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FROM EXPERIMENTS ON ELECTRON-CAPTURE BETA DECAY

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and

The ISOLDE Collaboration

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DETERMINATION OF THE ELECTRON-NEUTRINO MASS FROM EXPERIMENTS ON ELECTRON-CAPTURE BETA DECAY

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Abstract: The IBEC theory has been tested for the case of ^{193}Pt . The Q_{EC} value is 56.3 ± 0.3 keV, and the data make it possible to give an upper limit on the electron neutrino mass of 500 eV (90% C.L.). The partial beta-decay half-life for M capture in ^{163}Ho is $(4.0 \pm 1.2) \times 10^4$ y and the ^{163}Ho - ^{163}Dy mass difference is 2.3 ± 1.0 keV. From these independent Ho results a half-life of $(7 \pm 2) \times 10^3$ y and an upper limit on m_{ν_e} of 1.3 keV can be deduced.

1. Introduction

The possibility that neutrinos can be massive is at present attracting considerable theoretical and experimental attention. Most of the modern particle theories could incorporate and even suggest non-zero masses ranging between some hundred electronvolts and downwards [see, for example, De Rújula¹⁾]. Furthermore, the missing-mass problems in cosmology could be solved if neutrinos had masses of the order of some tens of electronvolts^{2,3)}. In view of the fundamental importance of these problems, more and better experiments are clearly needed.

There are essentially two ways of performing measurements of neutrino masses: the neutrino oscillation experiments (see, for example, ref. 3), and the studies of kinematics of weak interaction decay processes. Here we shall not concern ourselves with the former experiments, which may be very sensitive but which depend on a combination of mass differences and mixing angles. We shall instead focus our attention on the kinematic experiments which provide a direct limit to the mass, and in Table 1 we summarize the present status⁴⁻¹⁰⁾ for the different neutrino mass determinations.

In all the experiments on the electron-antineutrino mass, where the most stringent results are available, the determination of the mass has been obtained from a study of one single, very favourable decay process: namely the β^- decay of tritium:

With its low Q-value, tritium is clearly ideal for studies of this type. The determination of the antineutrino mass is based on the expected modification of the high-energy end-point of the continuous β^- spectrum¹¹⁾. The most striking result is, of course, the lower limit claimed by the ITEP (Moscow) group. This result has actuated many groups all over the world to try to make a verification of it. One obstacle to further progress seems, however, to be the corrections for atomic and molecular excitations in the final state, which are specially pronounced in the tritium decay.

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Table 1

Experimental neutrino mass limits, August 1982

	Mass limit	References	Conf. level (%)
$m_{\bar{\nu}_e}$	< 55 eV	Bergkvist ⁴⁾	90
	~ 35 eV	a) Lyubimov et al. ⁵⁾	99
	< 65 eV	Simpson ⁶⁾	95
m_{ν_e}	< 4.1 keV	Beck and Daniel ⁷⁾	67
	< 500 eV	This work	90
m_{ν_μ}	< 570 keV	Daum et al. ⁸⁾	90
	< 500 keV	Anderhub et al. ⁹⁾	90
m_{ν_τ}	< 250 MeV	Bacino et al. ¹⁰⁾	95

a) limits $14 \text{ eV} < m_{\bar{\nu}_e} < 46 \text{ eV}$.

We shall now turn our attention to the corresponding antiparticle, the electron-neutrino, which is associated with β^+ and electron-capture (EC) decays. A novel and intriguing method for determining its mass was proposed by De Rújula¹²⁾ a little more than one year ago. The suggestion is to study the shape near the end-point of the continuous internal bremsstrahlung spectrum (IB) in electron-capture beta decay. The IBEC spectrum is modified by a finite neutrino mass in a way that is completely analogous to that for the tritium electron spectrum: it has a horizontal tangent if the mass of the neutrino is zero and would be modified to have a vertical tangent if $m_{\nu} \neq 0$.

2. The theory of IBEC

The IBEC radiation is emitted in beta decay by the capture of bound atomic electrons according to the scheme

$$A_Z + e_{n,\ell,j}^- \rightarrow A_{Z-1} + \nu_e + \gamma_{IB}, \quad (2)$$

where n, ℓ, j are the quantum numbers of the bound electrons. This process has a three-body final state, and the spectrum of emitted photons is continuous with a maximum energy

$$k_{\max}^0 = Q_{EC} - B[n,\ell,j]; \quad m_{\nu} = 0, \quad (3)$$

where Q_{EC} is the energy available for EC decay and $B[n,\ell,j]$ is the binding energy of the captured electron.

For Q_{EC} large, compared with atomic binding energies, the dominant contribution to the IBEC spectrum arises from capture from the S-states. The shape of the S-wave IBEC spectrum was first derived by Møller¹³⁾ and by Morrison and Schiff¹⁴⁾. The shape is very simple and is found to be proportional to a universal three-body phase-space factor (daughter atom and two light particles) divided by k :

$$\frac{d\omega}{dk} \sim \phi(k) = k(k_{\max}^0 - k)[(k_{\max}^0 - k)^2 - m_{\nu}^2]^{\frac{1}{2}}, \quad (4)$$

where k is the photon energy and $k_{\max}^0$ its maximum allowed value for vanishing neutrino mass. The ratio of the radiative-to-non-radiative S capture is of the order of 10^{-4} and is proportional to $k_{\max}^{02}$. At low value for $k_{\max}^0$, which is clearly most

favourable for a neutrino-mass hunt, the S-wave IBEC intensities therefore become extremely low. The reason why an IBEC experiment may still compete successfully with the favourable tritium decay is due to the appearance of another mechanism: at low energies the IBEC spectrum arises mainly from P capture. This was first understood by Glauber and Martin¹⁵). In the P-wave IBEC the capture takes place from a virtual S-state associated with a radiative $P \rightarrow S$ electromagnetic transition. The resonant nature of the process leads to important enhancements of the photon intensity at low energies and, in particular, close to the resonance energies corresponding to $P \rightarrow S$ transitions, i.e. the normal atomic x-rays. The continuous nP IBEC spectrum differs, in fact, from an ordinary nS non-radiative capture followed by the radiation of a characteristic x-ray only in a relaxation of the requirement of energy conservation in the intermediate state. In the immediate neighbourhood of the line, the process is identical to the real, resonance emission of x-rays. On the other hand, the P-state intensity remains high also for energies that are considerably different from the resonance energies. The intensity observed at the off-resonance energies arises in the nP IBEC process, and there several virtual n'S-states contribute significantly to the photon spectrum.

The shape of the nP IBEC spectrum is, as demonstrated by Glauber and Martin¹⁵), proportional to the product of $\phi(k)$ [eq. (4)] and a matrix element $Q_{np}^2(k)$:

$$\frac{d\omega}{dk} \sim \phi(k) \cdot Q_{np}^2(k) . \quad (5)$$

The Q_{np} function was discussed in detail in ref. 15 for energies above the 1S x-ray pole, $k > B_{1S} - B_{2P}$, and later extended by De Rújula¹²) to the region below the pole. We show as example $Q_{2P_{3/2}}^2$ and $Q_{3P_{3/2}}^2$ functions for the case ^{193}Pt in fig. 1.

Fig. 1 The $Q_{2P_{3/2}}^2$ and $Q_{3P_{3/2}}^2$ functions for the element Pt calculated in the pole approximation [eqs. (10.5b) and (10.6b) in ref. 11]. The end-points of the respective IBEC spectra are indicated.

The EC Q-value has nuclear origin and varies for different isotopes of the same element, whilst the atomic binding energies are essentially constant. The challenge is thus to find nuclei with Q-values giving the maximum profit for the resonance enhancement. The ideal case would be one where Q has a value just below the S binding energy of one of the shells. The two most interesting cases found so far are ^{163}Ho and ^{193}Pt . In the following sections we shall describe the first results from our studies of their decay.

3. Detailed test of the theory for radiative P capture

The energy spectra of internal bremsstrahlung in electron capture have been measured for a large number of isotopes of elements, from Be ($Z=4$) to Tl ($Z=81$). The most recent review of the subject has been given by Bambynek et al.¹⁶⁾ in 1977. The 1S shape^{13,14)} of the spectra has been confirmed, and with the theory of Glauber and Martin¹⁵⁾ for the radiative P capture, the increase of the measured intensity at low energies could also be explained. The experimental results were, however, confined to the energy region above the 1S pole. As an example of the best data available, we show in fig. 2 the IB spectrum from ^{131}Cs ¹⁷⁾ measured in singles and in coincidence with K x-rays.

Fig. 2 Internal bremsstrahlung spectrum from ^{131}Cs measured by Biavati et al. (ref. 17). The curves show the prediction from the theory (ref. 15).

With the extension of the Glauber-Martin theory by de Rújula, further tests of the theory were needed -- especially data for energies below the 1S pole. An isotope with ideal parameters for this purpose is ^{193}Pt , which has a Q-value for electron capture some 20 keV below the K binding energy of the daughter atom, ^{193}Ir . Its decay can thus only take place via capture from the L, M, ... and higher shells. In the following we shall give the main findings from our studies of this nuclide.

3.1 THE PREPARATION OF THE ^{193}Pt SOURCE AND THE EXPERIMENTAL SET-UP

The source of ^{193}Pt used in our experiments contained 7×10^{13} atoms. The activity was extracted from about 1 kg of lead which had been used as target material at the ISOLDE facility at CERN. Only material that had had a cooling period of four years or more was chosen so that the only Pt isotope remaining was the long-lived isotope with mass 193 ($t_{1/2} = 50$ y). This activity could be extracted from the lead with a radiochemical method. First the lead was removed through vacuum sublimation; the remaining material, containing about 10^{16} atoms of ^{193}Pt , was then cleaned in a complicated sequence of liquid extractions and column separations. The decontamination factor obtained in this procedure was of the order of 10^{12} or better.

A cadmium plate was used as a source holder and the bremsstrahlung was measured with an intrinsic Ge detector with 200 mm² surface and a thickness of 6 mm. The counting efficiency of this detector was 13% over the energy region of interest. A Si detector was employed for the detection of the L x-rays from the Pt decay, and the source was sandwiched between the two detectors. The IBEC spectrum was recorded both in singles and in coincidence with L x-rays. The whole set-up was built into a graded shielding consisting of lead, cadmium, and copper.

3.2 TEST OF THE DOMINANCE OF P CAPTURE IN THE RADIATIVE DECAY OF ^{193}Pt

The non-radiative electron capture is dominated by capture from the S-states. For the $n = 2$ shell in ^{193}Pt , the scheme for the capture is

and the major L x-rays associated with this decay are

The shape of the Ir L x-ray spectrum is shown in fig. 3.

The dominant contribution to the radiative capture comes from the 2P shell, with a predicted 2S/2P capture ratio¹²⁾ of about 1%:

Fig. 3 Spectrum of Ir L x-rays in coincidence with internal bremsstrahlung. The curve shows the shape of the singles L x-ray spectrum from Ir. The components originating in L_I ($2S_{1/2}$) capture are indicated in the upper part of the figure, whilst some of the most prominent lines from L_{II} , L_{III} ($2P_{1/2,3/2}$) are shown in the lower part. The L_I lines are found to be suppressed with about two orders of magnitude in the coincidence spectrum (the hatched area). The weak line at 9.9 keV in the coincidence spectrum is due to cross-talk coincidences between radiation detected in the Ge detector and escaping Ge K x-rays.

The L x-ray spectrum in coincidence with IBEC is also shown in fig. 3. One observes that the lines with L_I origin are strongly suppressed in the coincidence data. A limit of 1.5% for the $2S_{1/2}$ contribution is obtained from the absence of the L_I lines in the complex at 12-14 keV. This amounts to a direct experimental proof that the low-energy internal bremsstrahlung originates in P-wave capture.

3.3 THE ^{193}Pt Q-VALUE

Hopke and Naumann¹⁹⁾ determined the Q_{EC} of ^{193}Pt from the end-point of the bremsstrahlung spectrum. Their result is $Q = 60.8 \pm 3.0$ keV. We have analysed our coincidence data in order to try to improve the precision of the Q-value.

The IBEC spectrum in coincidence with L x-rays has (disregarding the minute $2S$ contribution) two components originating in the capture from the two spin-orbit partners $2P_{1/2}$ and $2P_{3/2}$. These differ in energy by 1.6 keV, which would complicate the Q-value analysis. However, the high-resolution data allow the selection of a region in the L spectrum with a relatively clean origin in one of the two states. The best line for this purpose is the one at 9.14 keV (fig. 3), which is of pure $L_{III}M_{IV}M_{V}$ origin. The presence of radiationless transitions within the shell -- Coster-Kronig transitions -- gives, however, a contribution from the L_{II} subshell of about 10% in the coincidence data. This gives only a small correction; thus we base our analysis on the 9.14 keV line. The Kurie plot of the data is shown in fig. 4. The end-point of the spectrum is at 45.3 keV and we arrive at a Q-value for ^{193}Pt of

$$Q_{EC} = 56.6 \pm 0.3 \text{ keV} .$$

Fig. 4 Kurie plot of the ^{193}Pt IBEC spectrum. The points at 23-25 keV are influenced by the presence of Cd x-rays originating in fluorescence excitation of the Cd source holder. The Q-value obtained from this plot is 56.6 ± 0.3 keV.

3.4 TEST OF THE PREDICTED IBEC INTENSITY AND THE SPECTRAL SHAPES

The IBEC spectra measured in singles and in coincidence with L x-rays are shown in figs. 5 and 6. The experimental points are plotted on an absolute scale so that they are given as the intensity per keV. Both sets of data have been corrected for the detector response function. The curves show the spectra calculated according to the prescription given in ref. 12. Also, these curves are given on an absolute scale. The comparison furnishes a very striking agreement with the theory -- for the absolute intensities the agreement is quantitative!

Fig. 5 IBEC spectrum from ^{193}Pt measured in singles. The curves show the calculated spectra from the capture in different subshells. The Q-value used in the calculation is 56.6 keV. The experimental points and the calculated curves are given independently on an absolute scale. The spectrum below 26 keV, which is not shown here, is dominated by L x-rays and pile-up from them.

Fig. 6 Bremsstrahlung spectrum from ^{193}Pt obtained from a measurement of coincidences between IB and L x-rays. The lines 23 and 26 keV are from fluorescence excitation of the Cd source holder. The curve is the calculated $2P_{1/2} + 2P_{3/2}$ IBEC shape given on an absolute scale. Some leftovers from the random Lx-Lx coincidences are seen in the lower part of the spectrum.

It is also interesting to investigate the spectral shape in more detail by dividing out the trivial phase-space factor from the data. The shape factor obtained

in such an analysis is shown in fig. 7 together with the calculated matrix element Q_{2p}^2 . Again we find excellent agreement with the theory. It should be noted that the predicted S spectrum, if plotted in fig. 7, would be a straight line with a relative intensity of about 1%.

Fig. 7 Shape factor plot of the ^{193}Pt IBEC spectrum from 2P capture. The Q_{2p}^2 function is given on the same arbitrary scale as the experimental points.

3.5 A LIMIT ON m_{ν_e} FROM THE ^{193}Pt DATA

The case of ^{193}Pt with an end-point for the 2P IBEC of 45.3 keV is not an ideal case for a precise determination of the electron-neutrino mass. The information about m_{ν_e} is contained essentially within a distance of $m_{\nu_e}c^2$ from the end-point, and the useful fraction of the data is proportional to $(m_{\nu_e}c^2/k_{\text{max}})^3$. For a neutrino mass hunt, one should thus aim at a case with much lower Q-value. However, from our present data we may already improve on the limit on m_{ν_e} as compared to the best value given until now¹⁾. [Note: our limit is for m_{ν_e} as opposed to $m_{\bar{\nu}_e}$ (Table 1)]. In fig. 8 we show the upper part of the Kurie plot of the data together with curves corresponding to different assumptions on m_{ν_e} . If we set a limit corresponding to a 90% confidence level, we arrive at $m_{\nu_e} < 500$ eV.

Fig. 8 The high-energy part of the Kurie plot shown in fig. 4 together with the shape of the theoretical IBEC spectrum. A detector resolution of 500 eV FWHM has been assumed. The curves essentially display the expression

$$(k_{\text{max}}^0 - k)^{1/2} [(k_{\text{max}}^0 - k)^2 - m_{\nu}^2]^{1/4}$$

with different assumptions for the value of the electron-neutrino mass.

4. The best candidate to date: ^{163}Ho

The most promising case for future neutrino mass determinations from IBEC spectra is the long-lived radioactive isotope ^{163}Ho . This isotope was discovered by Naumann et al.¹⁹⁾ who detected²⁰⁾ radiations of approximately 1.3 keV which were interpreted as Auger electrons and x-rays following M capture. This assignment was recently confirmed through a measurement²¹⁾ with a high-resolution Si(Li) photon spectrometer. The result and the limit²⁰⁾ set on the L capture-branch brackets the

Q-value between the limits $2.05 < Q < 9.1$ keV. These limits are, however, clearly inconsistent with the half-life of 33 ± 23 y (ref. 20) since the upper limit of the Q-value can be shown to correspond to a lower half-life limit of 150 y. In the following we shall report on a half-life determination of ^{163}Ho by counting M-shell radiations from carefully prepared sources containing a known number of atoms. We have also determined the Q-value by a novel technique based on single-nucleon transfer reactions.

4.1 THE PREPARATION OF THE ^{163}Ho SOURCES

The radiations from ^{163}Ho are of extremely low energy, and the expected half-life is so long that it was felt necessary to aim at having a source with a level of radioactive impurity well below 10^{-12} . The source would have to contain a known number of atoms, preferably in the form of a mono-atomic layer in order to permit the counting of M-shell radiations with energies just above 1 keV. We have reached this objective by a combination of mass separation, radiochemistry and highly sensitive ion beam analysis.

The radioactivity was produced in the ISOLDE facility connected to the CERN Synchro-cyclotron. A hot tantalum target, consisting of rolls of $10\text{ }\mu\text{m}$ foil to give a target thickness of 122 g/cm^2 , was bombarded with a $2.4\text{ }\mu\text{A}$ beam of 600 MeV protons; rare-earth elements evaporating from the target were ionized by surface ionization and mass separated. The sample collected at mass 163 consisted predominantly of the elements holmium to lutetium (the yield is increased by collecting also the isobars, which decay to ^{163}Ho). The collection took place in a Faraday cup: from the integrated current the number of atoms on the $10\text{ }\mu\text{m}$ tantalum collector foil was calculated to be 1.36×10^{15} . After some weeks of cooling, the main contaminants in the sample (determined by gamma spectroscopy) were ^{147}Gd (1.4×10^{12} atoms collected as an oxide side-band), and ^{167}Tm and ^{169}Yb (both about 4×10^9 atoms from "tails" in the separator). A further purification was obtained by a complex procedure based on wet chemistry. The collector foil was dissolved in the presence of 3 mg of lanthanum carrier and microgram amounts of other rare earths, except holmium. For tracing purposes a small amount of short-lived ^{160}Ho was added. The separation was carried out in standard precipitation steps followed by ion-exchange chromatography on an Aminex A5 column with 0.11 M α -hydroxyisobutyric acid as the eluant. The holmium fraction was cleaned twice, again by the same procedure. From the shape of the elution curves (see fig. 9) it was estimated that each step gave a decontamination of a factor 10^3 from the heavier rare earths (such as Tm, Yb) and considerably more from the lighter ones. Thus the total decontamination offered by the combination of mass separation and chemistry was of the order of 10^{14} - 10^{15} . The yield in the chemical procedure was 44%.

Fig. 9 Ion-exchange chromatogram for the first holmium separation. Note that the tailings, of which only Eu (from $^{147}\text{Eu}^{160}\text{O}$) is seen, have been eluted at a higher concentration of the eluant.

Two thin sources were prepared from this stock of radioactivity by vacuum evaporation from a rhenium ribbon at 1800°C. The first (source A) was made before the ^{160}Ho tracer had decayed, so that the yield could be determined: the result of 49% corresponds to 1.9×10^{13} atoms in the central part of a 64 cm² tantalum backing.

A second thin source (source B) was prepared by evaporating a sample of 14.6% of the original stock onto a $0.1 \times 20 \times 20$ mm³ beryllium foil. In an experiment with a Sm tracer and the same geometry, the evaporation yield was estimated to be 35%, which would correspond to 3.1×10^{13} atoms. A second estimate came from counting sources A and B in a 10×10 cm² multiwire proportional chamber (MWPC) filled with an argon+methane mixture; from the relative count rates, one finds 4.5×10^{13} atoms of ^{163}Ho . A third and entirely independent check on the contents of source B was obtained by means of a highly sensitive surface-analysis technique: elastic Coulomb scattering of alpha particles in back angles at relatively low energy offers a sensitive probe for surface layers and a good mass resolving power arising from the kinematic energy loss in the collision. The experiment, carried out with a beam of 3.5 MeV alpha particles from the Aarhus single-stage Van de Graaff accelerator, shows (fig. 10) a well-resolved peak at the holmium mass position with an intensity (integrated over the source) of 5.0×10^{13} atoms. There

Fig. 10 Energy spectrum of 3.5 MeV alpha particles scattered from the centre of foil B through 170°. Surface impurities such as holmium appear as clearly resolved peaks, whilst bulk impurities give rise to a step function which reflects the energy loss of the alpha particle inside the target. The energy scale was calibrated by scattering the beam from a thin target of gold. The inset shows that the high-energy region is dominated by a peak at mass 164 ± 2 with weaker peaks around 183 and 203, presumably Ho, Ta/Re, and Au/Pb, respectively. The intensity of the holmium peak, integrated over the area of the foil, gives an independent check on the number of atoms in the source.

is thus excellent agreement with the Faraday-cup and chemical-yield data. On the basis of these results, we stress that a consistent scale for the number of ^{163}Ho atoms on the sources has been obtained by two entirely independent techniques. We also note that the counting rates of 1 keV M-Auger electrons agree when measured from two different sources on backings with very different Z (4 and 73), so that back-scattering and self-absorption effects cannot be excessive.

4.2 THE ^{163}Ho HALF-LIFE

Knowing the number of atoms in the samples, the half-life may be determined from the decay rate of the source.

The rate of M-Auger electrons in the MWPC gave a partial M-capture half-life of 51,000 y (see Table 2).

Both the M-Auger electrons and M x-rays (fig. 11) were counted from source B. On the basis of the Auger electron decay rate of 32.4 s^{-1} and with the 4.5×10^{13} atoms in the source, we calculate a partial M half-life of 30,000 y.

Table 2

Determinations of the partial M-capture half-life of ^{163}Ho

Source	No. of atoms ($\times 10^{-13}$)	M disintegration rate (s^{-1})	$t_{\frac{1}{2}}^{\text{M}}$ (y)
A	1.9	8.2 c)	5.1×10^4
B		32.4 d)	
	4.5 a)	27.4 e)	3.0×10^4 g)
	5.0 b)	21.6 f)	

- a) From the ratio of counting rates $B/A = 2.34$ measured with a MWPC.
- b) From surface analysis by Rutherford scattering (see Fig. 12).
- c) M-Auger electrons counted with a MWPC.
- d) M-Auger electrons counted with a single-wire proportional counter.
- e) M x-rays counted with an argon-filled proportional counter; 2 μm mylar absorber with calculated transmission for M x-rays of 48%. Assumed M fluorescence yield 0.98%.
- f) As (e) but 4 μm mylar absorber, calculated transmission 29%.
- g) Based on (a) and (d).

Fig. 11 Spectrum of M x-rays from ^{163}Ho measured through a 2 μm mylar foil to absorb Auger electrons. After correction for background, only a broad peak near 1.3 keV remains. The fit shown uses the experimental resolution determined with Al x-rays and a fine structure corresponding in energy and relative intensities expected theoretically.

The various measurements summarized above serve as a set of cross-checks for safeguarding against systematic errors. For this reason it would have little meaning to quote a best value, and we choose instead to represent the data by a single number

$$t_{\frac{1}{2}} = (4.0 \pm 1.2) \times 10^4 \text{ y}.$$

4.3 ESTIMATE OF THE ^{163}Ho QEC VALUE

The transition probability for allowed electron-capture decay involving the atomic sub-shell x is given by the expression

$$\lambda_x = \left(\frac{g^2}{4\pi^2} \right) [M_F^2 + M_{GT}^2] n_x \beta_x^2 B_x \phi_x, \quad (6)$$

where g is the strength of the weak interaction; the M 's denote Fermi and Gamow-Teller nuclear matrix elements; n_x is the occupation number (unity for a full shell); β_x^2 the squared electron wave function at the origin of the bound state x ; and B_x is a correction for electronic exchange and overlap. The quantity ϕ_x represents the phase-space factor which, for a neutrino mass of zero, is simply the square of the neutrino energy $q_x = Q - E_x$, where Q is the total energy available and E_x the total excitation energy of the final atomic state, not counting the rest mass of the captured electron.

Consider now the ^{163}Ho experiment which determined

$$\lambda_{M_I} + \lambda_{M_{II}} = \lambda_M = \frac{\ln 2}{t_M} \quad (7)$$

It is clear that since the quantities $n_x \beta_x^2$ and B_x are known and tabulated²², it is possible to determine the phase-space factor ϕ_{LI} if the nuclear matrix element can be calculated. (The capture from the M_{II} shell contributes only 10%).

In the large majority of nuclear decays, the precise calculation of nuclear beta-decay rates is next to impossible. For the ^{163}Ho case, there is an accidental advantage that comes to our aid. In order to explain why this is so, we must briefly recall some of the properties of single-particle states of strongly deformed nuclei²³.

The single-particle states of strongly deformed nuclei may be characterized by a set of Nilsson (asymptotic) quantum numbers $\Omega^\pi [N n_z \Lambda]$. Here Ω denotes the projection of total angular momentum on the nuclear symmetry axis, and the parity π is $= (-1)^N$, where N is the total number of quanta in an harmonic oscillator representation. The quantities n_z and Λ are the number of oscillator quanta along the nuclear symmetry axis and the projection of orbital angular momentum on the nuclear symmetry axis. A rare and well-studied set of allowed beta transitions, called "allowed", unhindered" (*au*), proceeds between states that obey the asymptotic selection rules $|\Delta\Omega| = 1$, $(\Delta N, \Delta n_z, \Delta\Lambda) = 0$, and $\Delta\pi = \text{no}$. These transitions have very large transition probabilities and have been the subject of several studies. From the general systematics of Nilsson states in the rare-earth region, it is clear that the ^{163}Ho beta decay must be *au* and proceed from the state $\pi^{7/2} [523]$ (ground state of all deformed Ho isotopes) to $\nu^{5/2} [523]$. Here π and ν denote "proton" and "neutron".

It turns out that it is possible to write the reduced transition probability for an *au* transition in a deformed odd-mass nucleus:

$$|M_{GT}|^2 = \frac{C_A^2}{C_V^2} \gamma_1^2 \langle I_i \Omega_i | 1(\Omega_f - \Omega_i) | I_f \Omega_f \rangle^2 R_{\text{pair}} R_{\sigma\tau}, \quad (8)$$

where the terms denote the ratio of GT/F coupling strength, the square of the single-particle matrix element γ_1 (which varies with nuclear deformation), a statistical factor, and corrections for pairing and spin-isospin polarization. The last term has a large absolute influence as it contributes with a factor of about one eighth (ref. 24), but is expected to vary little between neighbouring nuclei as it is dominated by the large Coulomb energy shift of the Gamow-Teller Giant Resonance.

By taking only the statistical factor and the pairing correction into account, it is possible to calculate $|M_{GT}|^2$ for ^{163}Ho from the same beta transition observed in neighbouring nuclei. It turns out that this conversion is most accurate if R_{pair} for the case chosen for comparison contains the same emptiness and fullness coefficients as ^{163}Ho (25). This effect, illustrated in table 3, arises because the errors in the assumed single-particle energies roughly cancel in this case.

Table 3

Calculations of pairing corrections for electron-capture beta decays (EC) of the type $7/2^- [523] \rightarrow 5/2^- [523]$.
(The framed pair was used to calculate the ^{163}Ho nuclear matrix element)

	R_{pair}	Ref. 24	Ref. 25
$^{163}\text{Ho} \left\{ \begin{array}{l} u_p^2 \\ u_n^2 \end{array} \right.$		0.21	0.354
$^{161}\text{Ho} \left\{ \begin{array}{l} u_p^2 \\ u_n^2 \end{array} \right.$		0.36	0.508
$^{165}\text{Er} \left\{ \begin{array}{l} v_p^2 \\ v_n^2 \end{array} \right.$		0.52	0.436
$^{163}\text{Er} \left\{ \begin{array}{l} v_p^2 \\ v_n^2 \end{array} \right.$		0.42	0.271

Using as our reference ^{161}Ho [$t_{1/2} = 2.48$ h, $Q = 853 \pm 3$ keV, $7/2 \rightarrow 5/2$ branch 75%, $\log ft = 4.97$, Lederer et al.²⁶] we find for ^{163}Ho a $\log ft$ value of 5.12.
We assume a 25% error in the semiempirical calculation and combine it with the observed ^{163}Ho M-shell capture rate to obtain

$$\phi^{\frac{1}{2}}(M_I) = 0.53 \pm 0.10 \text{ keV} \quad (9)$$

after correction for M capture. With the assumption of $m_{\nu_e} = 0$ this corresponds to

$$Q_{\text{EC}} = 2.58 \pm 0.10 \text{ keV} . \quad (10)$$

The partial half-life and the theoretically known ratios for M/N/O capture (given by the electron wave functions at the origin) result in a ^{163}Ho half-life of $(7 \pm 2) \times 10^3$ y.

4.4 A m_{ν_e} LIMIT FROM THE COMBINATION OF THE PHASE-SPACE FACTOR AND THE Q-VALUE FROM NUCLEAR REACTION STUDIES

A measurement of Q without any neutrino mass dependence may be obtained from nuclear reaction experiments. Such a direct determination of the ^{163}Ho - ^{163}Dy mass difference has been performed at the Niels Bohr Institute tandem accelerator and multigap magnetic spectrograph²⁷). The reaction chain used was*)

Nearby reference lines were detected in the same spectrum from elastic scattering

The novel feature of this technique is that one detects the τ 's as singly charged. These follow a path through the spectrograph close to the one of the tritons so that a nearby reference line is obtained. The Q -value can then be extracted from the sum of the energy differences of the two pairs (d,d') and (t,τ^+) corrected for the difference in recoil energy ΔE_R and the $(t,^3\text{He})$ mass difference.

$$Q = \Delta E(\tau,t) + \Delta E(d,d') + \Delta E_R + \Delta M(t,^3\text{He}) . \quad (13)$$

The result from this measurement²⁷) is 2.3 ± 1.0 keV. The ultimate precision in the experiment is expected to be appreciably better than the one quoted here.

*) We have used the conventional symbols t and τ for ^3H and ^3He .

Fig. 12 Plot of $\phi^{1/2}(M_I)$ versus Q for different assumptions on the neutrino mass. The shadowed area corresponds to the limits set by the two present experiments and gives an upper limit of 1.3 keV.

The reaction Q -value and the phase-space factor may be combined to give a limit on m_{ν_e} . This is graphically illustrated in fig. 12, where $\phi^{1/2}$ is plotted against Q for different assumptions on m_{ν_e} . The hatched areas correspond to the present experimental limits on Q and $\phi^{1/2}$. The limit set on m_{ν_e} in this way is 1.3 keV. This limit can certainly be further improved with this technique, but the most promising prospects for future progress are to measure the IBEC spectrum from ^{163}Ho and to deduce the mass from its shape.

5. Future prospects for a determination of m_{ν_e}

In this report we have demonstrated the existence of large enhancements of the IBEC intensities for the case of ^{193}Pt . In the case of ^{163}Ho the Q_{EC} value is only about 500 eV from the 3S binding energy. The close presence of the 3S pole thus gives a very large enhancement effect in this case. The isotope ^{163}Ho would then be the best case known, although better ones might still be found.

The next step in our measurements will most likely be the detection of IB-Auger electron coincidences. The best rates are expected to come from the 4P capture:

and

Calorimetric experiments may even be more promising since the process of electron ejection in electron capture²⁸⁾ (EEEC) dominates over the IBEC spectrum by almost three orders of magnitude in the Ho case.

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