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FIRST STEPS TOWARDS THE MEASUREMENT OF
NEUTRINO MASSES IN ELECTRON CAPTURE *)

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ABSTRACT

The Aarhus-CERN-Risø collaboration has performed preliminary experiments whose goal is to measure $m(\nu_e)$ in processes involving weak capture of orbital electrons. I discuss the measurement of the lifetime and Q-value of the key isotope : ^{163}Ho . X-ray enhancements in the internal bremsstrahlung spectrum in e-capture (IBEC) may make the rate large enough for IBEC to be competitive with ^3H β -decay. The theory of these enhancements has been checked in ^{193}Pt decay. Future possibilities and a new methodology are briefly discussed.

*) From a talk at the Third Workshop on Grand Unification at the University of North Carolina, Chapel Hill, NC, April 1982.

FOREWORD

I have been asked by Paul Frampton, organizer of this TWOGU, to report on the progress of experiments aiming at the measurement of $m(\nu_e)$ in electron capture. It is very easy for a theorist to report on experiments: one need not understand what one is saying, and the audience reacts with a motherly patience of an unusual kind. The people responsible for the work I will talk about are: J.V. Andersen, D.F. Anderson, G.J. Beyer, G. Charpak, B. Elbek, H.⁰A. Gustafsson, P.G. Hansen, B. Jonson, P. Knudsen, E. Laegsgaard, J. Pedersen and H.L. Ravn.

INTRODUCTION

"Research is when one does not know what one is doing"¹⁾. In this sense, the attempts to measure neutrino masses are among the purest forms of research: we have no serious prejudices about the answer. All one can say, and this is a very positive statement, is that the arguments defending massless neutrinos are very weak. Our present understanding of elementary particles and their interactions is based on unified gauge theories. In their realm, everything not explicitly verboten is allowed, and happens. Non-vanishing neutrino masses and mixings, in all models but one [minimal $SU(5)$ ²⁾], are not forbidden. The mass spectrum of all particles, not only neutrinos, remains an absolute mystery, perhaps the biggest single challenge to contemporary particle theory. Measurements, or even upper limits, on neutrino masses could conceivably constitute an important clue.

The most restrictive experiments on electron (anti-) neutrino masses deal with Tritium beta decay, and they are briefly discussed in the next section. The goal is to devise alternative methods to measure or constrain the electron neutrino mass with comparable or superior precision. We shall see that we are still far from this difficult goal, and that hope is also far from being lost.

TRITIUM BETA DECAY

The best upper limits on electron (anti-) neutrino masses

$$m(\bar{\nu}_e) < 60 \text{ eV} \quad (90\% \text{ confidence}) \quad [\text{Bergkvist}^{3)}] \quad (1)$$

$$m(\bar{\nu}_e) < 65 \text{ eV} \quad (95\% \text{ confidence}) \quad [\text{Simpson}^{4)}] \quad (2)$$

and the celebrated ITEP result giving a lower limit:

$$14 \text{ eV} < m(\bar{\nu}_e) < 46 \text{ eV} \quad (99\% \text{ confidence}) \quad [\text{Lubimov et al.}^{5)}] \quad (3)$$

result from the analysis of the shape of the electron energy spectrum⁶⁾ in Tritium beta decay near its endpoint, E_{max} . Tritium is a substance of choice because $E_{\text{max}} \sim 18.6 \text{ keV}$ is a particularly low value, the complete spectrum is particularly "short" and the fraction of events in a fixed interval near the endpoint is particularly large. For $m_\nu = 0$, the fraction of events in the window $E_{\text{max}} - 30 \text{ eV} < E_e < E_{\text{max}}$ would be $g \sim 10^{-8}$ in Tritium decay. We will in all cases define this fraction of events (normalized to the total decay rate) as the theoretical figure of merit, g , in a given process.

In ^3H β -decay the nuclear charge changes by a factor of two. The electron in the ^3H atom, with $Z = 1$ and principal quantum number $n = 1$, does not have the correct wave function to feel fully at home in the daughter atom with $n' = 1$, $Z = 2$. Thus, the decay of atomic Tritium will proceed with several branches with different n'

The mass differences between the differently excited $^3\text{He}^+$ ions are of the same order of magnitude, or smaller, than the resolution of existing experiments [i.e., $\text{He}^+(n'=2) - \text{He}^+(n'=1) \sim 41 \text{ eV}$]. Moreover the expected branching ratios for different n' do not differ by orders of

magnitude [70% for $n' = 1$, 25% for $n' = 2$, ..., in atomic tritium⁷⁾]. Thus, the shape of the spectrum tens of eV's from the endpoint, where one hopes to see the neutrino mass effects, is fairly complicated. There are two complementary ways out of this problem:

- i) Trust the theory of the spectral shape.
- ii) Improve the resolution to such a level that the different decay branches are experimentally observable.

Clearly, the very difficult second way out would be the most satisfactory, particularly for experiments whose source is not atomic Tritium or a beam of tritons. I will not further discuss the "molecular" problems in the decay of Tritium containing molecules⁵⁾ or Tritium-coated surfaces³⁾, and refer the reader to the recent literature on the subject⁸⁾. My feeling is that we have no serious reason to distrust the ITEP result, and every reason to attempt to reproduce it independently, as well as to develop the theoretical understanding of endpoint shapes in different environments.

It must be emphasized that the problems associated with the several branches of Tritium decay do not apply to inclusive or calorimetric experiments. This type of experiment measures all the energy of Tritium decay (but that of the escaping neutrino) rather than the energy of a single electron. Since J.J. Simpson has reviewed this approach at this Workshop, I will not further elaborate upon it.

ELECTRON CAPTURE; ^{163}Ho DECAY

In β -decay, the sensitivity to a neutrino mass occurs for electron energies close to their maximum kinematically allowed value. There, the neutrino energy is smallest and the effects of $m_\nu \neq 0$ would be largest. No further thought is required to conclude that any process involving very low energy neutrinos is of interest; provided its rate is not ridiculous. It is very easy to imagine many such low energy processes and somewhat more difficult to overcome the proviso concerning their rate. An example: ^{187}Re beta-decays with $E_{\text{max}} \sim 2.6$ keV, but its lifetime is $4 \cdot 10^{10}$ years. Even if other very low energy β -decays existed, their fate would be similar: β -decay rates go down fast with the available energy. There is a form of inverse β -decay: orbital electron capture, where the problem of diminishing rate with diminishing phase space is less serious. In electron capture a nucleus (Z, A) transmutes to $(Z-1, A)$ as an orbital electron is captured and converts into

a neutrino. The $\ell = 0$ electron wave functions at the origin grow with $Z^{3/2}$, somewhat compensating in large Z materials for an eventually small energy release. The isotope ^{163}Ho decays by electron capture to ^{163}Dy , with a record low Q value (mass difference between the neutral atoms in their ground state). For this reason ^{163}Ho , one way or another, is a good thing to have at hand, in view of possible measurements of neutrino masses. [Another reason, concerning internal bremsstrahlung and electron ejection in ^{163}Ho decay, will be presently discussed.]

Up to a few months ago, the data concerning ^{163}Ho were contradictory. Nuclear reaction data⁹⁾ gave a Q -value of -2.9 ± 3.1 keV. Electron capture by ^{163}Ho had been observed from the M shell but not from the L shell^{10),11)}, bracketing the Q value between the corresponding Dy ionization energies: $9.1 \text{ keV} > Q > 2.05 \text{ keV}$. Wapstra and Bos⁹⁾ suggested a readjustment of the capture result¹⁰⁾ to 6 ± 3 keV, and combined it with the nuclear reaction data, to give $Q = 2.6 \pm 3$ keV. The nuclear matrix elements in ^{163}Ho decay can be estimated with confidence by comparison with ^{161}Ho decay^{12),13)}. This allows one to turn the limit $9.1 \text{ keV} > Q$ into a lower limit of 150 years for ^{163}Ho decay^{1),12),13)}. The half-life of ^{163}Ho , as measured in 1968, was 33 ± 23 years¹⁰⁾. New attempts to clarify this perversely controversial body of data seemed mandatory.

An Aarhus-CERN-Risø collaboration has recently measured¹³⁾ the M-capture half-life of ^{163}Ho and the ($^{163}\text{Ho}, ^{163}\text{Dy}$) Q -value to be

$$T_{1/2}^M = (4.0 \pm 1.2) 10^4 \text{ years} \quad (4)$$

$$Q = 2.3 \pm 1.0 \text{ keV} \quad (5)$$

As we proceed to explain, this implies a half-life $T_{1/2}(^{163}\text{Ho}) = (7 \pm 2)10^3 \text{ y}$. This preliminary experiment can also be used to set an upper limit $m(\nu_e) < 1.3 \text{ keV}$ ¹³⁾.

A considerable initial difficulty in experiments involving very low energy radiation is the preparation of the radioactive source. Any radioactive contaminants constitute a higher energy background, and must be eliminated to a very high degree. This is particularly true for internal bremsstrahlung experiments (to be discussed in the next chapter) where one is searching for a very tiny signal: the levels of radioactive decontamination must reach one part in 10^{14} or 10^{15} . This

decontamination level has been achieved in the preliminary ^{163}Ho experiment and the method¹³⁾ deserves a little pause.

A 2.4 μA beam of 600 MeV protons from the CERN PS is shot into a Tantalum target. Rare-earth elements from the hot target evaporate, are surface ionized and mass separated in the ISOLDE facility. The mass 163 elements are collected and counted in a Faraday cup. A brief "cooling" time allows them to decay into the element of interest ^{163}Ho [or into stable ^{163}Dy]:

The on-line separator is not perfect, after some weeks of cooling a gamma ray spectroscopy analysis of the source reveals a contamination of ^{147}Gd (at the 1 per thousand level) and ^{167}Tm , ^{169}Yb (both at the $3 \cdot 10^{-6}$ level). There remain eleven or twelve orders of magnitude to go in the level of decontamination. This extra purification is achieved by a somewhat complex wet chemical procedure involving a triple ion-exchange chromatography. The method is summarized in next page. For tracing purposes a small amount of short lived ^{160}Ho is added; measurement of its activity results in a yield of 44% for the chemical clean-up. The purified stock of radioactivity is vacuum evaporated onto a backing, with ^{160}Ho still a tracer, to check the evaporation yield. After all this fiendishly complicated gymnastics one may or may not trust the estimated number of Ho atoms in the source. This number is measured independently by back scattering of α -particles (from the Aarhus single stage Van der Graaf accelerator) on the source. A typical recoil energy spectrum at 170° , from incident α 's of 3.5 MeV, is shown in Fig. 1. Peaks in the spectrum reflect surface impurities, bulk

Figure 1

impurities give rise to step functions. If the well-resolved peak at mass 164 ± 2 is interpreted as ^{163}Ho , its integrated number of atoms ($5 \cdot 10^{13}$ for one of the sources) is in excellent agreement with the number obtained from the Faraday cup counting, chemical separation and subsequent evaporation. Thus the method of making small but very pure sources seems to be under control. No major problem in the purification of mightier sources is foreseen.

When an electron is captured by the nucleus of ^{163}Ho , a hole is left in the daughter ^{163}Dy atom, which subsequently emits Auger electrons and X-rays (preferentially the former for holes in M or higher levels). The radiation from M holes is the more energetic and readily detectable [the ionization energies in Dysprosium are $E(M_1) = 2.05$ keV, $E(M_2) = 1.84$ keV, $E(N_1) = 0.416$ keV, $E(N_2) = 0.332$ keV, capture from levels of higher angular momentum is negligible]. The M X-ray spectrum has been measured with considerable resolution by a group in the USA¹⁴⁾. The Aarhus-CERN-Risø collaboration¹³⁾ has measured M X-rays and Auger electrons from the carefully prepared sources described in the previous paragraph. The detectors in this preliminary experiment (a multi-wire proportional chamber and a gas flow proportional counter) had a very coarse resolution, but were good enough to observe the M Auger and X-ray signals at the expected energy. Since the number of atoms in the source is known, this allows one to determine the half-life for M-capture, already quoted in Eq. (5). A theoretical M-Auger fluorescence

yield¹⁵⁾, must be used to compute the half-life from the X-ray yield. The M-Auger and X-ray measurements result in compatible lifetimes. The error given in Eq. (5) brackets the measurements from different sources, detectors and measured particles.

The M capture rate can be written as

$$\omega = K G_F^2 \mathcal{N}^2 [A(M_1)\phi(M_1) + A(M_2)\phi(M_2)]$$

$$\phi(M_1) = p_\nu E_\nu = [Q - E(M_1)] [(Q - E(M_1))^2 - m_\nu^2]^{1/2}$$

where ϕ is a phase space factor, G_F is Fermi's coupling constant, K is a number, $A(M_i)$ are atomic factors, essentially squared electron wave functions at the origin, and $\mathcal{N}$ is the square of a nuclear matrix element. The numbers one would like to extract from the data are Q and m_ν . All other factors are known including, in the rather exceptional case of ^{163}Ho , the nuclear matrix element^{12),16),17)}. I will not indulge here in the details of the semi-empirical determination of $\mathcal{N}[^{163}\text{Ho}]$, that are given at length in Ref. 13). The point is that the phase space factor can be determined. For the dominant M_1 -capture term, the result is:

$$\begin{aligned} \phi(M_1) &= (Q - 2.05 \text{ keV}) [(Q - 2.05 \text{ keV})^2 - m_\nu^2]^{1/2} = \\ &= (0.53 \pm 0.10 \text{ keV})^2 \end{aligned} \quad (6)$$

which does not fix Q and m_ν but a combination thereof. If m_ν is set to zero, the Q -value is

$$Q[\text{EC}, m_\nu=0] = 2.58 \pm 0.10 \text{ keV} \quad (7)$$

Clearly a value of m_ν at the level of tens of eV would only affect this result by a negligible correction of order $1 + (m_\nu/530 \text{ eV})^2/2$. The Q -value of Eq. (7) is only 530 eV above $E(M_1, \text{Dy}) = 2.05 \text{ keV}$. This means that N-capture will beat M-capture, thanks to its much bigger phase space, and in spite of a suppressed wave function at the origin. Thus the half-life of ^{163}Ho is much shorter than the measured M-half-life. A calculation with capture from all levels taken into account gives the result $T_{1/2} = (7 \pm 2) \text{ millenia}$, quoted before.

The soul is not entirely satisfied in setting $m_\nu = 0$ to obtain the result of Eq. (7). For this reason, the Aarhus-CERN-Risø collaboration¹³⁾ has directly measured Q in an independent nuclear reaction experiment, having nothing to do with neutrino masses. The central idea is to determine Q -values (mass differences) from the kinematics of the reactions

Reference lines are given by the elastic scattering of ^2H and ^3He ; singly ionized ^3He was used, to provide a nearby reference line for tritons. A very preliminary experiment of this kind has been run with the Niels Bohr Institute tandem accelerator, and its pretty details are outlined in Ref. 13). The $(^{163}\text{Ho}, ^{163}\text{Dy})$ Q -value is obtained from the combined results of Eqs. (8a,b) and has already been quoted in Eq. (5). The error bars in this experiment, and the limits on m_ν to be presently discussed, are expected to become considerably tighter in the near future.

Given the nuclear reaction Q -value of Eq. (5) and the electron capture phase space measurement of Eq. (6), a domain of possible values of Q and m_ν can be determined. This is graphically done in Fig. 2, where $\phi^{1/2}(M_1)$ is plotted against Q . Curves for the function $\phi^{1/2}(Q, m_\nu)$ of Eq. (6) are given; as functions of Q for different values of m_ν (in keV). The horizontal strip is the experimental value of $\phi^{1/2}$. The vertical strip is the nuclear-reaction experiment value of Q . They overlap in the dotted region, giving a rough upper limit $m_\nu \lesssim 1.3$ keV.

Figure 2

This limit will improve as the error bars, particularly from the nuclear reaction experiment, narrow down. Should they converge towards the lowest allowed Q-values, the electron neutrino is a tachyon ($m_\nu^2 < 0$).

THEORY OF INTERNAL BREMSSTRAHLUNG IN ELECTRON CAPTURE: (IBEC)

A photon may be emitted as a radiative correction in an electron capture process

$$Z \rightarrow (Z - 1)^H + \gamma + \nu \quad (9)$$

Here Z and $(Z - 1)^H$ refer to atoms, the daughter one being left with a hole H in the orbital from which the electron is captured. Photons, on the other hand, are emitted in electron capture as X-rays that "follow" the dominant non-radiative capture process

$$Z \rightarrow (Z - 1)^{\tilde{H}} + \nu \quad (10a)$$

$$\downarrow \rightarrow (Z - 1)^H + \gamma \quad (10b)$$

The photon spectrum in Eq. (9) is referred to as an "Internal bremsstrahlung spectrum", while the approximately monochromatic photons of Eq. (10b) are referred to as X-rays. Since photons are not unlike each other, it is not difficult to find situations where the distinction makes no sense¹⁸⁾. As an example, consider the case $H = nP$; the hole in Eqs. (9) and (10b) is in an angular momentum $L = 1$ state. In a non-relativistic approximation, an $L = 1$ wave function vanishes at the origin and "direct" capture from such an orbital is forbidden. The way the process of Eq. (9) takes place for $H = nP$ is via the two steps Eqs. (10a,b). The electron is captured from a level $\tilde{H} = \tilde{n}S$ and the photon originates in the transition $\tilde{H} \rightarrow H\gamma$. For photon energies corresponding to X-ray lines, $E_\gamma = E_H - E_{\tilde{H}}$, the process is resonant and the photon can be called an X-ray. At energies not corresponding to X-ray lines the photon yield can be regarded as a bremsstrahlung spectrum or as a sum of tails of Breit-Wigner shaped X-ray lines.

The Q-value ($Q = M(Z) - M(Z-1)$) in electron capture decays is typically much bigger than the (positive) ionization energy $E(H)$ of the missing electron in the daughter atom. The energetics of a typical three body decay, Eq. (9), is shown in the left-hand side of Fig. 3.

Figure 3

The mass difference between parent and daughter atoms is $Q - E[H]$. Recoil effects are negligible and $E_\gamma + E_\nu = Q - E[H]$, in an obvious notation. The maximum photon energy, upon neglect of the neutrino mass, is also $Q - E[H]$. A typical $H = 2P$ photon spectrum is shown in the right-hand side of Fig. 3. The process occurs via capture from $\tilde{n}S$ states, as in Eqs. (10). For $\tilde{n}S = 1S$, there is a photon energy $E_\gamma = E[1S] - E[2P]$ at which the spectrum peaks at an X-ray resonance, as in the figure. Virtual capture from $\tilde{n} > 1$ states also contributes to the matrix element, giving poles at virtual (negative) photon energies: $E_\gamma = E[nS] - E[2P]$, also symbolically shown in the figure. The endpoint of the photon spectrum in the three body decay Eq. (9) is sensitive to a neutrino mass in the same way as the endpoint of the electron spectrum in β -decay. But the photon spectrum matrix element at the endpoint is typically very small: $E_\gamma \approx Q - E[2P]$ is far away from the X-ray resonances where the matrix element is large. An example: the figure of merit for the dominant (2S) spectrum in the favourable case of ^{55}Fe decay (number of events in the last 30 eV divided by the total decay rate) is $g \sim 4 \cdot 10^{-16}$, to be compared with $g(^3\text{H}) \sim 10^{-8}$. A neutrino mass hunt with ^{55}Fe would be out of the question: rates are too ridiculous.

The problem of tiny IBEC endpoint rates may be solvable, and the possibility of neutrino mass measurements in IBEC processes may be resurrected. Refer for definiteness of the 2P spectrum of Fig. 3. The endpoint energy $Q = E[2P]$ and the resonant energy $E[1S] - E[2P]$ are independent quantities. For isotopes with $Q \approx E[1S]$ the rate would be enhanced at the endpoint energy of interest to the neutrino mass hunter. Even for $Q < E[1S]$ (no accidental degeneracy within a few X-ray widths), there is a considerable enhancement factor of the bremsstrahlung spectrum¹⁹⁾. There is a short list of elements¹⁹⁾ with $Q < E[1S]$, ^{193}Pt is an example. The arguments can be repeated, and the figures of merit further increased, for elements with $Q < E[2S]$ (here the list is short: ^{163}Ho and nothing else known).

^{193}Pt decays by electron capture into ^{193}Ir . The decay energetics is shown in the left-hand side of Fig. 4. Capture from the 1S level is energetically forbidden. The shapes of the $H = 2P$ and $H = 3P$ spectra are given in the right-hand side of the figure. The resonances due to intermediate 1S capture now lie above the endpoint, but their presence enhances the matrix element at that point. In the 3P spectrum the $2S \rightarrow 3P$ resonance is real, the zero above it reflects the interference of this resonance with the virtual $1S \rightarrow 3P$ one. The figure of merit for the 2P spectrum in ^{193}Pt is $g \sim 4 \cdot 10^{-13}$, a three orders of magnitude improvement over the typical case of ^{55}Fe , but still small enough to make experiments attempting to measure neutrino masses at the ~ 30 eV level extremely difficult. ^{163}Ho may be the only hope.

Figure 4

The 2P spectrum ends at $Q - E[2P]$, and the spectra for capture from higher levels end up at a higher energy: $Q - E[3P]$ for the case of 3P capture. The endpoint of the 2P spectrum is therefore submerged in a large background of photons from other captures. To see a clean endpoint one must disentangle the different spectra. This may be done in a coincidence experiment. The 2P spectrum, for instance, may be observed via the chain

$$Z \rightarrow (Z - 1)^{2P} + \gamma + \nu \quad (11a)$$

$$\downarrow \rightarrow (Z - 1)^{3S} + \gamma_X \quad (11b)$$

where the $2P \rightarrow 3S$ X-ray signs the 2P hole. Coincidence experiments of this type have been performed in the past, but not, to our knowledge, with the measurement of neutrino masses in the back of the mind.

Atomic and molecular interplay problems are much less serious in IBEC coincidence experiments than in Tritium beta decay¹⁹⁾. In electron capture the nuclear charge changes from Z to $Z-1$, a small fractional change in comparison to 3H decay. Moreover, it is not the charge, but only the charge distribution in the inner atom that changes. The outer atomic electrons, that may change level by a few eV, are practically insensitive to the small rearrangement of charge in the inner atom.

COINCIDENCE IBEC EXPERIMENTS IN ^{193}Pt

The Aarhus-CERN-Risø collaboration²⁰⁾ has made a preliminary measurement of the bremsstrahlung 2P spectrum in coincidence with the subsequent X-rays, as in Eqs. (11). The immediate aims are to check the theory of resonant enhancements, described in the previous chapter, and to demonstrate the coincidence method in a search for neutrino mass limits. Confidence in the theory may pump enthusiasm into the effort of pushing the ^{163}Ho measurements to their status of the art limit, where a hope exists to measure neutrino masses in the range of interest (Tritium-like or better).

To have an early start, the ^{193}Pt source was not made by isotope separation at ISOLDE. An estimated 10^{16} atoms of ^{193}Pt per typical running period should have survived in old lead targets used for the production of mercury isotopes. About 1kg of lead from these targets was sublimated and treated with a complicated sequence of liquid extractions

and chromatographic purifications, not unlike the ^{163}Ho ones. About $5 \cdot 10^{14}$ ^{193}Pt atoms were obtained this way, with a decontamination factor of order 10^{12} to 10^{13} .

Bremsstrahlung photons from this source were measured with a Ge detector and L X-rays in coincidence were measured with a Na I detector. The data I will present are from a mere nine days of running plus nine days of background counting. Data from longer running periods and better sources and detectors should be available in the near future.

The single photon bremsstrahlung spectrum is shown in Fig. 5. The theoretical prediction¹⁹⁾ is shown as the full line. Both theory and experiment are given in an absolute scale. The data have not been deconvoluted from the detector response, which is not bell-shaped, but has a low energy plateau and an escape peak. This quantitatively explains the data excess at the lower energies. Notice the suppressed energy scale: enormous L X-ray peaks at $E < 20$ keV are not shown.

The bremsstrahlung spectrum in coincidence with L X-rays is shown in Fig. 6, and compared with theory¹⁹⁾ (full line) in an absolute scale. The L X-ray peaks that should not be present in these data are now enormously suppressed, but still there. This is a limited time-resolution effect, what remains are accidental coincidences of radiation from two different atoms.

Figure 5

Figure 6

The agreement between theory and data is better than expected. The number of atoms in the source is not known with absolute precision. The theory ignores relativistic and screening effects, and is only semi-empirically improved to give the resonance positions at their correct values. Better data could only make the agreement worse. The agreement corroborates the presence of the resonance enhancement factor in ^{193}Pt IBEC. In this preliminary experiment the X-ray detector was not good enough to distinguish 2S from 2P X-rays, and to disentangle the corresponding IBEC spectra. Therefore, we should not yet have convinced the reader that the predicted enhancement of the 2P IBEC spectrum over the 2S IBEC spectrum (by a factor of ~ 100) is what is being observed. This can be done by a more detailed look at the shape of the data. The 2S spectrum is predicted to have a shape given essentially by phase space: $k(k_{\text{MAX}} - k)^2$, where k is the photon energy. In the 2P spectrum this shape is modulated by a matrix element $Q_{2P}^2(k)$ that has a virtual pole at the position of the $1S \rightarrow 2P$ resonance (19 keV above the endpoint). The number of events, divided by phase space, is shown in Fig. 7. The data agree in shape and magnitude with the theoretical 2P matrix element Q_{2P}^2 . In the same absolute scale the 2S prediction would be a horizontal line ~ 0.01 above the abscissa.

Figure 7

Figure 8

A typical neutrino mass hunt plot for the 2P spectrum is shown in Fig. 8. To get a straight line one must divide the number of events by photon momentum and by the non-trivial matrix element Q_{2P}^2 , then take the square root: this is neither a Kurie nor a Jordan plot, but the idea is the same. The endpoint energy is ~ 45.1 keV, giving a $Q[^{193}\text{Pt}, ^{193}\text{Ir}]$ value of 56.8 ± 1 keV (to be compared with the previously measured value²¹⁾ of 61 ± 3 keV). The insert in the figure compares the data with the expected shapes for $m_\nu = 0, 2, 4.1$ keV. Neutrino masses above ~ 1 keV are excluded by this preliminary experiment. The peculiar figure of 4.1 keV does not reflect some peculiarity in the characters of the authors, but the fact that the best limit on the electron neutrino mass (as opposed to the electron antineutrino mass) is $4.1 \text{ keV}^{22)}$.

THE FUTURE ?

The theory of resonant enhanced IBEC has been checked in ^{193}Pt . This may be something to write to Physics Letters about, but certainly not home, since the theory is essentially non-relativistic QED. The Q value in ^{163}Ho decay is measured to be very small. This implies a relatively very large figure of merit for the Ho IBEC spectra. To give an example, the number of events in the last 30 eV of the 4P capture spectrum, normalized to the total decay rate, is $g \sim 2 \cdot 10^{-10}$, a six orders of magnitude improvement over the favourable typical case of a K-capturing isotope, ^{55}Fe .

Presumably the Aarhus-CERN-Risø collaboration will attempt to measure, among others, the following bremsstrahlung photon-de-excitation-electron coincidences:

$$^{163}\text{Ho} \rightarrow ^{163}\text{Dy}^{N_3} + \gamma + \nu \quad (k_{\text{MAX}} \sim 2290 \text{ eV}) \quad (15a)$$

$$^{163}\text{Dy}^{N_5;N_{6,7}} + e^- \quad (E_e \sim 135 \text{ eV}, \text{BR} \sim 61\%)^{(23)} \quad (15b)$$

The techniques to measure photon energies in the keV range with efficiency and precision still have a long way to be developed. This extra challenge only makes the experiment more tempting. A discussion of the prospects of an IBEC ^{163}Ho experiment: rates, backgrounds, etc., is now possible, given that the Q-value is known; and should appear soon⁽²⁴⁾.

The transitions in Eqs. (12a), (13a), (14a) and (15a) are dominated by M_1 -capture, that makes them resonant a mere 530 eV below their endpoints. The fluorescence yield of an M_1 hole is very small: the atom much prefers to de-excite by the emission of Auger and Coster-Kronig electrons. This is not only true for "monochromatic" X-ray or electron de-excitations, but also for their tails⁽²⁵⁾: the IBEC spectrum and the spectrum of electron ejection in electron capture (EEEC). This means that the rate of the three body-process of electron ejection

$$^{163}\text{Ho} \rightarrow ^{163}\text{Dy}^{H_1,H_2} + e^- + \nu \quad (16)$$

is much bigger at the endpoint than the corresponding IBEC rates. Once again the kinematics must be specified by the detection of a signature for the H_1, H_2 holes:

$$^{163}\text{Dy}^{H_1,H_2} \rightarrow ^{163}\text{Dy}^{H_1',H_1'',H_2} + e^- \quad (17a)$$

$$\quad \quad \quad \downarrow \rightarrow ^{163}\text{Dy}^{H_1',H_1'',H_2',H_1''} + e^- \quad (17b)$$

The possibility to measure neutrino masses in the three-electron coincidence experiments, Eqs. (16) and (17) has been discussed in Ref. 25). The energy of electrons in the range of hundreds of eV's can be measured with great precision with electrostatic methods. This may make this kind of experiment very tempting.

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