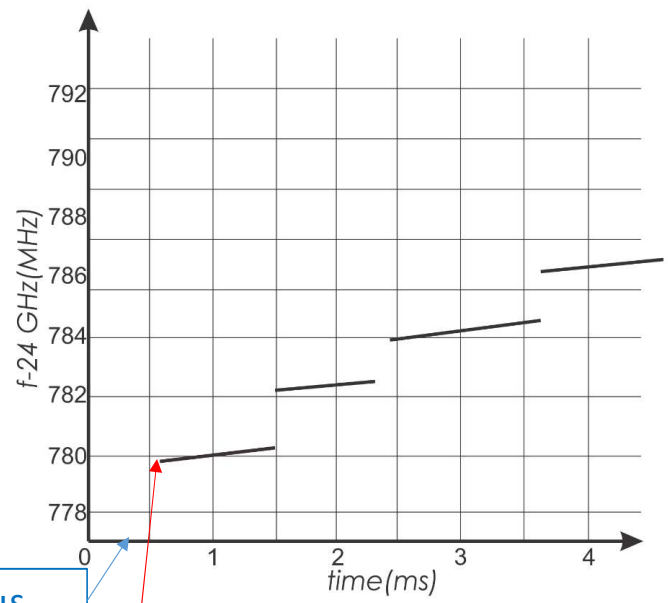
Some details



Motion can be thought off as cyclotron orbits, axial oscillations and magnetron motion.

$$\omega_c : \omega_z : \omega_{mag} = \sim 1 : 4 \times 10^{-3} : 2 \times 10^{-5}$$

Peak frequency of power spectrum versus time.



As electrons loose energy the cyclotron freq. goes up. Jumps due to collisions with hydrogen in imperfect vacuum

Time bins ~ 30 μs.

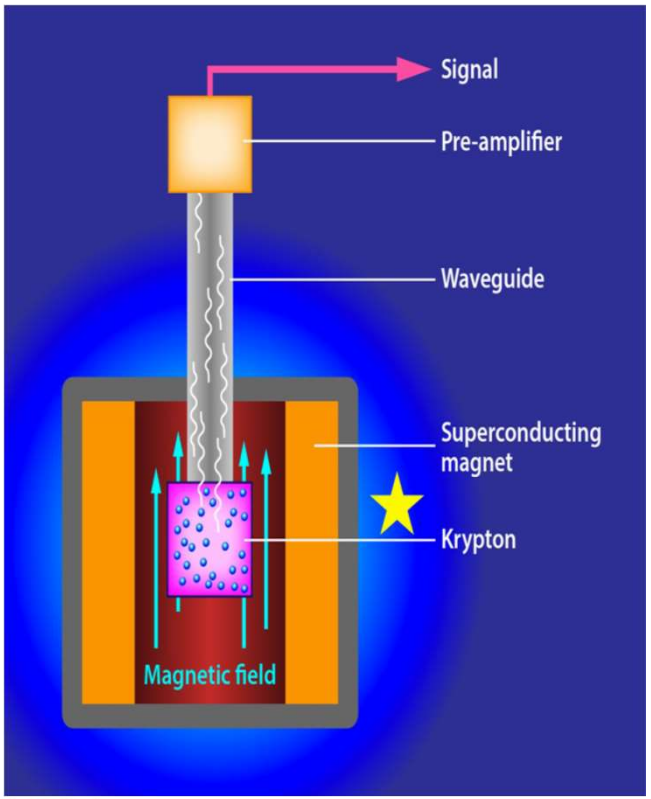
Initial frequency gives *E*

$$\omega = \frac{qB}{E}$$

Project 8 in a nutshell

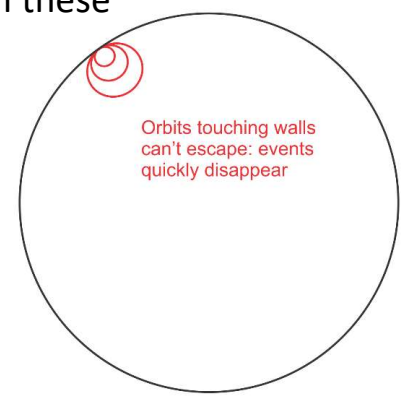
Looking at Tritium decay to get ν mass.
Electrons emitted in an RF guide within an axial *B* field. Antenna at end detects cyclotron radiation.

$$\omega = \frac{qB}{E}$$



Advantage

Electrons hitting walls quickly (<1 ns) loose energy and disappear.
No signal from these



For the same reason: background radiation hitting walls does not generate signals.

^{6}He little-b measurement at CENPA

M. Fertl[1], A. Garcia[1], M. Guigue[4], P. Kammel[1], A. Leredde[2], P. Mueller[2], R.G.H. Robertson[1], G. Rybka[1], G. Savard[2], D. Stancil[3], M. Sternberg[1], H.E. Swanson[1], B.A. Vandeevender[4], A. Young[3]

[1]*University of Washington,* [2]*Argonne National Lab,* [3]*North Carolina State University,* [4]*Pacific Northwest National Laboratory*

- Goal: measure "little b" to 10^{-3} or better in ^{6}He
  - Highest sensitivity to tensor couplings
- Determine shape of beta spectrum in search for tensor couplings.
- Use Cyclotron Emission Spectroscopy. Similar to Project 8 setup for tritium decay but need to extend the technique to higher energy betas and to a precision determination of a continuum spectrum. Non trivial: under development.
- **In 1 day of running would determine *b* one order of magnitude better than any previous experiment.**

Decay rate: C_T and C_T' represent the new physics. C_A is the usual axial coupling constant for Weak Int.

$$dw = dw_0 \left[1 + a \frac{\vec{p}_e}{E_e} \cdot \frac{\vec{p}_\nu}{E_\nu} + b \frac{\Gamma m_e}{E_e} \right]$$

$$a \approx -\frac{1}{3} \frac{2|C_A|^2 - |C_T|^2 + |C_T'|^2}{2|C_A|^2 + |C_T|^2 + |C_T'|^2}$$

$$b \approx \frac{\mathrm{Re}\left[2C_A\left(C_T + C_T'\right)\right]}{2|C_A|^2 + |C_T|^2 + |C_T'|^2}$$

Little-*b* is called "Fierz interference" and depends linearly on the new couplings. This makes it a more sensitive probe of the new physics.

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^{6}He little-b measurement at CENPA

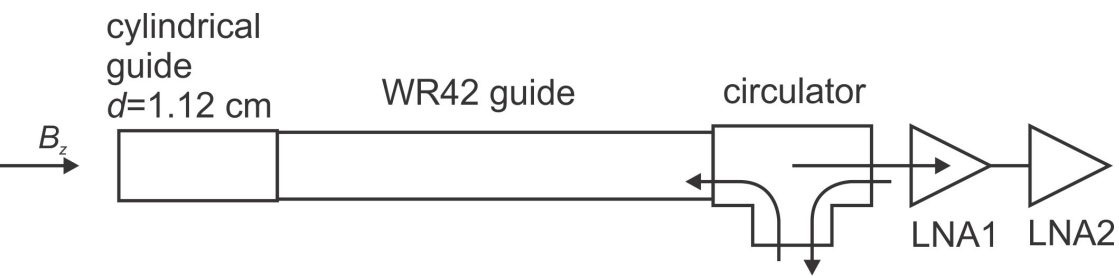
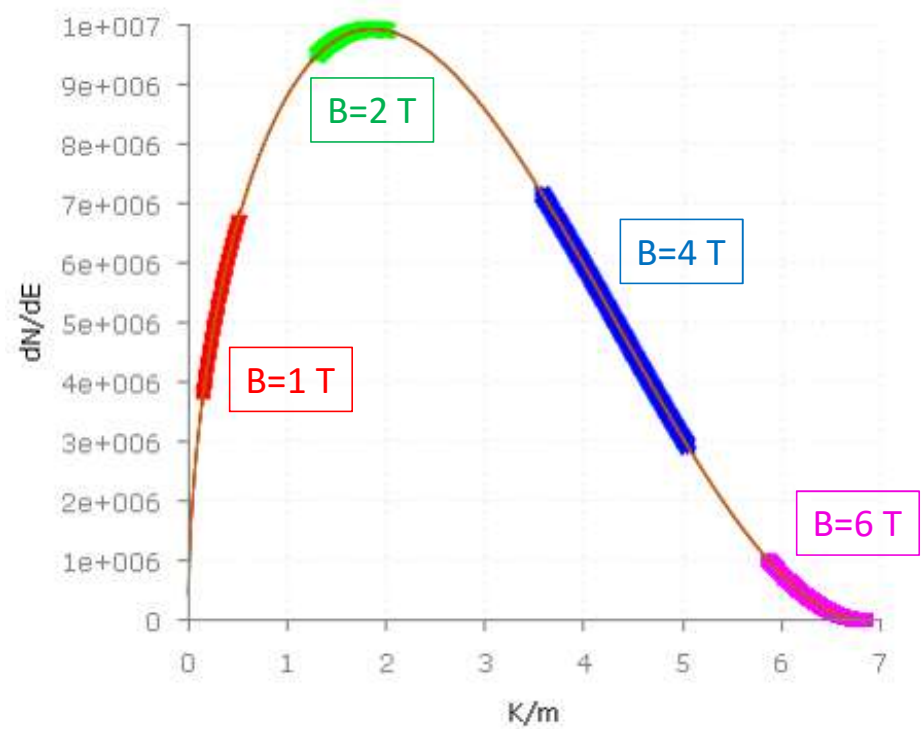


TABLE I. Approximate rates of incoming ^{6}He atoms, decays, and observed events.

Stage	Rate (1/s)
Incoming atoms	$\sim 10^{10}$
Decays within trap	$\sim 10^{7}$
Trapped betas	$\sim 3 \times 10^{5}$
Trapped betas (not hitting walls)	$\sim 10^{5}$
Events observed within frequency windows	$\sim 10^{4}$

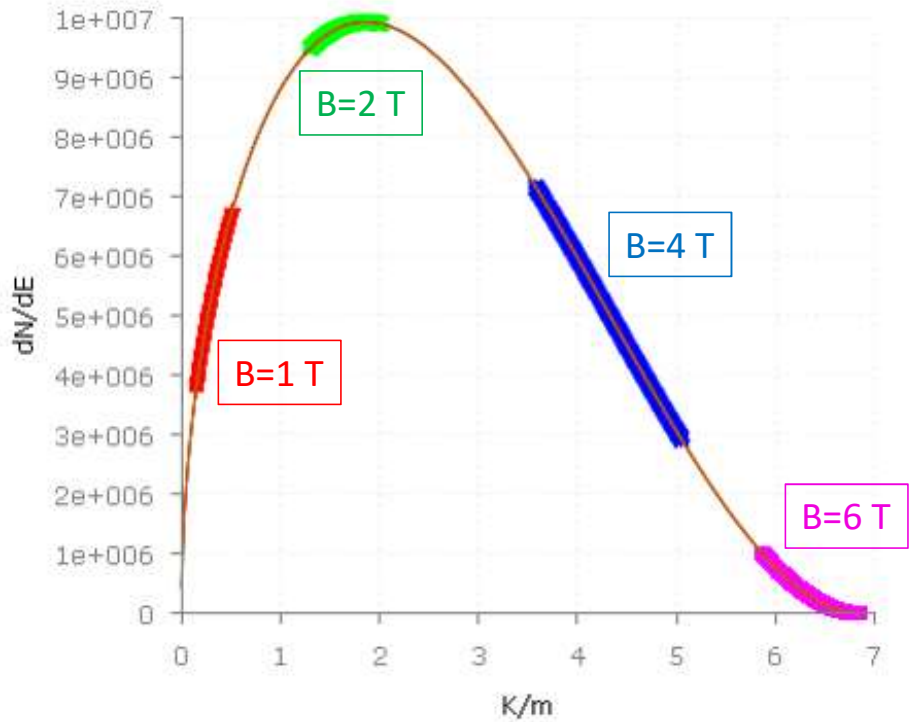
Assuming we measure in *f*=18-24 GHz.

Monte Carlo simulation of observation in **1 day of running**

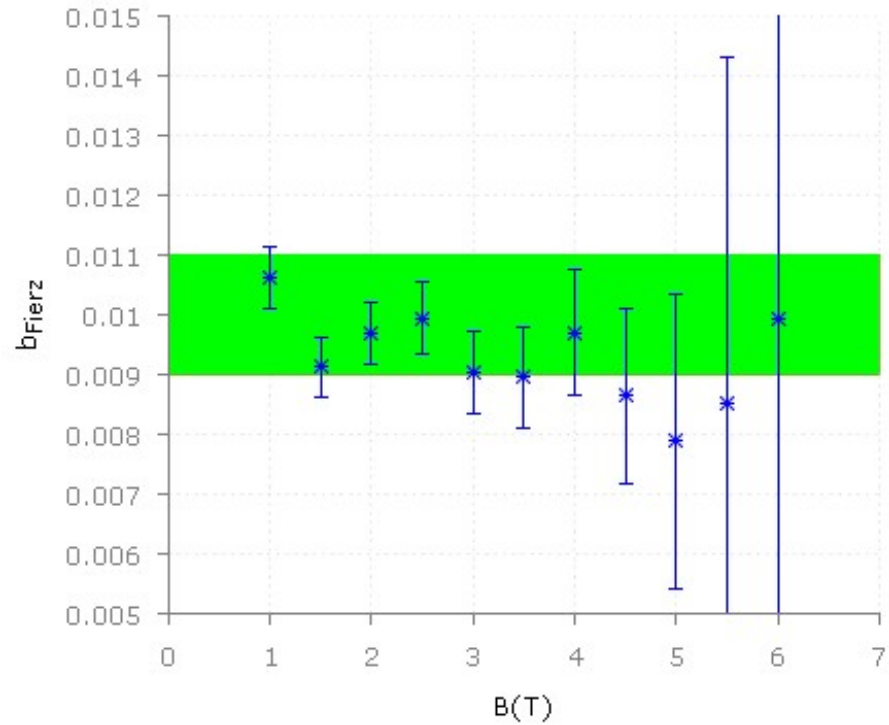


^{6}He little-b measurement at CENPA

Monte Carlo simulation of observation in
1 day of running

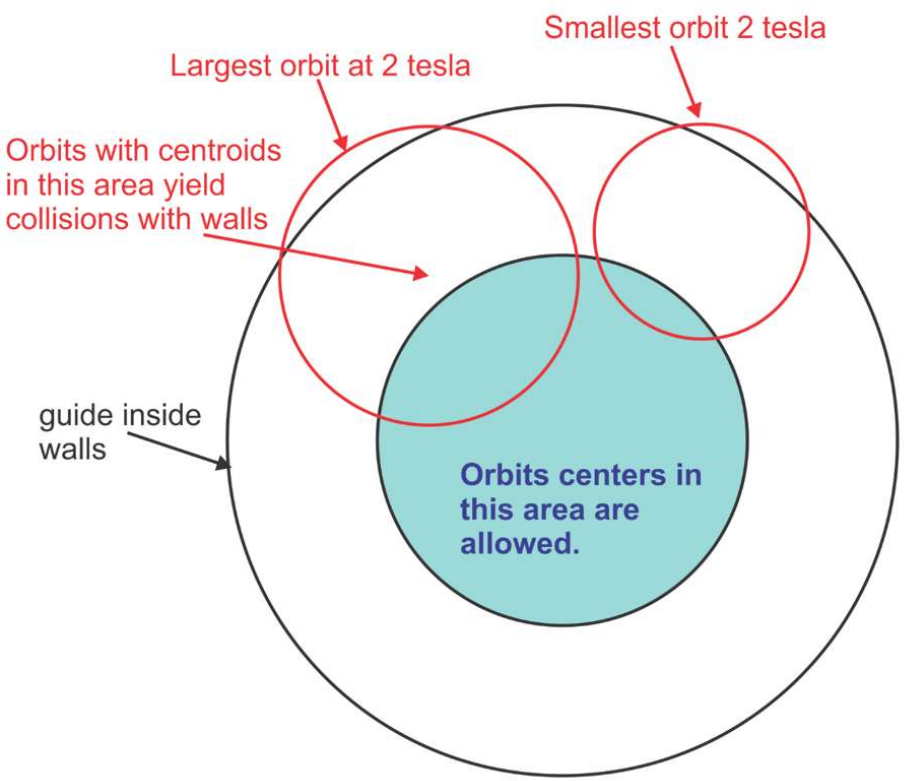


Extracting little *b* vs. B field
1 day of running each point
(assumed *b*=0.01)



Going for the beta spectrum continuum.

Obvious problem: efficiency depends on energy.



Assuming we measure in *f*=18-24 GHz.

Cross sectional view of guide with electron orbit at top left. For this radius there is a dead region shown by the white frame on the blue area.

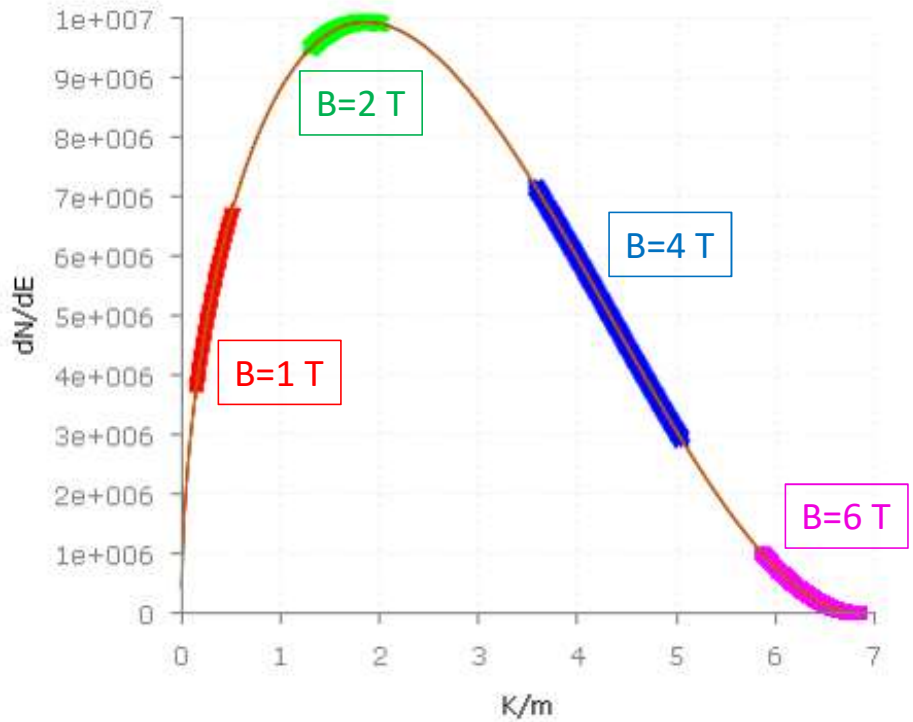
Since blue area depends on energy there is a systematic distortion of the spectrum

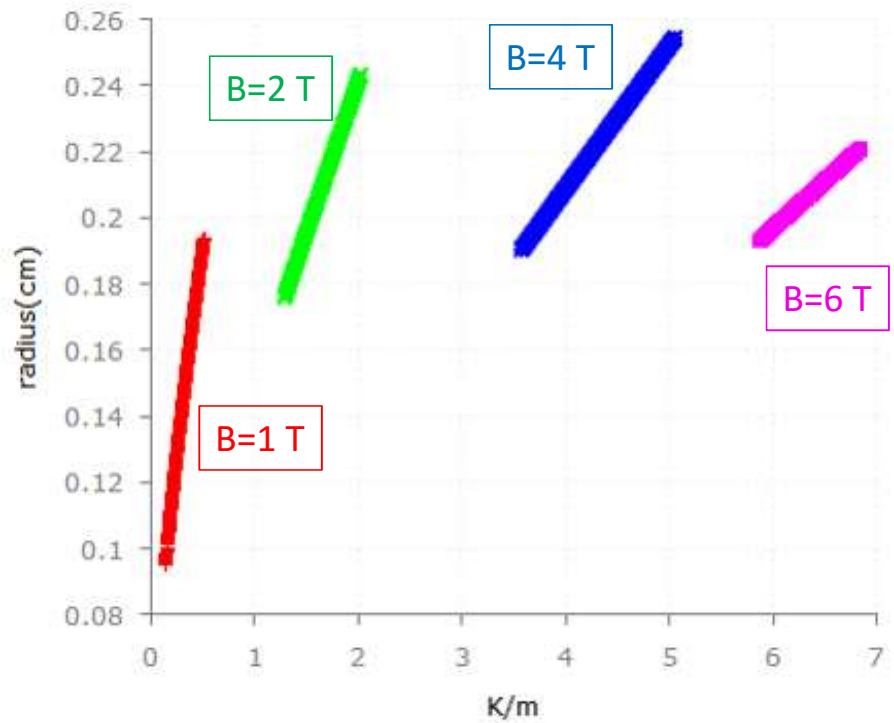
Can be studied by varying the *B* field using mono-energetic sources.

^{6}He little-b measurement at CENPA

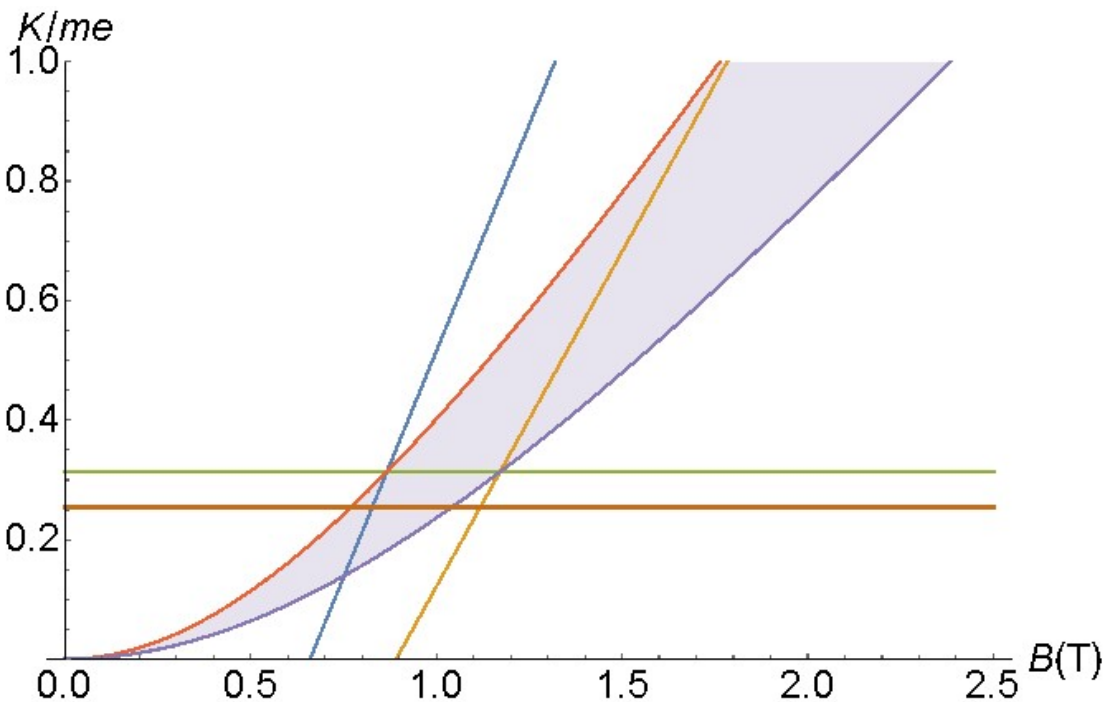
Radii vs. B field
Can use this to check geometric effect

Monte Carlo simulation of observation in
1 day of running





Geometric effect can be also measured using 131mXe:
Produces lines at 25, 129, 160 keV.



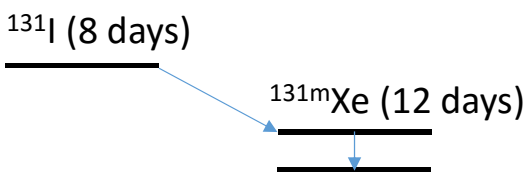
Study of geometric effect with 131mXe:
(efficiency variations due to orbits sizes)

The shaded curves are curves of constant cyclotron radii:
RED: 18 GHz
BLUE: 24 GHz

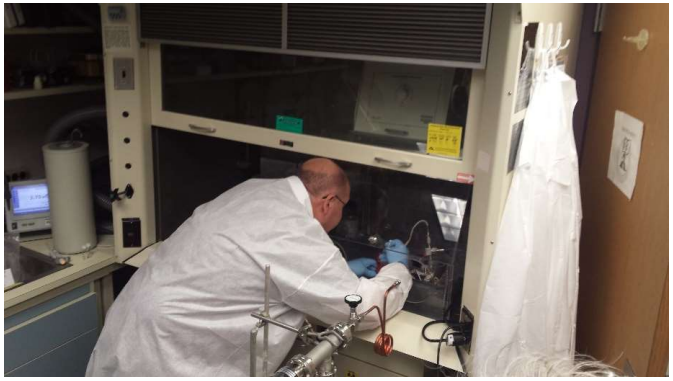
This part seems under control.

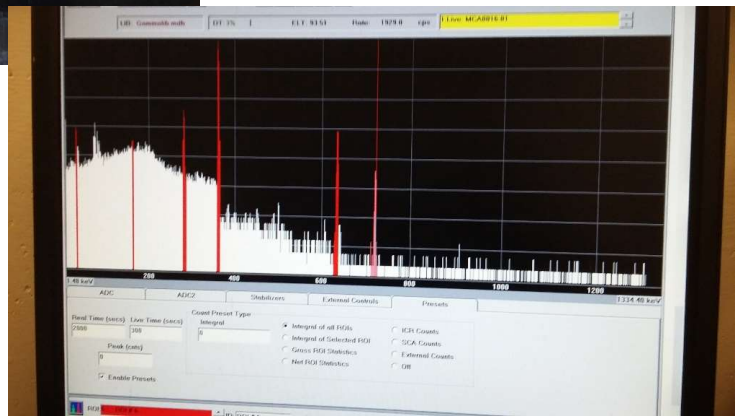
Preparation of a ^{131m}Xe source ($t_{1/2}$ ≈ 12 days)

Gives conversion electrons
E_e = 25, 129, 160 keV



Need about 50 mCi of ^{131}I (→ ^{131m}Xe with $t_{1/2}$ ≈ 8 days)
(30 μCi of ^{131}I is a safety concern)

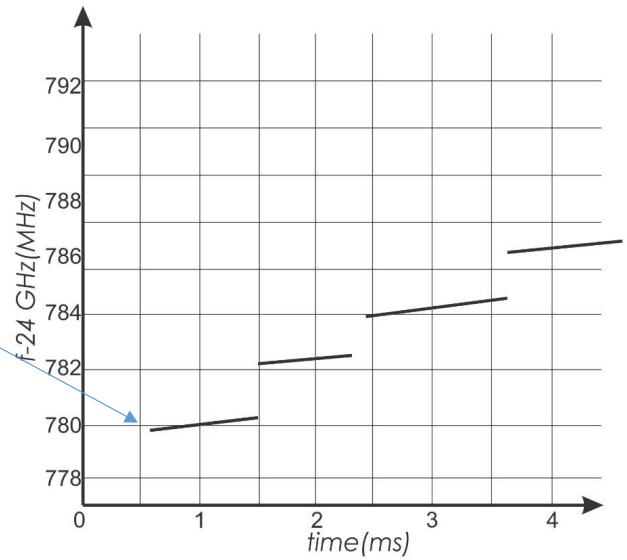




We have extracted
≈ 10^5 Becq. of ^{131m}Xe.
Ready to test in the Project 8 setup.

Other possible systematic effects under study:

- Can really identify initial frequency?



- Dependence on pitch angle

$$\omega_{\text{eff}} \approx \omega_c \left(1 + \frac{1}{2}\frac{\cos^2\theta'}{\sin^2\theta'}\right)\left(1 + \frac{Pt}{\gamma m_e c^2}\right)$$

- Dependence on exact shape of magnetic field?

$$\omega_c = \frac{qB}{E}$$

Part of our team are magnetic-field experts (working on *field team* for g-2)

- RF power variations with *E* induce efficiency dependency?

Can bypass problems comparing to other sources:

- **19Ne** should also present tensor currents, but **sign of *b* should be opposite**. Noble gas like 6He. Production works very well “on paper”.

- **14O** should *not* present tensor currents. Limits on b exist from measurements lack of log(ft) value dependence on endpoint. Would produce CO (previous work at Louvain and TRIUMF).

SUMMARY

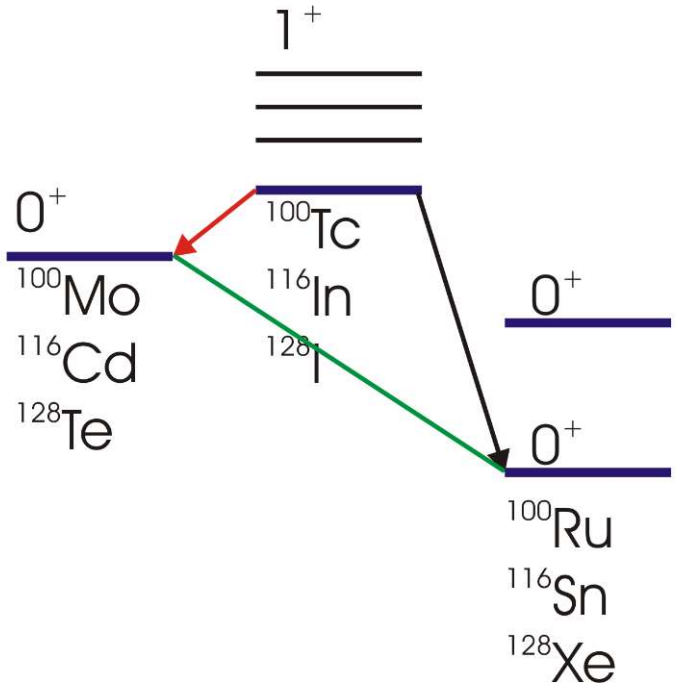
All indicates we should be able to overcome difficulties and produce the most sensitive measurement of little *b* for axial transitions extending the Project 8 technique to 6He, 19Ne, 14O decays.

A different application. Benchmarks for nuclear structure?

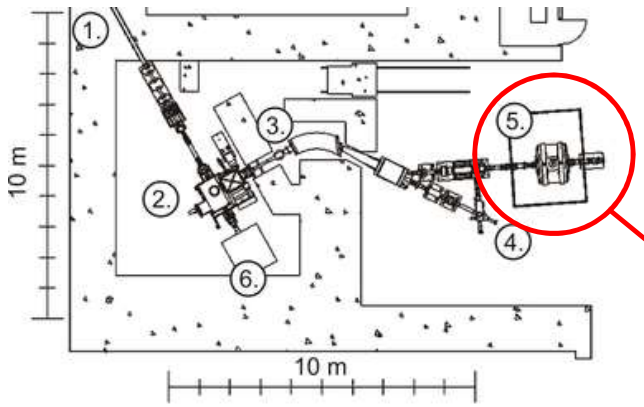
- $2\nu-2\beta$ decays
- single beta decays
- single electron capture decays

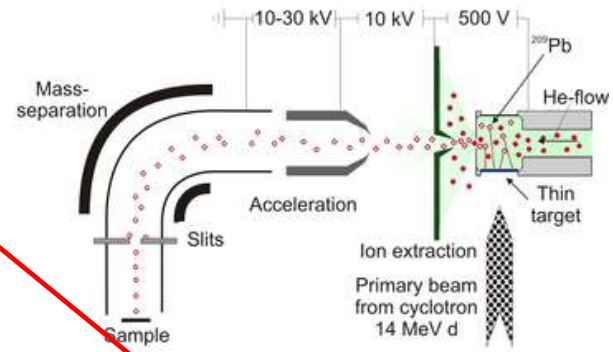
In 3 cases one can check all of the above for the same nucleus: *good for understanding overarching issues (role of p-p, p-h correlations, deformation, etc...)*

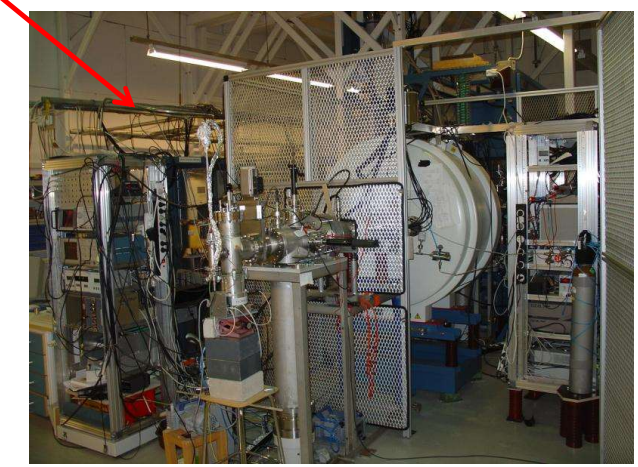
We developed a device to determine the tiny EC branches.



We developed a device to determine the tiny EC branches using the radioactive beams available at IGISOL (JYFLTRAP).







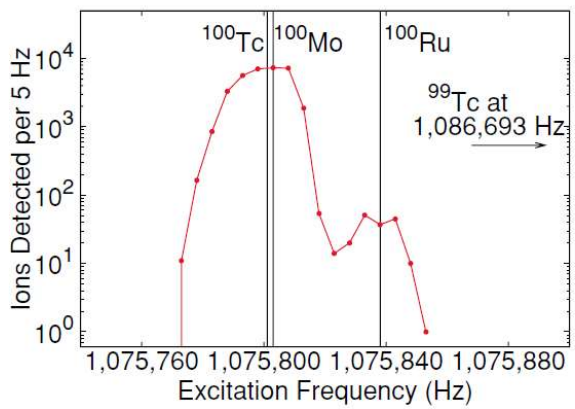
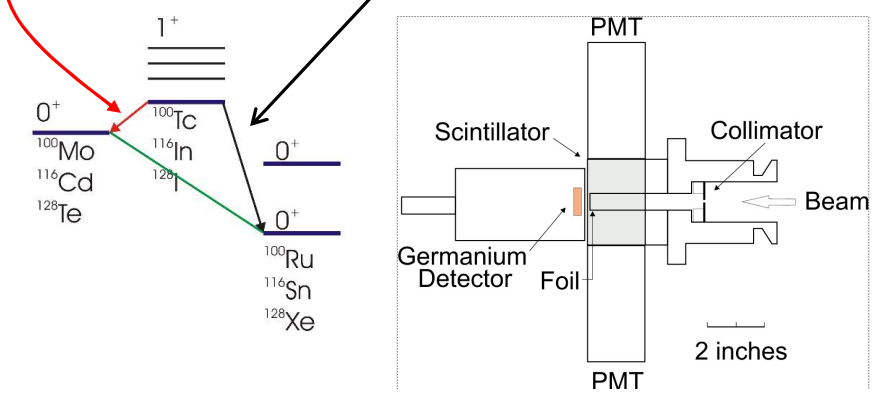


FIG. 2. (Color online) Mass scan to show the mass resolving power for $A = 100$ obtained with JYFLTRAP.

CENP Center for Experi...

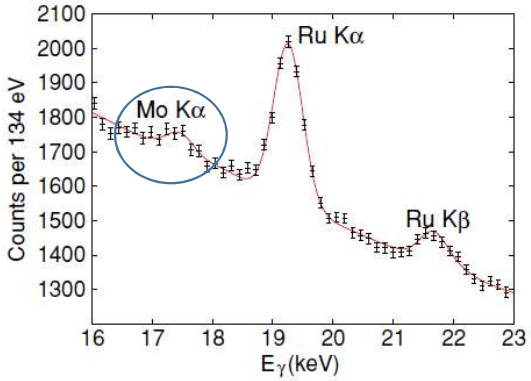
We developed a device to determine the tiny EC branches using the radioactive beams available at IGISOL (Jyvaskyla).

Use ion trap for clean activity
High-resolution Ge for x rays
Scintillator for vetoing beta- decays



Previous measurements limited by energy resolution:
With Project 8 technique could improve by 100!

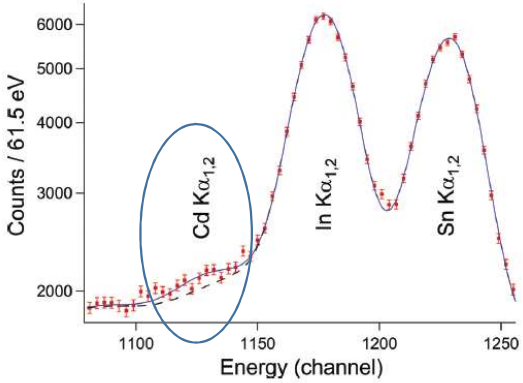
^{100}Tc EC decay:
BR(EC) = $(2.6\pm0.4)\times10^{-5}$



S. Sjue, Thesis 2008;
Sjue et al.,
PRC **78,** 064317 (2008)

^{116}In EC decay:
BR(EC) = $(2.3\pm0.6)\times10^{-4}$

PHYSICAL REVIEW C **87**, 031303(R) (2013)



Wrede et al.,
PRC **87**, 031303(R) (2013)

Both of our results are consistent with complete *ground state dominance*: just using the ground state accounts for the measured 2ν-2β decay rate.

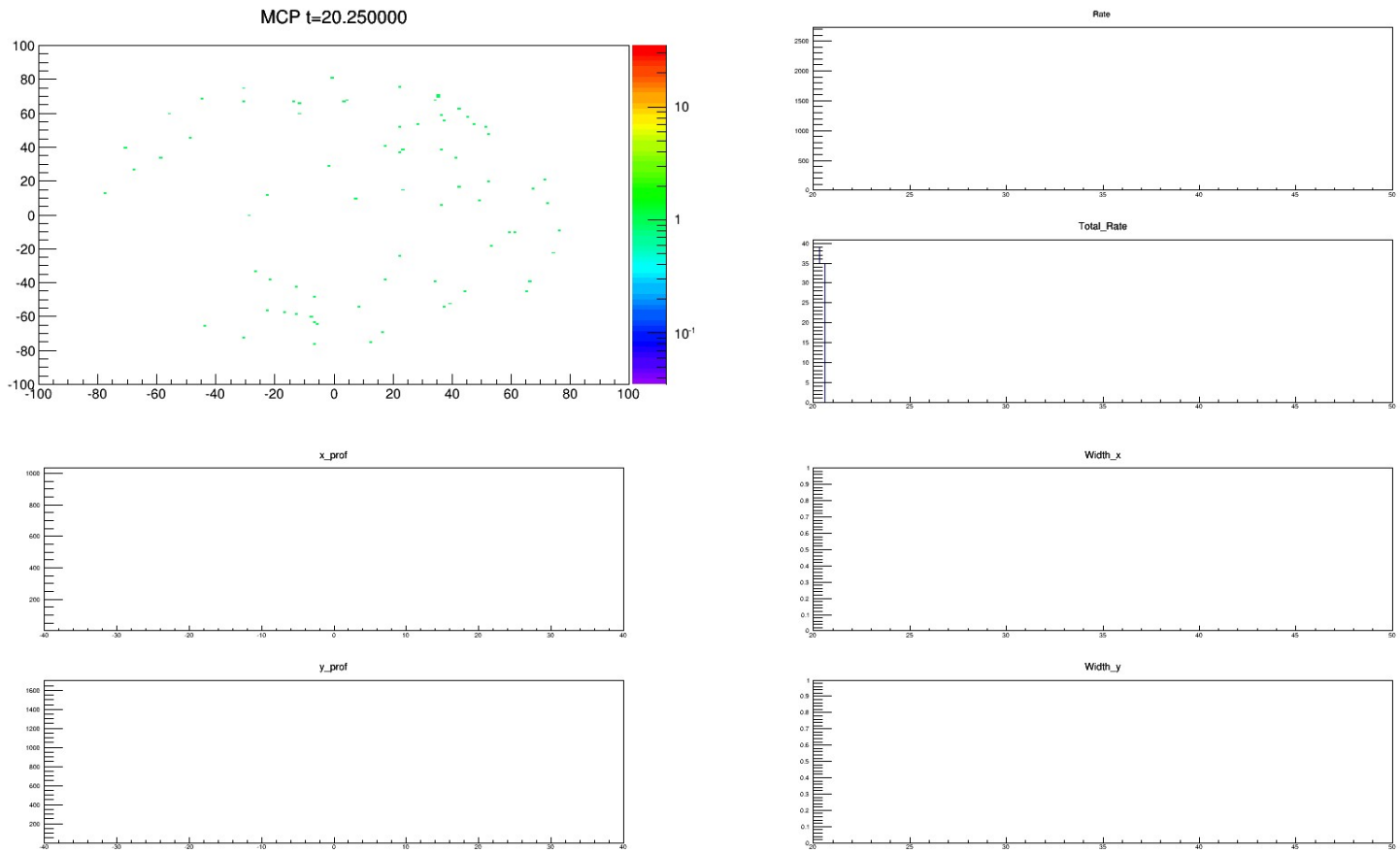
OVERALL SUMMARY

All indicates we should be able to overcome difficulties and produce the most sensitive measurement of little *b* for axial transitions extending the Project 8 technique to 6He, 19Ne, 14O decays.

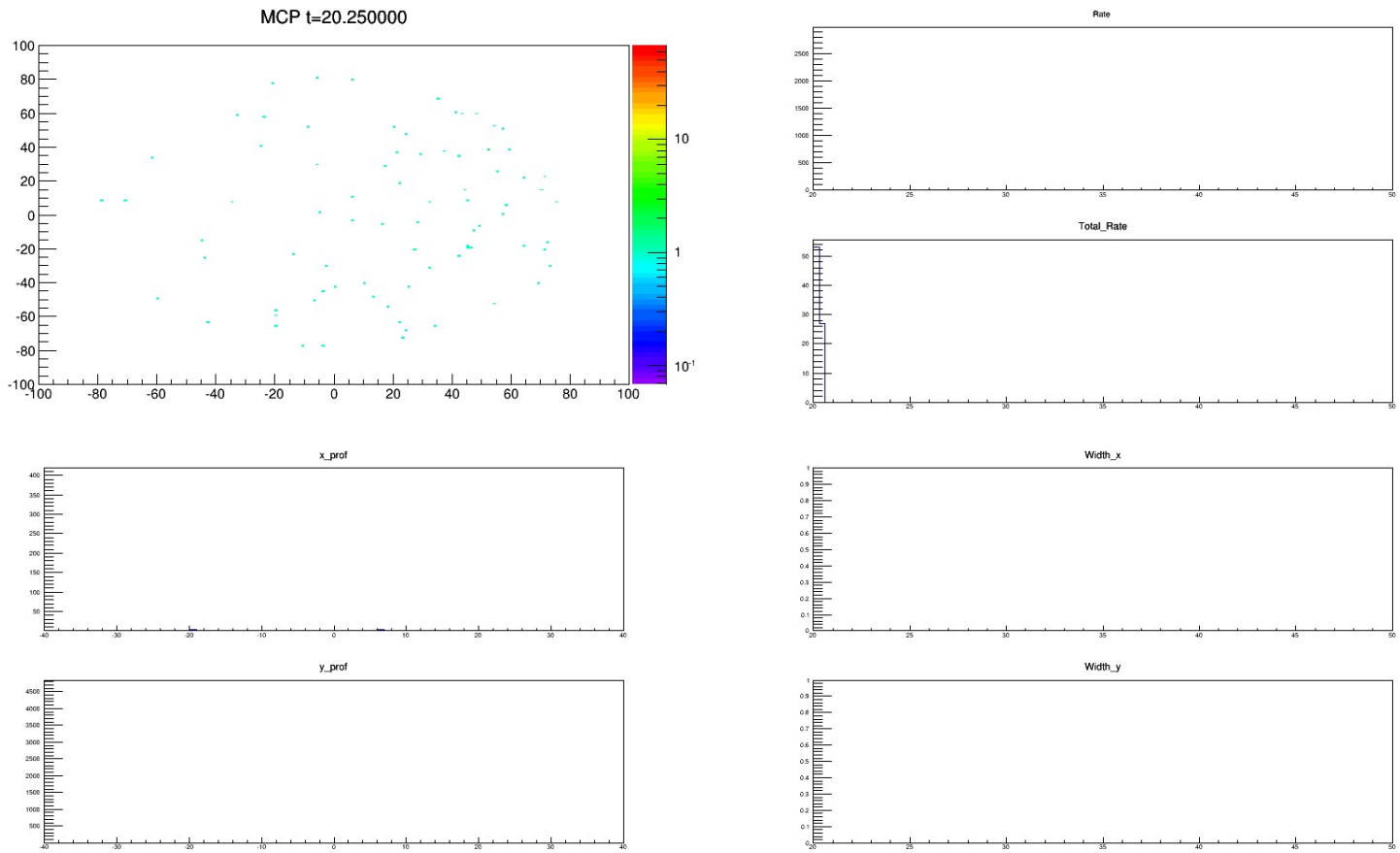
CRES technique developed by Project 8 collaboration could have important nuclear spectroscopy applications.

Backup slides

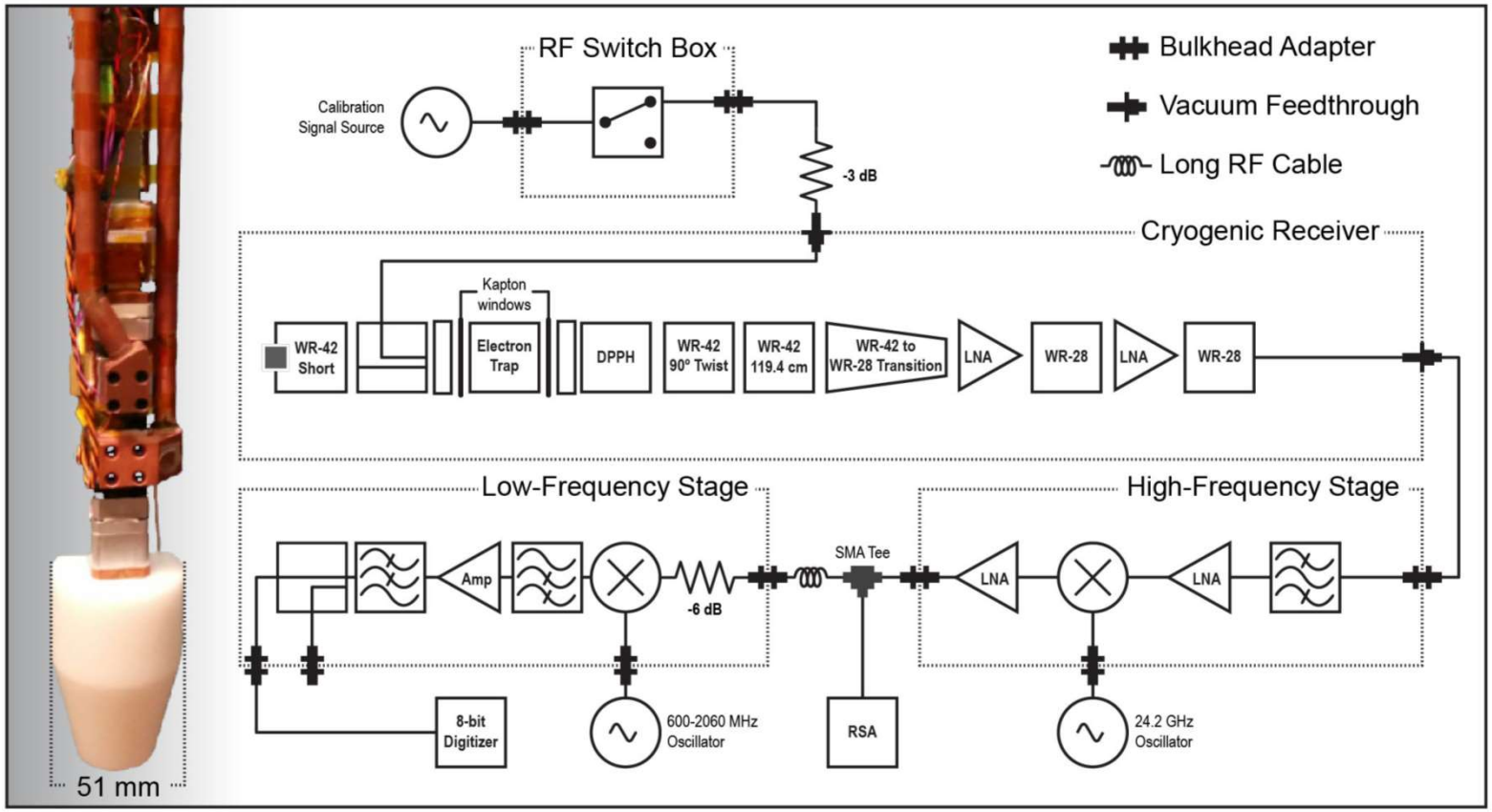
No guide beam



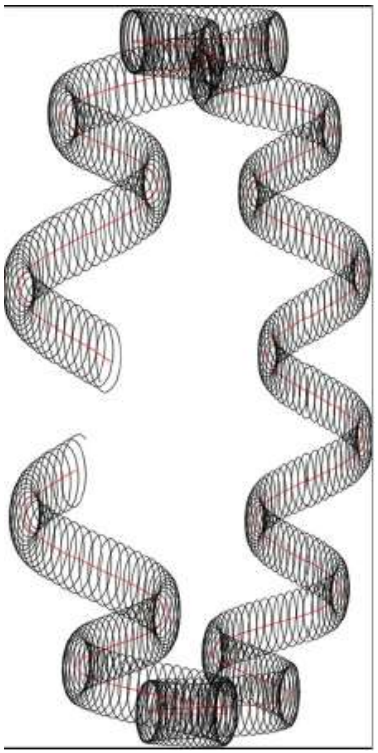
With guide beam



Project 8 electronics



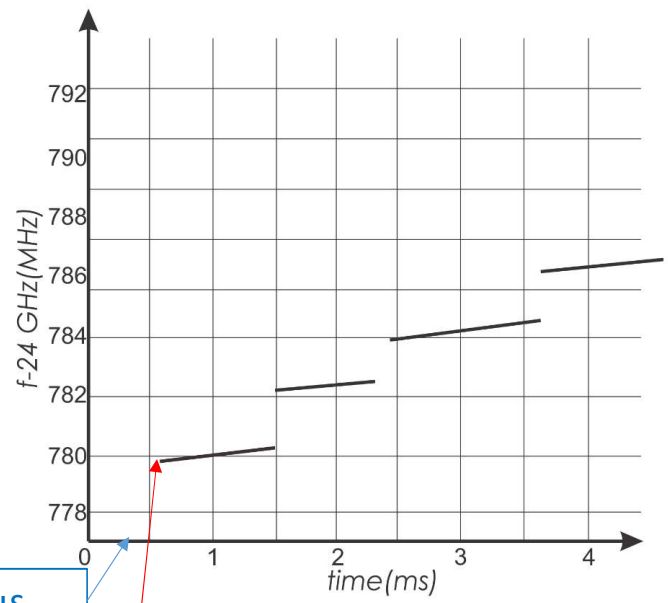
Some details



Motion can be thought off as cyclotron orbits, axial oscillations and magnetron motion.

$$\omega_c : \omega_z : \omega_{mag} = \sim 1 : 4 \times 10^{-3} : 2 \times 10^{-5}$$

Peak frequency of power spectrum versus time.



As electrons loose energy the cyclotron freq. goes up. Jumps due to collisions with hydrogen in imperfect vacuum

Time bins ~ 30 μs.

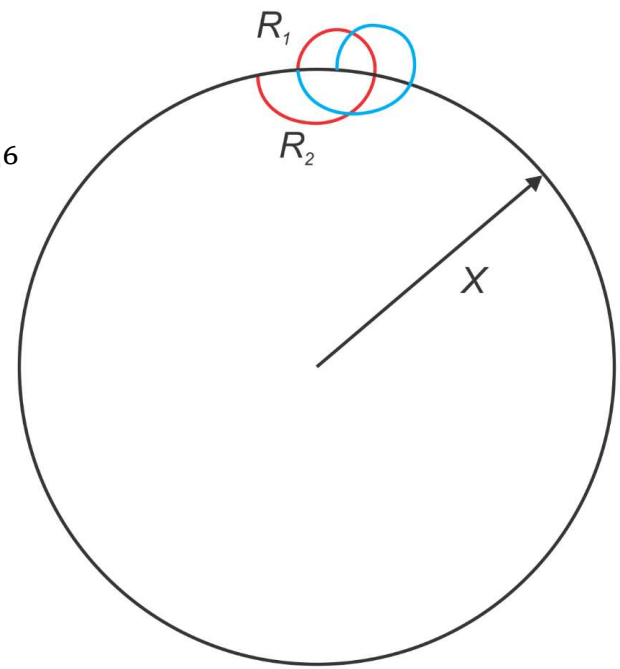
Initial frequency gives *E*

$$\omega = \frac{qB}{E}$$

Magnetron motion. For harmonic traps no bias (E-dependence)

$$\omega_m = \frac{\omega_z^2}{2\omega_c}$$

$$\frac{\omega_c}{\omega_m} = N \sim 10^6$$



For each cyclotron turn the orbits displaces:

$$\Delta \approx R_1 - R_2 \approx R(1 - B_1/B_2) \approx R\left(\frac{\partial B/\partial r}{B} R\right)$$

Then the radius X of magnetron motion:

$$X \approx \frac{N\Delta}{2\pi} \approx N\frac{R^2}{2\pi}\frac{\partial B/\partial r}{B}$$

Use $\frac{\partial B/\partial r}{B} \sim r\frac{10^{-2}}{cm^2}$ $\quad B \sim 1$ tesla

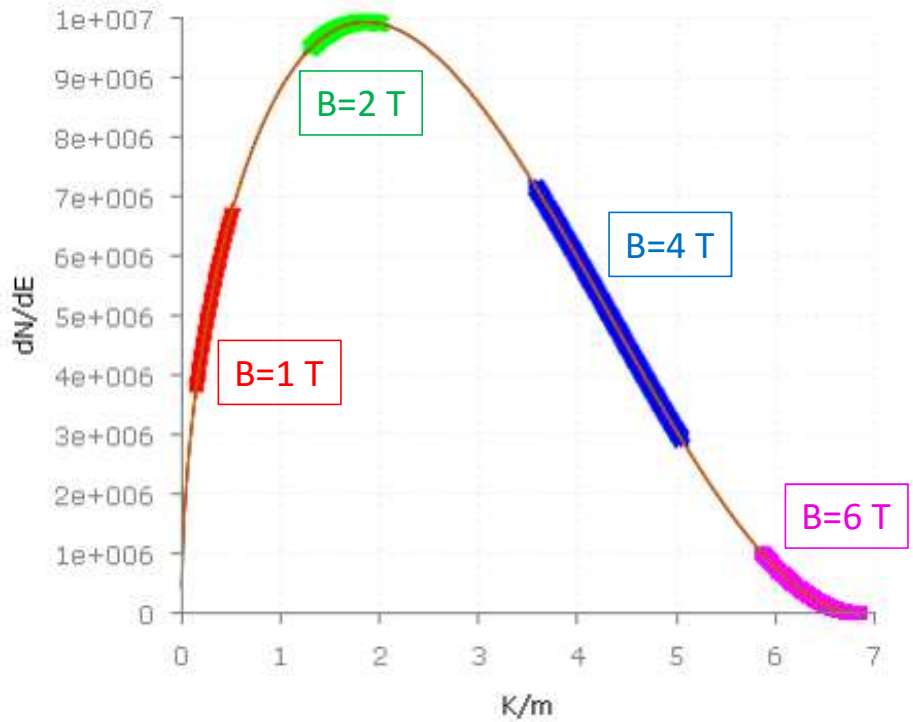
Harmonic trap

$$X \approx N\frac{R^2}{2\pi}X\frac{10^{-2}}{cm^2} \rightarrow N = \frac{2\pi}{10^{-2}R^2} \approx 10^5$$

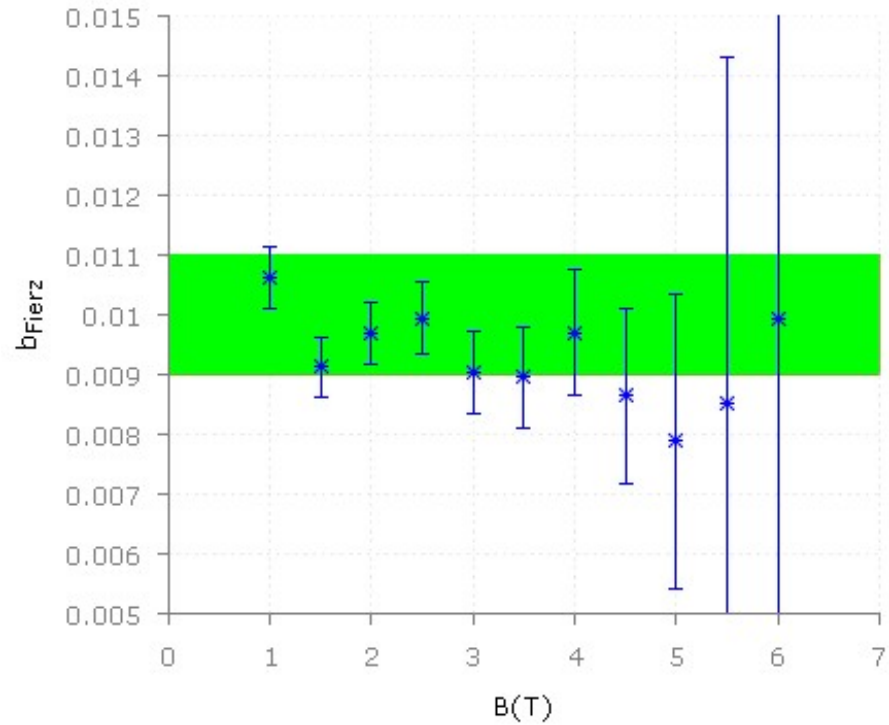
X cancels: magnetron radius independent on *R* in harmonic trap.
I don't get the 10^6 I am supposed to, but it makes sense given how I exaggerated the distortions in the first two equations above.

^{6}He little-b measurement at CENPA

Monte Carlo simulation of observation in
1 day of running



Extracting little *b* vs. B field
1 day of running each point
(assumed *b*=0.01)



^{6}He little-b measurement at CENPA

Monte Carlo simulation of observation in
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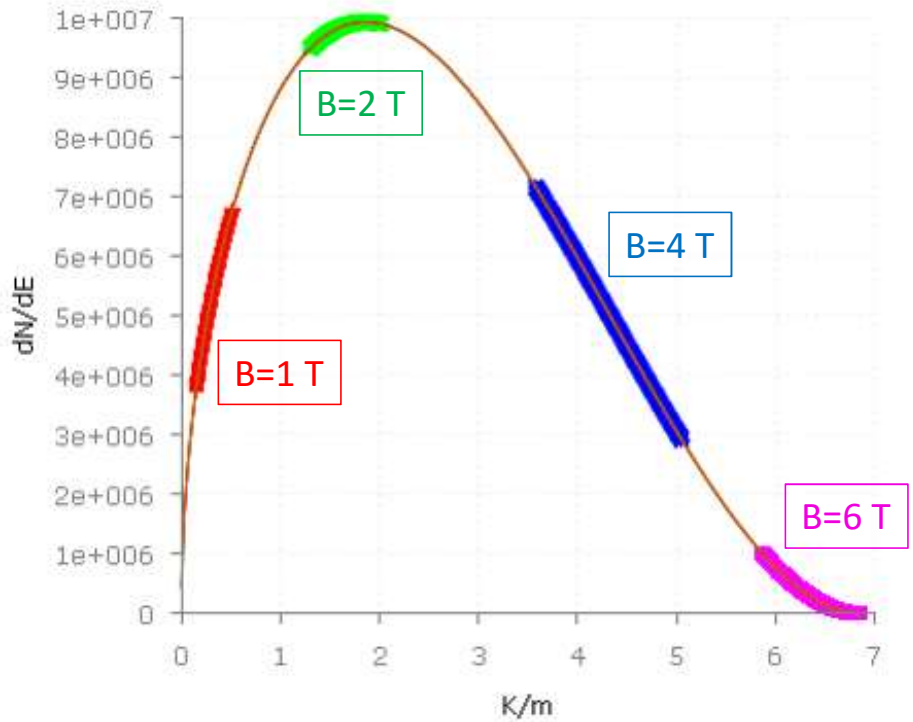
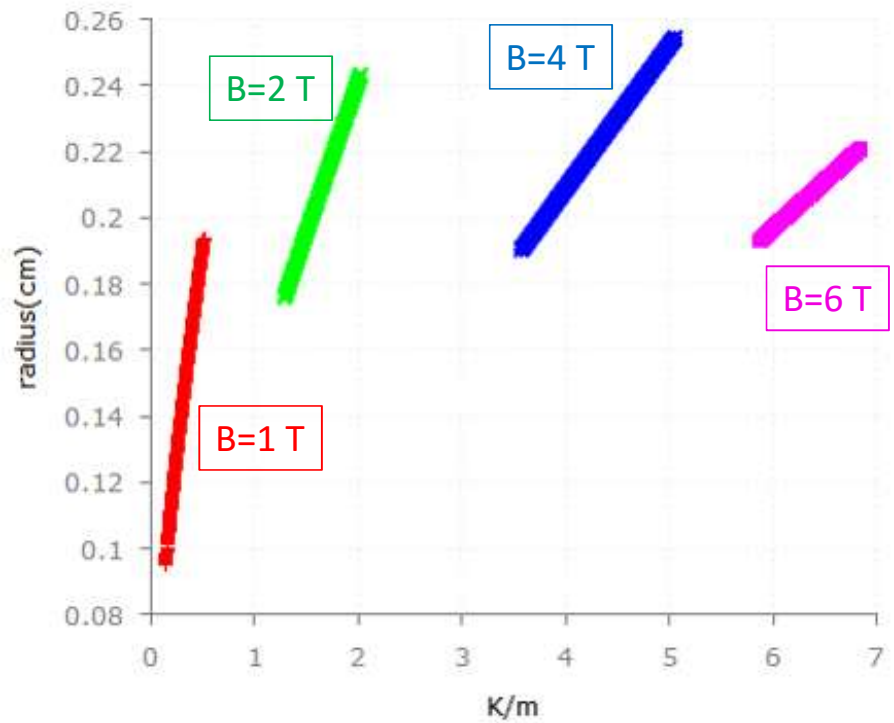


Radii vs. B field
1 day of running each point
(assumed *b*=0.01)



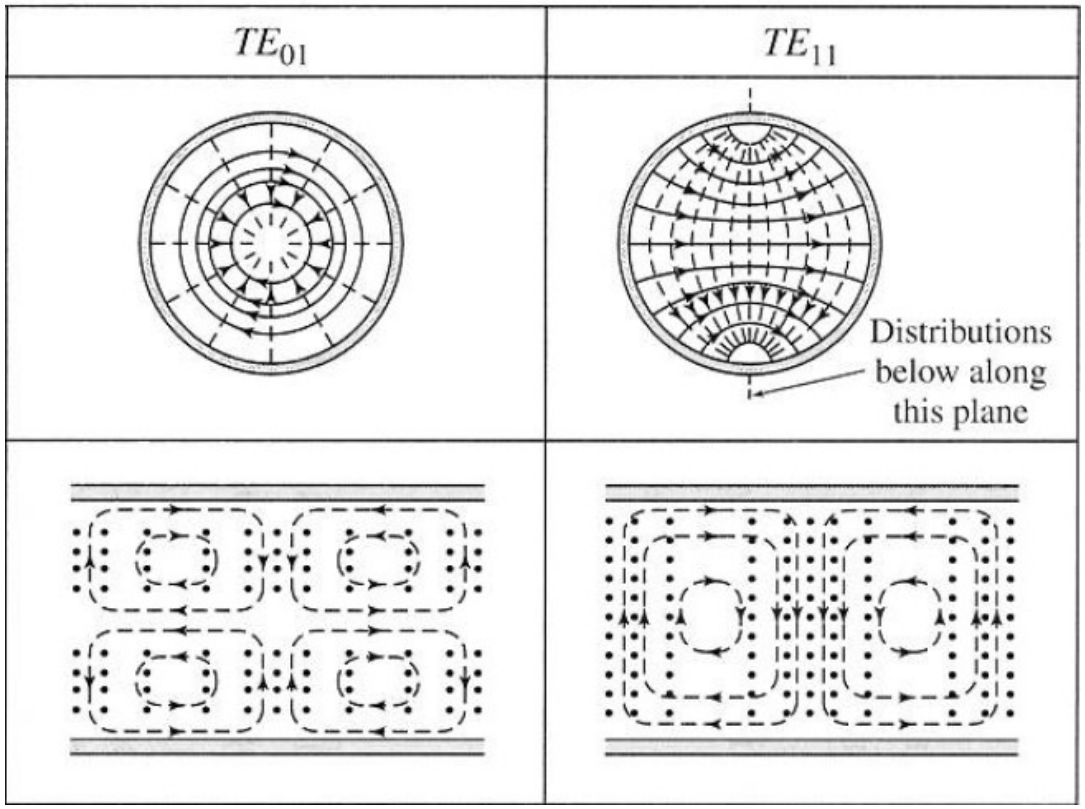
Now worked assuming we measure in 1 GHz intervals starting at *f*=18-24 GHz only TE11 mode (TM01 does not couple to WR42).

Cylindrical guide with *d*=1 cm. For 0.455" we will use divide by 1.1557.

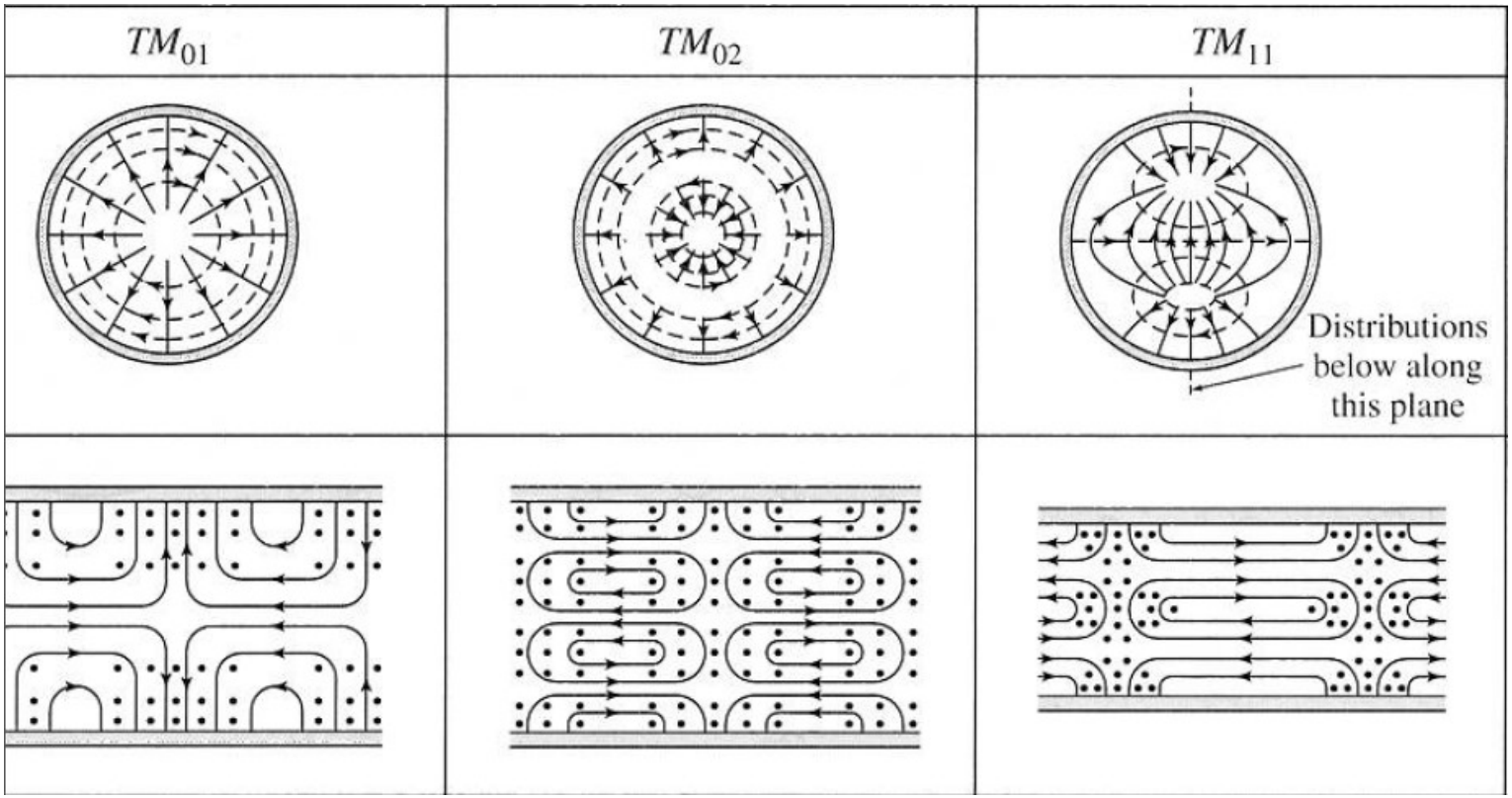
n	$f_{n,1}^{TE}$	$f_{n,2}^{TE}$	$f_{n,3}^{TE}$	$f_{n,1}^{TM}$	$f_{n,2}^{TM}$	$f_{n,3}^{TM}$
0	18.30	33.50	48.58	11.48	26.36	41.32
1	8.79	25.45	40.76	18.30	33.50	48.58
2	14.58	32.02	47.60	24.61	40.19	55.48

TABLE I. f_{min} for different TE and TM modes of a 1-cm diameter cylindrical guide.

TE modes
for cylindrical guides



TM modes
for cylindrical guides

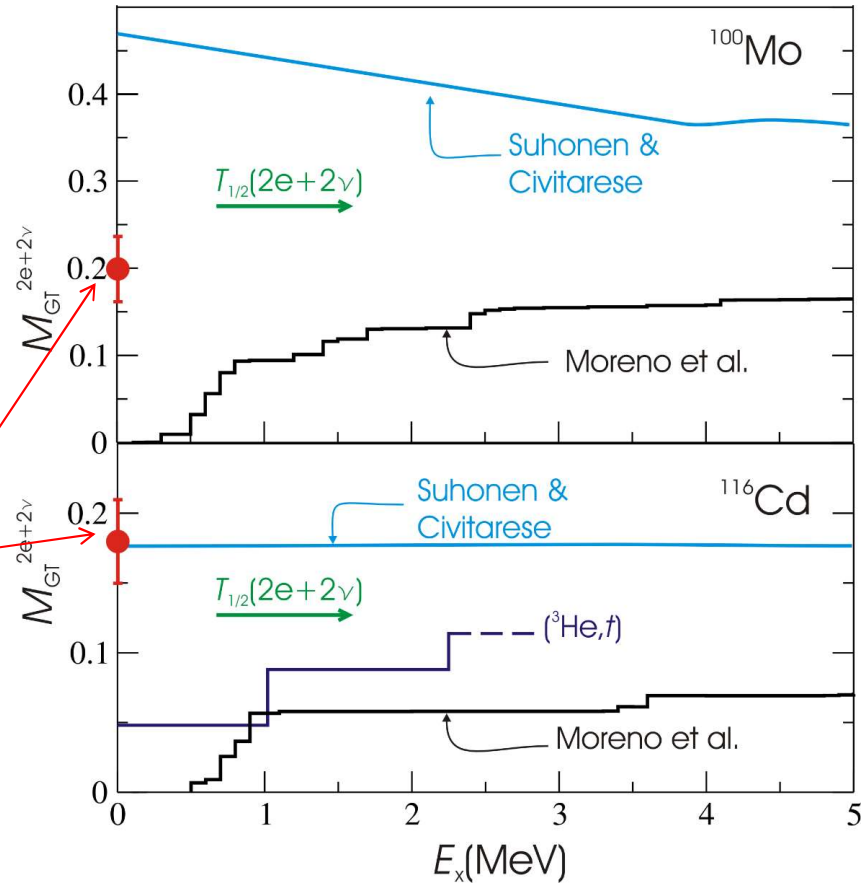


Comparison with 2 different QRPA calculations
(no other calculation yet available for A=100 and A=116)

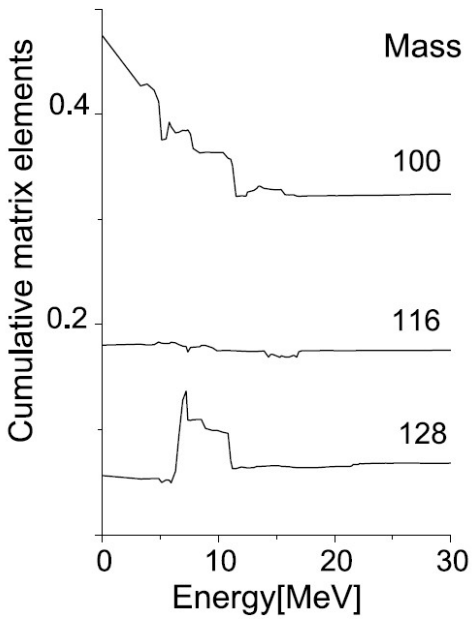
O. Moreno, R. Alvarez-Rodriguez, P. Sarriguren, E. Moya de Guerra, F. Simkovic, A. Faessler
J. Phys. G **36**, 015106 (2009)

Suhonen & Civitarese
Phys. Lett. **B725**, 753 (2013)

Our measurements

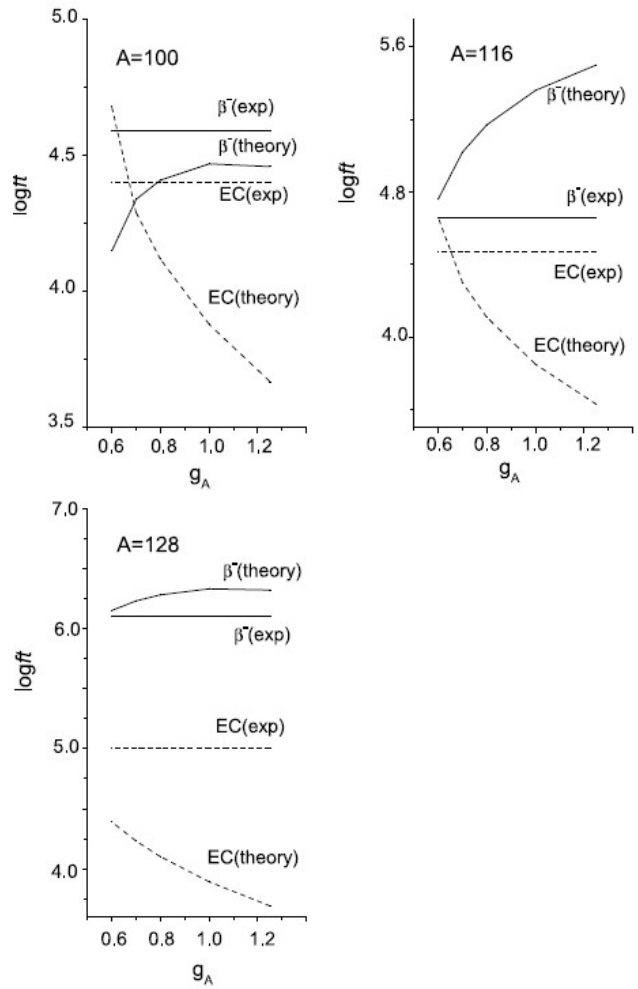


Suhonen & Civitarese
Phys. Lett. **B725**, 753 (2013)



M(2ν) keeps getting contributions up to *E*x ~ 12 MeV; very different behaviors for different cases.

Let g_A vary:
better agreement found using a different g_A for each nucleus



CENPA
Center for Experimental Nuclear Physics and Astrophysics