7 Neutrino Masses and Mixing

E. Holzschuh, W. Kündig, L. Palermo, and P. Wenk

The masses of the neutrinos are known to be small when compared with the masses of their charged partners. How small is unknown, however. If the neutrino masses are nonzero, it is considered likely that there is also neutrino mixing. In our project we are using β–spectroscopy to investigate these questions. Mixing would mean in this case that the electron neutrino, emitted in β–decay, is described by a superposition of states with two or more different masses m_i. The signature would be a characteristic 'kink' in an otherwise smooth β–spectrum at an energy $E_0 - m_i$, where E_0 is the endpoint energy for zero neutrino mass.

The objective of the project is a systematic search with high sensitivity in the β–decay of the isotopes ^{63}Ni and ^{35}S for neutrino masses up to 100 keV. The spectrometer, auxiliary experiments and some of the data with ^{63}Ni have been described in previous annual reports. During this budget period we have made a ^{35}S source with a new method and have taken data with high statistical precision. Also a computer program was developed to simulate the scattering of electrons in the spectrometer. Recently, P. Wenk has completed his dissertation [1].

The measurements where completed in February 1998. Thereafter we had to disassemble our spectrometer and to remove all parts for the reason that on this location at the Paul-Scherrer-Institute the new Swiss-Light-Source will be built.

7.1 Simulation of scattering

The spectrometer was designed to minimize the probability that electrons scattered from baffles etc. can reach the detector. It could however not completely be avoided and caused a (small) distortion of the measured β–spectra. Experimentally we have investigated scattering by accelerated photo-electrons with energies up to 50 keV. As the scattering distribution is a function of two variables, the initial energy of an electron and the energy with which it is detected, a complete measurement was not feasible. We have developed a Monte-Carlo program to simulate scattering. Figure 7.1 shows a comparison of the simulation with measured data. We find good agreement, but only if the most elaborate cross sections are used. The simulation gives us a good understanding of the scattering and we can use computed scattering distributions to correct the measured β–spectra.

7.2 Results for ^{63}Ni

A β–spectrum of ^{63}Ni was measured with a total of approximately 10^{10} counts. To analyse these high precision data we had to consider a variety of mostly small effects. Experimentally the most important effect is the increase of the accepted solid angle at the source due to acceleration. It was investigated by simulation. Relatively small effects are energy loss in the source layer, scattering in the spectrometer and dead time of the detector. Theoretically the β–decay of ^{63}Ni, assuming a (statically) screened nucleus, is well understood. However, the dynamical response of the atomic electrons to the decay causes quite significant effects. The probabilities for atomic excitation was computed [2] within the sudden approximation. The effect of electron exchange [3] in β–decay was for the first time only recently observed [4]. It is quite significant for our data.

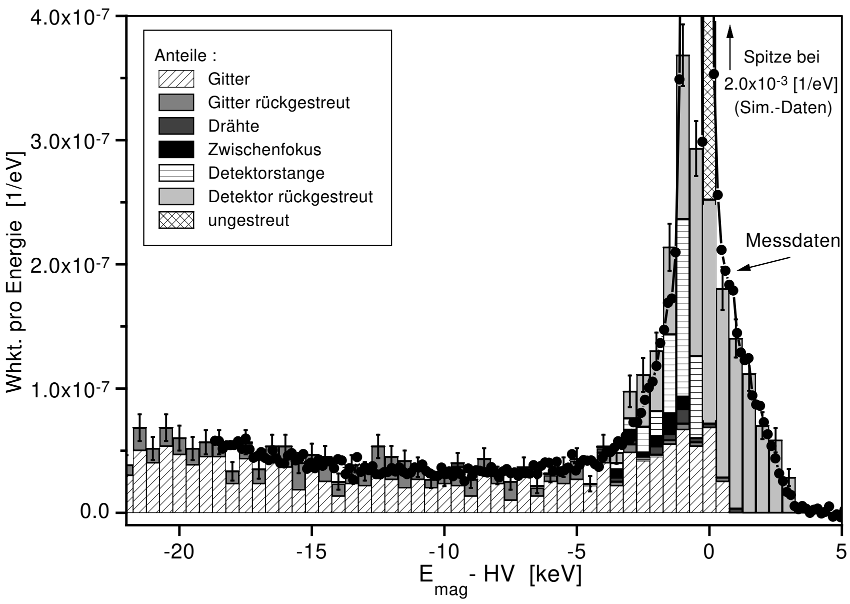

Figure 7.1: *Measured energy distribution (points) of accelerated photo-electrons, scattered in the spectrometer. The central line of unscattered electrons at zero energy (effectively at 40 keV) is a delta–like spike containing* 2×10^8 *counts. It has been suppressed by a factor* 10^4*. The result of the Monte-Carlo simulation is shown as a staircase function, with contributions from various parts of the spectrometer indicated.*

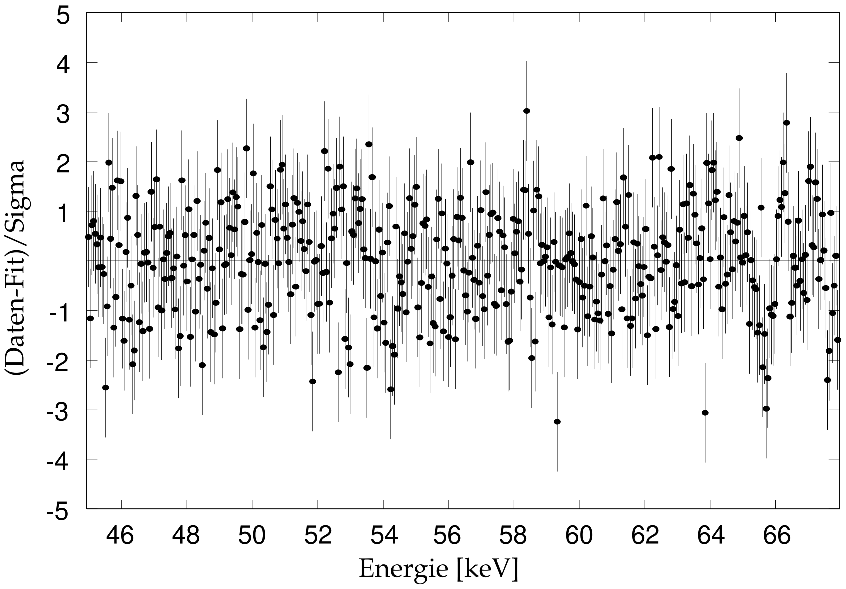

Figure 7.2: *Comparison of the* ^{63}*Ni data and best fit (preliminary) assuming no neutrino mixing.*

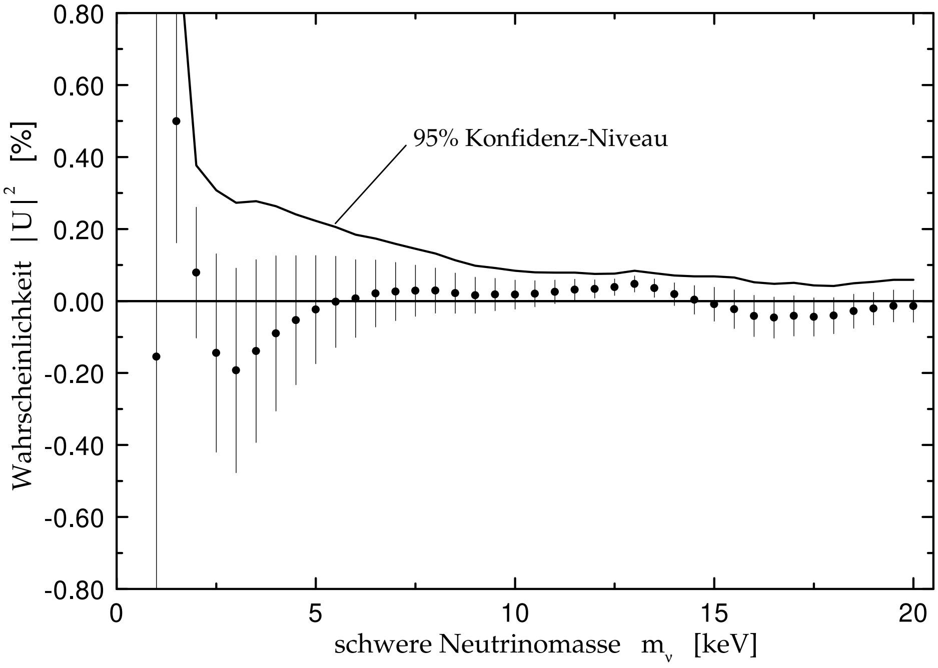

Figure 7.3: *Upper limits for the mixing probability of a heavy neutrino with assumed mass m_ν from the ^{63}Ni data (preliminary). Error bars correspond to the combined statistical and systematical errors.*

Figure 7.2 shows the difference between the data and a best fit, normalized with the standard deviation. The fit is good in general but significant deviations can be recognized close to and below the endpoint ($E_0 = 67\,\mathrm{keV}$). It is caused by a not quite adequate description of the excitation probabilities, mainly for L–shell electrons. An indication for the admixture of a heavy neutrino was not found in the ^{63}Ni data. The fitted mixing probability is plotted in Figure 7.3 for assumed neutrino masses up to 20 keV. The error bars correspond to the combined statistical and systematical errors and the solid line represents an upper limit with 95 % confidence. For small masses the theoretical uncertainty for the excitation probabilities contributes significantly to the total error. We are confident that we can improve on this. Therefore the results above should be considered preliminary.

7.3 The ^{35}S source

A thin and well characterized source is an essential prerequisite for a high precision measurement of a β–spectrum. Historically the isotope ^{35}S was used in many important investigations of the β–decay (see e.g. [5]). Nevertheless there does not seem to be a method in the literature for making good sources. First, we tried vacuum-evaporation of ^{35}S labeled methionine (an amino-acid) [6]. The method worked with non-active methionine. However, the active material decomposed during heating, probably due to radio-chemical effects.

We have found a new method which worked very well and which is also amazingly simple. As source substrate we used a thin foil (2000 Å) of a polyimid (Kapton) with $1.8 \times 3.6\,\mathrm{cm}^2$ area. A thin layer of copper (50 Å) was deposited by vacuum-evaporation on the foil. The foil was exposed to active H_2S in an inert gas. The H_2S gas was made by decomposing commercially available Na_2S with an acid. The copper reacted with the H_2S forming copper

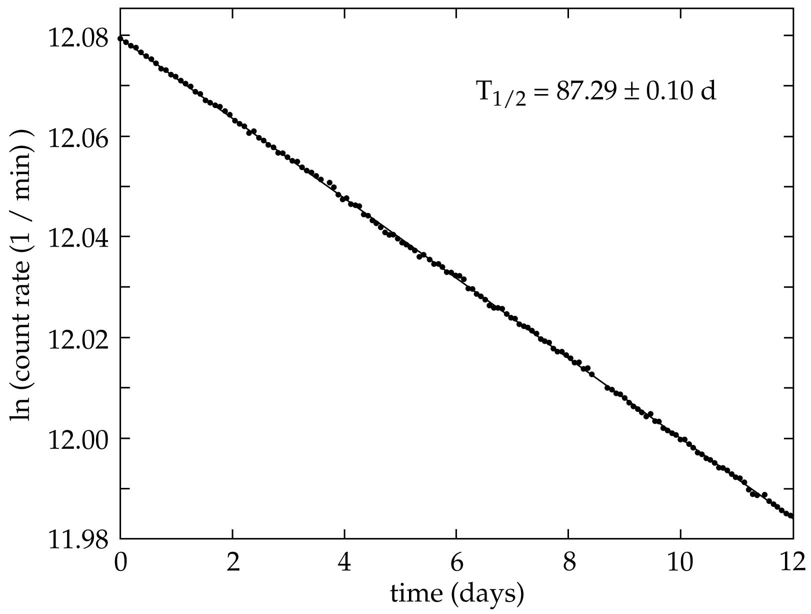

Figure 7.4: *Logarithm of the counting rate for the* ^{35}S *source as a function of measuring time and fit to an exponential decay curve.*

sulfide. We found that this method has nearly 100% efficiency. The source made had an initial activity of 5.5 mCi. It turned out to be chemically quite stable, also in vacuum. Initially a minor contamination of the spectrometer was observed, probably due to outgassing of H_2S from the foil or the support frame of the source. The counting rate with the ^{35}S source in the spectrometer is plotted in Figure 7.4 for 12 days of measuring time. A fit to a exponential decay curve gives a half-life which is compatible with literature values [7] for ^{35}S, demonstrating the chemical and thermal stability of the source.

7.4 Measurements with ^{35}S

The measurements with the ^{35}S source were started in July 1998 and completed in January 1998. The energy range of the measurements extended from 45 keV up to 170 keV (endpoint of ^{35}S is $E_0 = 167$ keV). This range was divided in five overlapping regions which were measured separately. There were several reasons for doing so. The measurements were performed by stepping a negative high voltage applied to the source. It turned out that this voltage had the required high stability only up to about 40 kV. The solid angle accepted by the spectrometer at the source increases with increasing voltage. For small acceleration it is relatively simple to correct a measured spectrum for this effect. At higher acceleration however, the correction becomes increasingly more complicated and may lead to systematic errors. With the newly made source, the count rate at low energies would have been simply too large. So we started the measurements with the high energy range and moved down as the source decayed. The highest counting rate encountered during the measurements was about 25 000 s^{-1}.

The set of the five measured ^{35}S spectra are shown in figure 7.5. The total number of data points is 1850 containing about 2×10^{10} counts. With such graphs it is thus not possible to show the individual data points let alone the size of the error bars. The upper right graph shows a small part of the data from run A near the endpoint, with error bars still smaller than the size of the data points.

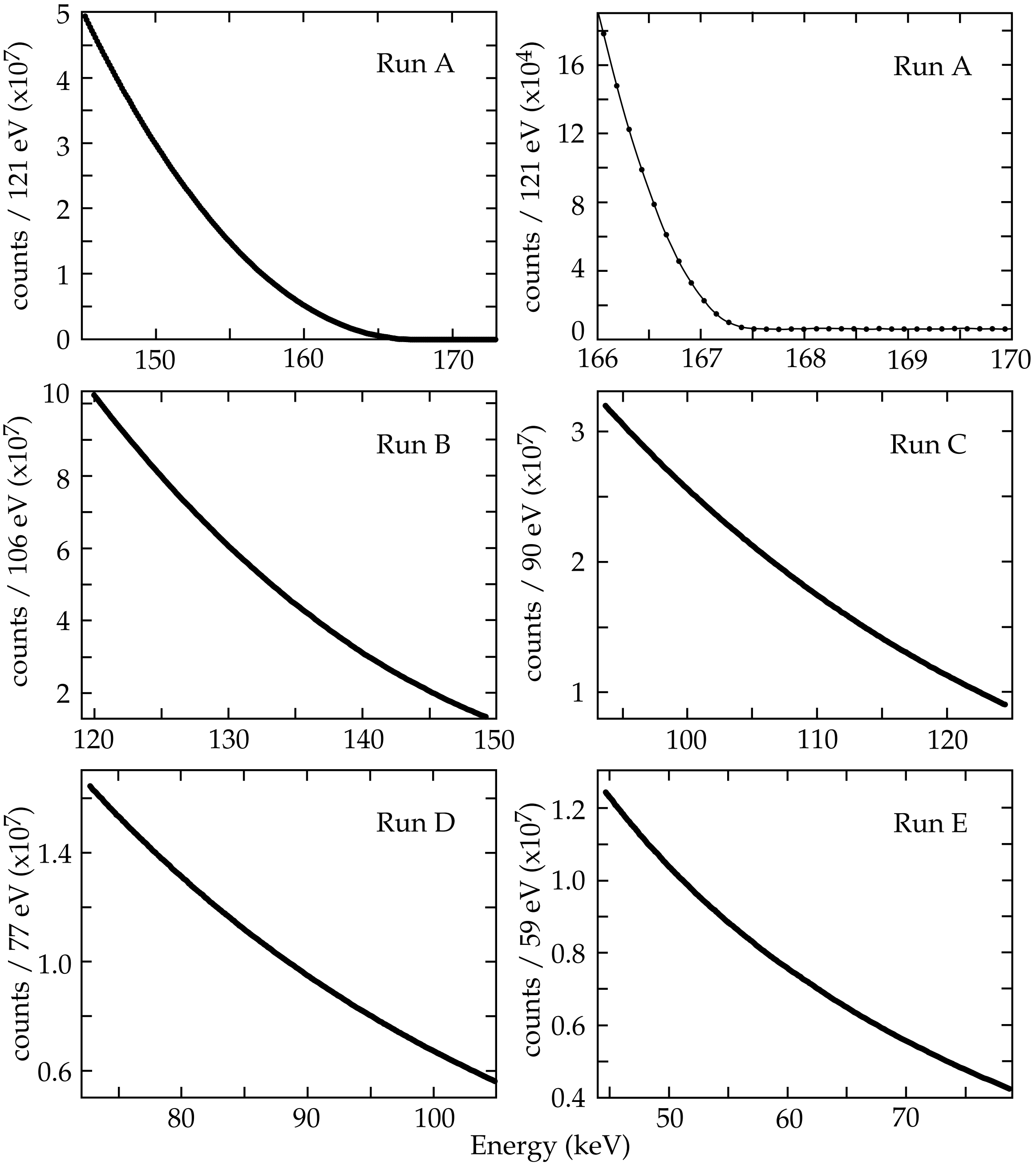

Figure 7.5: *Set of the measured β–spectra of ^{35}S. Part A (right) shows the data near the endpoint.*

The ^{35}S data will be the basis of L. Palermo's dissertation. The analysis of the data is presently in progress. As for the case of ^{63}Ni we have so far not seen an indication for the admixture of a heavy neutrino.

7.5 Conclusion

The measurements have been successfully completed. The acquired data represent by far the most precise β–spectra ever measured with this quality. Besides for the primary purpose of the project, the search for heavy neutrinos, the data are also useful for testing β–decay theory. Of particular importance in this respect are the various atomic effects, caused by the final state interactions. The theory for these effects is difficult and involves many approximations which cannot rigorously be justified. This is especially true for low energies and a comparison with our data should therefore be useful.

References

[1] . Wenk, Dissertation, Uni. Zürich 1997.

[2] . Schafroth, private communication.

[3] .R. Harston and N.C. Pyper, Phys. Rev. A 45, 6282 (1992).

[4] .C. Angrave *et al*, Phys. Rev. Let. 80, 1610 (1998).

[5] .D. Albert and C.S. Wu, Phys. Rev. 74, 847 (1948).

[6] .M. Apalikov *et al*, JEPT Lett. 42, 289, (1985).

[7] .M. Lederer *et al*, Table of Isotopes, John Wiley, New York, 1978, p. 74–75.