# LIMITS FOR THE ELECTRON NEUTRINO MASS FROM INTERNAL BREMSSTRAHLUNG

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ABSTRACT

Numerical non-relativistic calculations of internal bremsstrahlung spectra are described and compared with recent experiments. The spectra of the nuclei $^{193}$Pt (wherefrom $m_\nu$ limits have already been obtained) and $^{125}$I have been measured, both agreeing well with theory. From the measurements of $^{125}$I it is possible to deduce limits on the mixing parameter for heavy neutrinos in the mass range 15 keV to 45 keV. Predictions are presented for the spectrum of $^{163}$Ho, upto now the preferred nucleus for neutrino mass measurements using internal bremsstrahlung.

## 1. Introduction

Internal bremsstrahlung following electron capture (IB) is the second-order process in which a photon is emitted in a normal nuclear electron capture:

$$^{A}Z \rightarrow {}^{A}(Z-1)^{h} + \nu + \gamma. \quad (1)$$

The final state thus consists of the daughter nucleus with a hole h in an atomic shell (normally an s-hole or a p-hole), an electron neutrino and a photon. In general, only the photon is measured. The end point of the photon spectrum, which corresponds to emission of neutrinos of low energy, carries information on the neutrino mass in the same way as the tritium end point carries information on the anti-neutrino mass. Use of IB is the most obvious way to obtain direct mass limits on neutrinos to complement the limits on anti-neutrinos from tritium decay.

Interesting mass limits require IB-spectra with high relative intensity at the end point. This will occur for nuclei where the Q-value equals an atomic s-state binding energy $B_{ns}$. The reason is that all p-IB spectra (final state with a p-atomic hole) exhibit resonances at low photon energies, namely the x-rays. X-ray emission after electron capture is normally treated as a two-step process, but is covered by eq.(1). The x-rays are an integral part of the IB spectrum. Requiring the internal bremsstrahlung end point to lie at the position of an x-ray gives the mentioned relation $Q=B_{ns}$. For the resonant enhancement to work fully, this relation should be fulfilled within the width of an x-ray, i.e., O (10 eV). Untill now no nuclei has been found for which this is the case; the seemingly most promising candidate for neutrino mass measurements is $^{163}$Ho with[1]) $Q-B_{3s}$ ~750 eV.

Experimentally the IB-technique offers several advantages, as photons are detected instead of electrons, and as the shakeup and shake-off problems which plague the tritium experiments are virtually nonexisting here. The two main disadvantages are as follows. First the total IB-spectrum is intrinsically composite. Many atomic final states (though a finite number) are allowed in eq.(1), each with an associated partial IB-spectrum. The end points of the different spectra do not coincide. However, this can sometimes be turned into an advantage (this was the case for the $^{125}$I experiment of section 4) as a neutrino signal must occur at several correlated positions in the spectrum. Alternatively coincidence measurements can be used to pick out a single spectrum. Second we need to have reliable calculations of the matrix elements. The resonances which make IB-experiments possible stem from the atomic matrix elements. These matrix elements can in principle be calculated, the next section summarizes our (partial) solution of this problem. Experiments on $^{197}$Pt and $^{125}$I to test these calculations are then described, the limits one can extract on neutrino masses from these experiments are also given. At last some conclusions on the future work with IB will be given.

## 2. Calculations of IB spectra

The standard treatment of internal bremsstrahlung is due to Glauber and Martin[2]). They were mostly interested in predicting the spectrum above the x-ray region and used hydrogenic wave functions. DeRujula[3]) extended their work to include the low photon energies as well and suggested an empirical procedure in order to place the x rays at their experimentally observed positions. In subsequent works[4]) screening has been taken into account by use of non-relativistic wave functions. This brings the predicted x-ray energies in much closer agreement with the experiments than by use of hydrogenic wave functions.

A detailed discussion of the theory of p-IB is given in ref.4, we here just give the final formula. The intensity of np-IB (final state atomic np-hole) per decay as a function of photon energy K is:

$$\frac{1}{\omega_{tot}}\frac{d\omega_{np}}{dK} = \frac{2e^2}{\pi\hbar^3 c^3}\frac{S\,|M_{np}(K)|^2}{\sum_{n'l}|\psi^Z_{n'l}(0)|^2(Q-B^{Z-1}_{n_p})^2} \qquad (1)$$

$$S = \sum_i c_i K(Q-B^{Z-1}_{np}-K)((Q-B^{Z-1}_{np}-K)^2 - m_i^2c^4)^{1/2} \qquad (2)$$

$$M_{np}(K) = \sum_{j=1}^{N}\frac{\psi^Z_{js}(0)(B^{Z-1}_{np}-B^{Z-1}_{js})}{K+B^{Z-1}_{np}-B^{Z-1}_{js}+i\frac{\Gamma_{nj}}{2}}\int(\psi^{Z-1}_{js})^* z\,\psi^{Z-1}_{np}d\tau$$
$$+\sum_{j=N+1}^{\infty}\frac{\psi^Z_{js}(0)(B^Z_{np}-B^Z_{js})}{K+B^Z_{np}-B^Z_{js}}\int(\psi^Z_{js})^* z\psi^Z_{np}d\tau\ . \qquad (3)$$

Here Q is the nuclear Q-value, B and $\psi(0)$ the atomic binding energy and wave function at origin values with the subscript giving the atomic orbital and the superscript the nuclear charge (Z in the mother atom, Z-1 in the daughter atom). S is the kinematic factor which depends on the neutrino mass. Here the general formula is given for several neutrino masses $m_i$ of relative strength $c_i$ (this is only relevant if neutrino mixing occurs). $M_{np}$ is the second-order matrix element, the integrals stem from the atomic dipole matrix elements. Only the wave functions for the occupied levels are used, the last term in eq.(3) is approximated by a term $T_{np}/(K+t_{np})$, which is evaluated by means of sum rules (see ref.4 for details).

The corresponding formula for ns-IB is simply:

$$\frac{1}{\omega_{tot}}\frac{d\omega_{ns}}{dK} = \frac{c^2}{\pi m^2\hbar c^5}\frac{|\psi^Z_{ns}(0)|^2\ S}{\sum_{n'l}|\psi^Z_{n'l}(0)|^2(Q-B^{Z-1}_{n'l})^2} \qquad (4)$$

with S given in eq.(2) and the same notation as above.

3. The IB-spectrum of $^{193}$Pt

The isotope $^{193}$Pt is ideally suited for a test of the low energy IB theory as its $Q_{EC}$=56.6±0.3 keV[4] is less than the 1s-binding energy. For our measurements[5]) of its IB-spectrum we used a source of $7\times10^{13}$ atoms produced at the ISOLDE facility at CERN. The setup used a 200 mm$^2$ intrinsic Ge detector and a 100 mm$^2$ Si(Li) detector so that the total IB-spectrum as well as the

IB coincident with L x-rays (i.e. 2p-IB) could be measured. Refs.4,5 give the experimental details.

A comparison of the experimental and theoretical total IB spectrum is given in figure 1a on an absolute scale. The shape is reproduced very well by theory, while the absolute magnitude is good to within a factor of 2 only. Figure 1b gives the corresponding comparison for the 3p+4p+... IB-spectra. Again the shape fits well, while the absolute magnitude is somewhat off. Note the interference dip at 20 keV which arises when the amplitudes in the matrix element in eq.(3) sum to zero. As already reported[5]) a 90% conf. upper limit on the electron neutrino mass ($m_1$ of eq.(2), assuming $c_1 \simeq 1$) of 500 eV can be put from this experiment.

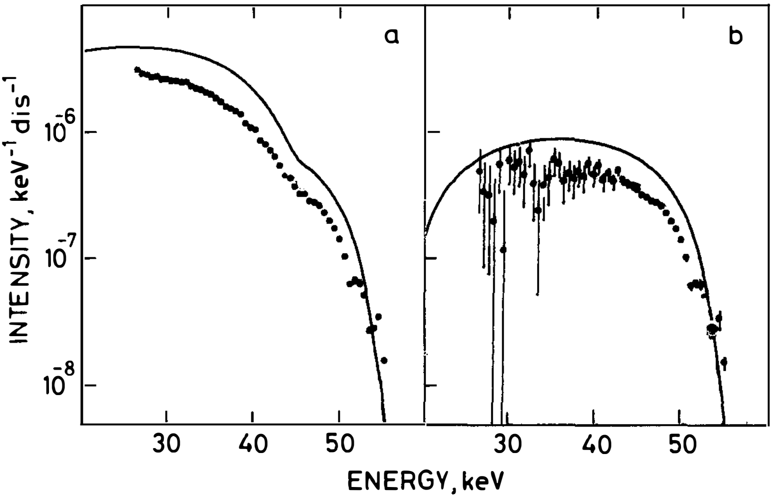


Fig.1. The internal bremsstrahlung spectra of $^{193}$Pt taken from ref.4. The solid line is the theoretical curve (see section 2), dots are experimental points. Figure 1a shows the total IB spectrum, figure 1b shows the (3p+4p+...)-IB spectrum.

4. The IB-spectrum of $^{125}$I

The isotope $^{125}$I has a $Q_{EC}$=186.1±0.3 keV somewhat higher than atomic binding energies. For this reason both s-IB and p-IB can be seen, the latter dominating at lower energies. A source of about $7\times10^{14}$ atoms was produced at ISOLDE. The total IB-spectrum was measured with two 200 mm$^2$ intrinsic Ge detectors. Reference 6 gives the experimental details.

Figure 2 gives the theoretical and experimental IB-spectrum on an absolute scale. Again the shape is reproduced very well, the absolute magnitudes agree within the 30% ,uncertainty on the normalization of the experimental spectrum. The data yield limits on neutrino-mixing. Assuming that only two neutrino masses are present, one of them very light, we get 90% conf.

upper limits on the mixing parameter $c_2$ of eq.(2) of 1-2% for neutrino masses $m_2$ in the range 15-45 keV. This excludes the suggested[7]) 3% 17 keV neutrino in accordance with experiments[8]) on $^{35}S$.

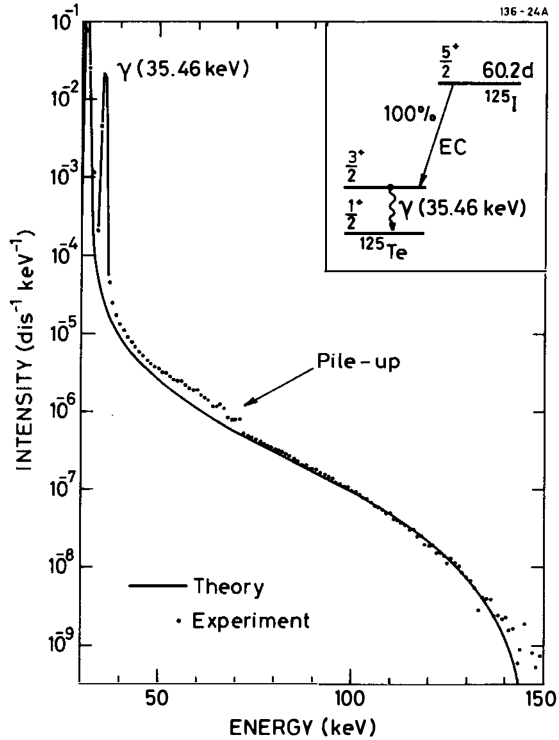


Fig.2. The total IB spectrum of $^{125}I$, the inset gives the decay scheme. The experimental spectrum is unfolded for detector response but not corrected for pile-up, which gives the structure in the spectrum below 70 keV.

## 5. Outlook

From the two comparisons we conclude that theory can give the shape of IB-spectra with high accuracy and absolute intensities within a factor 2 as long as we are well away from interference dips, where we are very sensitive to small changes in atomic parameters. The predicted spectrum[4]) for $^{163}Ho$, the most promising candidate for neutrino mass measurements, is given in figure 3. The most noticable feature is the interference dip right at the end point. We can not determine the exact position of this interference dip[4]), however, it will lie within 0.5 keV of the spectral end point, thus making neutrino mass measurements more difficult. We feel that to put interesting limits on $m_\nu$ from the IB-spectrum of $^{163}Ho$, it is necessary to use high efficiency detectors with better

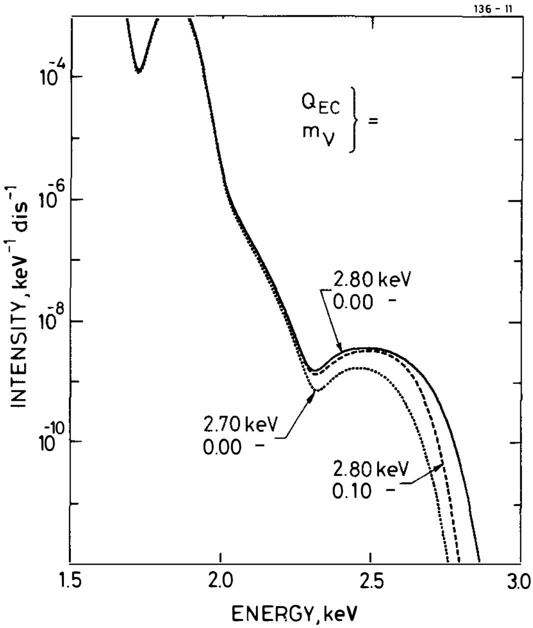


Fig.3. The theoretical total IB spectrum of $^{163}$Ho. A detector resolution (FWHM) of 0.1 keV has been folded in. Predictions are given for three sets of values of Q and m . The exact position of the interference dip is uncertain by about 0.5 keV.

resolution than offered by Si(Li) detectors. The possibility of finding a better isotope should not be excluded. Calorimetric measurements[9]) on $^{163}$Ho still seem promising as we here measure both the IB ("tails of x rays") and ejected electrons ("tails of Auger lines"), the last process being the dominating one.

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