Past searches for keV neutrinos in beta-ray spectra

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supported by GAČR, P203/12/1896

The v-Dark 2015 Workshop
TUM Institute for Advanced Study
Garching, Germany, Dec 7-9, 2015
1. β-ray spectroscopy
2. Constraints on $m_\nu$ of light neutrinos
3. Past searches for heavier neutrinos
4. Summary
1. β-ray spectroscopy

**History:** powerful tool of experimental nuclear physics

**Present:** model-independent constraint on the neutrino mass

Magnetic β-ray spectrometer
L. Meitner, O. Hahn, O von Bayern
Natural radioactive substances

**β-spectrum is continuous**

*J. Chadwick, 1914*

RaB+C \( ^{214}\text{Pb} + ^{214}\text{Bi} \)

\( E_\beta \) up to 3.3 MeV

Two detectors:
- current in ionization chamber
- Counts in Geiger counter

*Deutsches Museum in Munich*

O. Dragoun
Theory of $\beta$-decay assuming existence of both neutrino of W. Pauli and weak interaction (E. Fermi, 1934):

$$\frac{dN}{dE} = A \cdot F(E, Z + 1) \cdot p \cdot (E + m) \cdot (E_0 - E) \cdot \sqrt{(E_0 - E)^2 - m_\nu^2}$$

Kurie graph

$$K = \left[ (E_0 - E) \sqrt{(E_0 - E)^2 - m_\nu^2} \right]^{1/2}$$

E. Fermi from measured $\beta$-spectra of that time:

$m_\nu << m_e$, probably $m_\nu = 0$
2. Constraints on $m_\nu$ of light neutrinos

Iron magnetic β-ray spectrometer

$\Delta E_{\text{instr}} = 1.5$ keV at $E = 167$ keV

$\Omega/4\pi = 1 \cdot 10^{-3}$

Kurie plot:

$E_{\nu} < 5$ keV

Cook et al.
Phys. Rev.
73 (1948) 1395.
From \( m_\nu < 5 \text{ keV} \) (1948) to \( m_{\nu_e} < 2.3 \text{ eV} \) (2005)

- MAC-E filter at Mainz Uni. \((\Delta E_{FW} = 5 \text{ eV})\)
- Now: KATRIN monitor spectr. \((\Delta E_{FW} = 1 \text{ eV})\)

\[ |\nu_\alpha> = \sum U_{\alpha i} |\nu_i> \]
\[ \alpha = e, \mu, \tau \]
\[ i = 1, 2, 3, (4?) \]

Calculated \( \beta \)-spectrum of tritium
\[ m_1 = 0.2 \text{ eV} \]
\[ m_2, m_3, |U_{ei}|^2 \text{ from oscil. exp.} \]

\[ m_{\nu_e} = \sqrt{\sum_{i=1}^{3} |U_{ei}|^2 \cdot m_i^2} = 0.20057 \text{ eV} \]
3. Searches for heavier neutrinos

R. E. Shrock (1980):

- search for neutrino mass states $m_i$ in $\beta$-spectra
- the kink at $E_0 - m_i$ with amplitude $|U_{ei}|^2$
- $|U_{e4}|^2 < 0.1$ for $0.1 \text{ keV} \leq m_4 \leq 3 \text{ MeV}$

Kurie plots of tritium $\beta$-spectrum

$$s_{\text{exp}}(E) = \int R(E, E') \cdot s_{\text{th}}(E', m_{\nu_e}) \cdot dE'$$
3.1 The first claim for the 17 keV neutrino

- Tritium ions (10 – 15 MeV) implanted into Si(Li) detector.
- Depth (0.25 – 0.45 mm) sufficient to stop all betas and bremsstrahlung photons

Deviation at 1.5 keV → massive v component
mass of 17.1 ± 0.2 keV
admixture of 3 ± 1 %.

Later, improved screening correction for low-energy beta → admixture reduced to 1.1 ± 0.3 %.
3.2 Further **claim for** the 17 keV neutrino (**an example**)

Hime and Jelley

\[ |U_{e4}|^2 = 0.85\% \]

\[ |U_{e4}|^2 = 0 \]

Kink expected at \( Q_{\beta} - m_\nu = 150 \text{ keV} \)

**Semiconductor spectrometer**

- Si(Li) detector
- Anti-scatter baffle
- \(^{35}\text{S source}\)
- Detector aperture
- Source aperture
3.3 Evidence against the 17 keV neutrino (an example)

Magnetic spectrometer with 30 independent detectors

Conversion electrons from $^{109}$Cd calibration source

Response function of the whole setup


$^{63}_{28}Ni \rightarrow ^{63}_{29}Cu$

$Q_\beta = 67$ keV

Emission of $100\gamma$ photon

Low-energy tail

$Q_{\text{EC}} = 214$ keV

$Q_{\text{CC}} = 214$ keV

$^{109}_{47}Ag$

$^{109}_{48}Cd$

$^{109}_{49}Cd$

KLM&KLN Auger
$|U_{e4}|^2$ upper limits from $^{63}\text{Ni} \beta$-spectrum

17 keV ν admixture

**free:** $|U_{e4}|^2 = (-1.1 \pm 4.5) \cdot 10^{-4}$  
$\chi_r^2 = 1.01$

**fixed:** $|U_{e4}|^2 = 0.01$  
$\chi_r^2 = 1.45$

Ohshima et al.  

$|U_{e4}|^2 = 0.01$  
22 σ away

Upper limits including systematic uncertainties

$|U_{e4}|^2$ at 95 % CL:

- $< 0.073 \%$  
  for $m_4 = 17$ keV

- $< 0.15 \%$  
  for $m_4 = 10.5$ to 25 keV

Fits and statistical uncertainties
3.4 **Evidence against** the 17 keV neutrino (*an example*)

- **Si(Li) spectrometer** with **magnetic guiding**

- **Solid angle** $\Omega = 2\pi$ sr
  - weak source (kBq) $\rightarrow$ smaller $E_{\text{loss}}$
  - $\rightarrow$ smaller pileup

- **No baffles** $\rightarrow$ smaller $e^-$ scattering

- **Adjustable impinge angle**
  - $\rightarrow$ smaller $e^-$ backscattering
  - 80° on source, 30° on detector

- **Magnetic mirror effect**
  - $e^-$ backscattered with $\theta > 30^\circ$ are returned to detector within ns
  - $\rightarrow$ reduced backscattering tail

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Mortara et al.
Comparison of measured $\beta$-spectra with theory (Mortara et al.)

**Pure $^{35}$S source**

$Q_{\beta^-} m_4 = 150$ keV

$|U_{e4}|^2 = 0.85\%$

$\chi^2_r = 2.8$

**Composite $^{35}$S + $^{14}$C source**

 Added 1.35% of $^{14}$C

Fitted:

$^{35}$S + $(1.4\pm0.1)\%^{14}$C

$\chi^2_r = 1.06$

$^{35}$S only

$\chi^2_r = 3.59$

- **No shape corrections were needed**
- **Experiment had sufficient sensitivity**

Fitting admixed $\beta$-spectrum is more difficult than searching for a kink
\[ |U_{e4}|^2 \] upper limits from \(^{35}\text{S} \) \( \beta \)-spectrum

\[ Q_{\beta^-} = 167 \text{ keV} \]

The 17 keV \( \nu \) admixture:
not \( \approx 1 \% \)
but \( < 0.18 \% \)

Mortara et al.
70 (1993) 394
3.5 Our experience from searches of keV neutrinos

a) False 0.3% admixture of 17 keV \( \nu \) in \( ^{35}\text{S} \) \( \beta \)-spectrum

\[
S_{\text{exp}}(E) = \int R(E, E') \cdot s_{\text{th}}(E', m_{\nu_e}) \cdot dE'
\]

Müller et al. Z. Naturforsch. 49a (1994) 874

Together with Tech Uni München

Neglected scattering on diaphragm
\[\rightarrow\] wrong \( R(E, E') \)
\[\rightarrow\] false 0.3 % admixture of the 17 keV neutrino
b) Precision description of measured $^{241}\text{Pu} \beta$-spectrum

$Q_\beta = 20.8 \text{ keV}, \ T_\frac{1}{2} = 14 \text{ y}$

Dragoun et al.
J. Phys. G
25 (1999) 1839

Vacuum evaporated source
• $\gamma$-spectroscopy: activity, purity, homogeneity
• $\alpha$-spectroscopy: thickness

Our electrostatic electron spectrometer

Adjustable $\Delta E_{\text{instr}}$

Known spectrometer response function $R(E, E')$
MC simulation of electron energy losses within radioactive samples

*individual elastic and inelastic electron collisions*

**Verification of Pu energy loss function**

- **Calculated shapes**
  - Lorentzian for natural width
  - Gaussian for resolution function
  - MC simulated energy losses

**Application to $^{241}$Pu $\beta$-ray source**

- **Energy losses**
  - due to backscattering
  - within Pu layer
  - within contamination overlayer

*Measured* at JINR Dubna
Electron spectra of $^{241}\text{Pu}$ and $^{241}\text{Am}$

Source: $^{241}\text{Pu}$
6.5 MBq, $4.2 \cdot 10^{15}$ atoms
1.7 nm thick

Electrostatic spectrometer:
- region of 0.2 to 9.2 keV
- 5 eV step, 1 s exposure per point and sweep
- 10 000 sweeps, 5700 h, $10^8\beta$-particles

Measured shape reproduced down to 2 keV without any artificial fitting parameter

Upper limits on $|U_{e4}|^2$ from three $\beta$-emitters
c) Test of measurement stability

- Comparison of partial spectra taken in successive time intervals
- **Universal method:**
  - no theoretical spectrum is needed
  - no test run is needed

\[
\chi^2_r(j, m) = \frac{1}{n-1} \sum_{i=1}^{n} w_{jm} \cdot \left( k_{jm} - \frac{N_j^m}{N_i} \right)^2
\]

Dragoun et al.
Nucl. Instr. Meth.
116 (1974) 459

See also Végh et al.
Nucl. Instr. Meth.
A281 (1989) 605

No.1 shifted by 1 \cdot 10^{-4}
3.6 The best upper limits on $|U_{e4}|^2$

Derived from measured $\beta$-ray spectra

- $^3$H, MAC-E-Filter
- $^3$H, MAC-E-Filter
- $^{187}$Re, low-temp. calorim.
- $^3$H, magn. spectr.
- $^3$H, implant. in Si(Li) spectr.
- $^{63}$Ni, magn. spectr.
- $^{63}$Ni, magn. spectr.
- $^{35}$S, Si(Li) sp. + magn. colim.
- $^{64}$Cu, magn. spectr.
- $^{20}$F, magn. spectr.

See also Kink search in $\beta$-decay
Review of Particle Properties
http://pdg.lbl.gov/2015
4. Summary

- **Past β-spectroscopy:** \(|U_{e4}|^2 < 4 \cdot 10^{-3}\) for \(m_4 = 2 - 40\) keV
  \(< 5 \cdot 10^{-4}\) for \(m_4 = 14 - 20\) keV

- **17 keV neutrino:** \(|U_{e4}|^2 \approx 1\%\) found in 7 different experiments
  at 4 different institutions
  using 5 different isotopes

- **Lesson for future experiments:**
  - **Calibrations** should bracket the studied interval
  - Examine **long-term stability** of the apparatus
  - \(\chi^2\) test is not enough, prove sufficient **sensitivity**
  - MC simulations are educational, but examination of **systematic uncertainties** is unavoidable

**NOW DISSPROVED**
see review by Wietfeldt and Norman Phys Rep 273, 149

**False results** mainly caused by
- electron energy losses in sources
- electron scattering on slits
- inaccurate response function

Good luck to our followers!