Search for 17-keV neutrinos in ^{63}Ni beta decay

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The electron spectrum of ^{63}Ni between two Si(Li) detctors is analyzed. A limitation is found on the mixing parameter: $|U_{eH}|^2 \leqslant 0.0015$ (at a 90% C.L.).

Whether the mass and current states of neutrinos are identical is one of the most pressing problems in elementary particle physics. Searches for neutrino oscillations at reactors and accelerators, on the one hand, and analysis of the kinetics of two- and three-particle decays accompanied by neutrino emission, on the other, have so far yielded no more than limitations on the masses and mixing angles. Exceptional cases are the analysis of the beta spectra of the nuclei ^{3}He, ^{35}S, ^{14}C, and ^{63}Ni (Refs. 1–7) and the bremsstrahlung spectra of ^{55}Fe and ^{71}Ge (Refs. 8 and 9), from which it can be concluded that a neutrino with a mass of 17 keV and a mixing angle $\sim$0.1 exists. These results stand in clear contradiction of the data of corresponding experiments which have used magnetic spectrometers[10–13] or, as in Refs. 1–9, semiconductor detectors to measure the energies of the electrons or γ rays.

The reliability of the interpretation of these experiments depends on how well the response function of the detector is known. As has been pointed out elsewhere,[14] the question of whether a heavy neutrino exists could have been resolved reliably through the observation of a peak in the second derivative of the spectrum. The use of an analytic expression for the response function, in particular, for its low-energy part, or the introduction of corrections in the expression for the spectrum always raises questions.[4,15]

In the present study a thin layer of ^{63}Ni ($T_{1/2} \approx 100$ yr, $E_0 \approx 67$ keV) was deposited directly on the gold coating of a Si(Li) detector. This detector was pressed tightly (without any gap) against a second, identical detector, and a bias voltage (1 kV) was applied to the common p-type contact which formed. In this geometry, with the detectors connected in anticoincidence, the contribution of backscattering electrons to the low-energy part (the tail) of the response function of the detectors was effectively suppressed. For normal incidence of the beta particles on the surface of the detector, the relative number of such electrons is about 15%. With the detectors butted together and connected in anticoincidence, the low-energy part of the distribution function is determined primarily by electrons which are emitted at small angles from the surface and which lose some of their energy in the dead layer of the detector. The magnitude and shape of the tail of the resolution function in our case are thus different from those of Refs. 2–7. The way in which this tail is actually taken into account may be the reason for discrepancies.

The ^{63}Ni working source, 5 mm in diameter, with an activity of 3.6×10^3 Bq, was deposited on the gold surface of a Si(Li) detector by electrolysis. The thickness of the sources was 15 μg/cm^2, and the thickness of the deposited gold was 30 μg/cm^2. Particular attention was paid to the radiochemical purity of the ^{63}Ni. To produce this isotope, 1 mg of ^{62}NiO was bombarded in a reactor at a flux density of 10^{14} n/(cm$^2\cdot$s). After a wait, the nickel oxide was dissolved in hydrochloric acid and subjected to a double chromatographic purification, first on a cation-exchange resin from 8M HCl and then on a cation-exchange resin as the acidity of the eluant was raised smoothly from 0.01 to 1.8 M. The purified $^{63}NiCl_2$, with a specific activity of 10^3 Bq/μg had a background γ-ray activity of less than 10^{-4}.

After the nickel was deposited, the detectors were connected tightly together, placed in a cryostat, and cooled to liquid-nitrogen temperature. The two detectors had similar spectrometric channels: a preamplifier with a continuous drain coupling, a cooled field-effect transistor, an amplifier with a time constant of 2 μs, a circuit for selecting superpositions with a time resolution of 0.3 μs, and a 12-bit analog-to-digital converter with a calibration $\sim$ 0.1 keV/channel. The maximum deviation from a linear energy calibration, carried with the help of γ lines of ^{241}Am and ^{169}Yb and also x-ray lines of elements excited by a ^{241}Am source, did not exceed 25 eV. The resolution measured with the help of the 59-keV γ line of ^{241}Am was 1.1 keV. The discrimination threshold for the selection of coincident events was set at 3 keV. Two pulse-height spectra, each with 4096 channels, of the noncoincident signals from the detectors; a two-dimensional spectrum of coincident events; and pulse-height spectra of signals selected by the rejection circuit were stored in the computer memory.

Several series of measurements, each lasting $\sim$15 h, were carried out. During the time intervals between series of measurements, the detectors were calibrated on the basis of the γ lines of ^{241}Am within a statistical error $\sim 5\times10^{-3}$. The stability was monitored during the measurements with the help of a stable-amplitude generator. Measurements were continued until a statistical base of 1.1×10^7 events/keV was built up near 50 keV. After the main measurements were completed, submicrogram amounts of ^{169}Yb and ^{109}Cd were deposited in succession on the ^{63}Ni spot, and the shift if the conversion-electron lines and the change in their half-width in comparison with the response function of the detector for the ^{241}Am γ rays were determined in the same geometry. During calibration in this geometry, there is an additional broadening of the electron line, due primarily to the detection of x radiation accompanying the conversion electrons. In the analysis of the results, the width of the lines at half-maximum are thus treated as an adjustable parameter. This approach led to a better agreement near the limiting energy.

When the measurements were completed, the pulse-height spectra of each series were converted into energy spectra; the slightly different calibration coefficients were taken into account in the process. The gain values for the different series were altered, and the data from the two detectors were summed for a final analysis in 1-keV intervals, in order to reduce the differential nonlinearity due to the amplitude-to-digital converter. Figure 1 shows the energy spectrum of noncoincident beta particles from ^{63}Ni for one series of measurements, the spectra of electrons detected by the two detectors in the same series, multiplied by a factor of 3 for comparison, and the overall

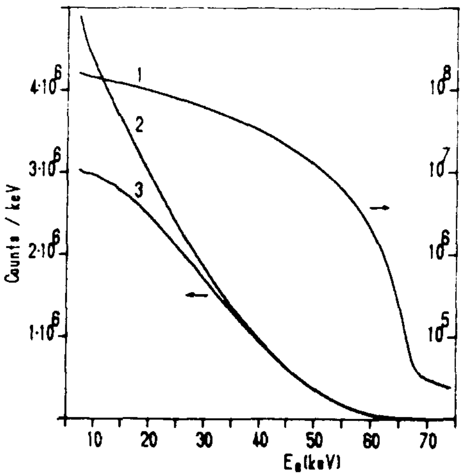

FIG. 1. *1*—Total energy spectrum adopted for the analysis; *2*—spectrum of noncoincidence events for one series of measurements; *3*—spectrum of events detected by the two detectors, multiplied by 3, for one series of measurements.

electron energy spectrum for all 20 series, in logarithmic scale. For energies about 30 keV the spectra are independent, and double events have a similar shape. The backscattering probability determined for the electrons is 23%.

The experimental spectrum of ^{63}Ni beta particles which was found was compared with the theoretical spectrum by searching for a minimum of the functional χ^2. First, two parameters of the linear approximation of the background were found for the interval 69–75 keV. These parameters were used for the entire spectrum and were not varied. These two parameters actually described the background due to the natural radioactivity and the background from superimposed pulses which were not selected by the rejection circuit. The remainder of the spectrum was compared with the expression

$$N(E_i)=A\sum_k F(E_k,Z)S(E_k,E_0,U_{eH},M_\nu)R(\sigma,E_i,E_k)[1+\alpha(E_0-E_k)],$$

where A is a normalization constant, $F(E_k, Z)$ is the Fermi function with a correction for screening, R is a Gaussian resolution function with a standard deviation σ, and $S=(1-|U_{eH}|^2)S(M_\nu=0)+|U_{eH}|^2S(M_\nu=17\text{ keV})$ is the sum of the two beta spectra, with a limiting energy E_0 and a neutrino mass M_ν. The parameter α has been introduced to offset the low-energy tail in the resolution function. In a search for a minimum of the functional χ^2, we thus varied four parameters: A, E_0, σ, and α. This fitting procedure leads to an acceptable value of χ^2 in the interval 30–75 keV. The distribution of values of χ_i with the parameters from the optimum fit at a fixed value $U_{eH}=0$ is shown in the upper part of Fig. 1 ($\chi_n^2=1.39$). For the fixed value $M_\nu=17$ keV, the minimum value of χ^2 is found at $|U_{eH}|^2=0.0002$. The model selected for the theoretical function thus agrees with theoretical results under the assumption $U_{eH}=0$. The solid curve shows the additional contribution to the spectrum (not normalized) in the case in which a 17-keV neutrino is emitted with a probability $|U_{eH}|^2=0.001$.

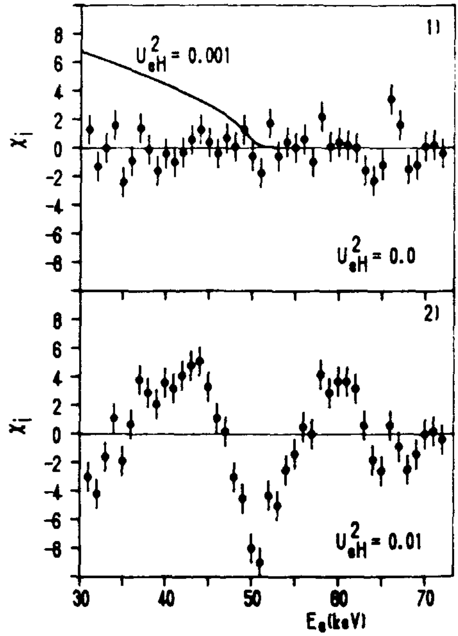

FIG. 2. Results of an optimum fit for $M_\nu = 0$ and $|U_{eH}|^2 = 0$ (top) and $M_\nu = 17$ keV and $|U_{eH}|^2 = 0.01$ (bottom). The solid curve shows the additional contribution to the spectrum (not normalized) for $M_\nu = 17$ keV and $|U_{eH}|^2 = 0.001$.

The results of the optimum fit for the values $|U_{eH}|^2=0.01$ and $M_\nu=17$ keV, which nearly correspond to the average value of the parameters found in the experimental studied of Refs. 1-9, are shown in the lower part of Fig. 2. The value $\chi^2_n=12.3$ found here contradicts the results which support the existence of a heavy neutrino; for 40 degrees of freedom, it corresponds to 50 standard deviations. If we use a $\chi^2(U_{eH})$ dependence to determine a limitation on the possible value of U_{eH}, we find $|U_{eH}|^2 \leqslant 0.0015$ at a 90% confidence level. This value is close to the upper limits found in Refs. 10–13 and 16–19 on the mixing parameter ($\leqslant 0.003$ for ^{63}Ni and $\leqslant 0.0017$ for ^{35}S), and it is in substantial contradiction of the mean value $\sim(0.0085 \pm 0.001)$ from Refs. 1–9.

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