Search for heavy neutrinos in β decay

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The β spectrum of ^{35}S has been measured. Upper limits on the mixing ratios are found over the heavy-neutrino mass interval 5–80 keV/c^2.

If neutrinos have finite masses, the state ν_l, $l = e, \mu, \tau, ...$, can be represented as a superposition of the mass eigenstates ν_i, data on which can in principle be extracted from a study of weak interactions involving neutrino emission.[1,2] The most sensitive method for studying neutrino masses up to ~1 MeV/c^2 is to measure the β spectra of nuclei.

The best results in the region of small neutrino masses were obtained in the experiment of Ref. 3, where a study of β decay of tritium yielded limits on the masses of antineutrinos. Upper limits were also found on the mixing ratios for heavy-neutrino masses in the region 50–1500 eV/c^2. Neutrino masses of 0.1–10 keV/c^2 were studied in Ref. 4 on the basis of the β spectrum of tritium, and the neutrino mass region 30–460 keV/c^2 was studied on the basis of the $\beta^\pm$ spectra of ^{64}Cu in Ref. 5. The experiment of Ref. 6 dealt with the initial region of the β spectrum of tritium. It was reported there that a heavy neutrino with a mass ~17.1 keV/c^2 was observed with a mixing ratio of 3%. There has been no previous study of the neutrino mass region 10–30 keV/c^2.

In the present letter we report an experimental study of the β decay of ^{35}S with a limiting energy of ~167 keV, carried out to test the result of Ref. 6 and also to search for heavy neutrinos in the mass region 5–80 keV/c^2.

The β spectrum of ^{35}S is measured in the iron-free toroidal magnetic spectrometer of the Institute of Theoretical and Experimental Physics[7] over the energy interval 75–175 keV. The radioactive isotope ^{35}S is in the compound methionine, $C_5H_{11}NO_2S$; the sample has a specific activity ~290 Ci/mmole. The sources containing the ^{35}S are prepared by evaporating the active medium in a vacuum. In the preparation of a "point" source the substrates are conducting glasses.[8] This approach is a refinement of a procedure for preparing nonequipotential sources.[9]

The electrons are detected by a six-channel proportional chamber filled with isobutane to 0.58 atm. Each of the 6×2 slits of the chamber is 0.8 mm wide. The pulsed resolution of the apparatus, $\Delta p/p$, including the β source, the spectrometer, and the detector, is 4.8×10^{-4}; at an electron energy of 150 keV, this resolution corresponds to an absolute energy resolution of 129 eV.

By varying the spectrometer focusing current, we can systematically scan two intervals in the β spectrum: 75–175 keV, at a step of 1 keV and with an exposure time of 100 s per point (interval I), and 145–170 keV with a step of 0.25 keV and an exposure time of 200 s per point (interval II). The measurements were repeated many

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times (20 series). We detected a total of $\sim 170 \times 10^6$ decays of ^{35}S, including 28×10^6 decays in interval II.

The theoretical spectrum[1] (xdp/dE), convoluted with the resolution function of the spectrometer, can be written in the form

$$W_e(p) = \sum_i |U_{ei}|^2 W_i(p), \tag{1}$$

$$W_i(p) = CF(Z,E)p^3(E_0 - E)[(E_0 - E)^2 - M_{\nu_i}^2]^{1/2}[1 + \alpha(E_0 - E)][1 + \alpha'(E_0 - E)^2].$$

Here p and E are the momentum and total energy of the electrons, E_ν is the neutrino energy, $E_0 = E + E_\nu$, $F(Z, E)$ is the Fermi function, and C is a normalization constant. The additional power of the momentum arises in (1) as a result of the convolution. The coefficients in brackets with the adjustable parameters α and α' take into account quite accurately for these experimental conditions the backscattering of electrons from the source substrate, the energy dependence of the detector efficiency, missed counts due to the dead time of the electronics, and other small effects which are ignored in the theory or the experiment. The values found for the parameters α and α' as a result of the processing of the data are small. The energy E_0 in (1) turns out to be shifted slightly by the asymmetry of the resolution function (the optics, the energy loss in the source material, and the spectrum of final states formed during the decay of the sulfur to ^{35}Cl in the methionine). These effects are taken into account in an estimate of the limiting energy of the decay.

Figure 1 is a Curie plot $[W_x(p)/p^3F(Z,E)]^{1/2}$ based on the data in energy interval II; W_x is the experimental distribution after a subtraction of the background $(\sim 1.7\ \mathrm{s}^{-1})$; the Fermi function is taken from Ref. 10. The statistical base of this experiment is excellent, as can be seen from the region 148–152 keV, which has been singled out in Fig. 1.

In the analysis we consider only the first two terms in (1), with $M_{\nu_1} = 0$ (the value[3] $M_{\nu_1} \sim 30$ eV/c^2 goes beyond the sensitivity of this experiment) and

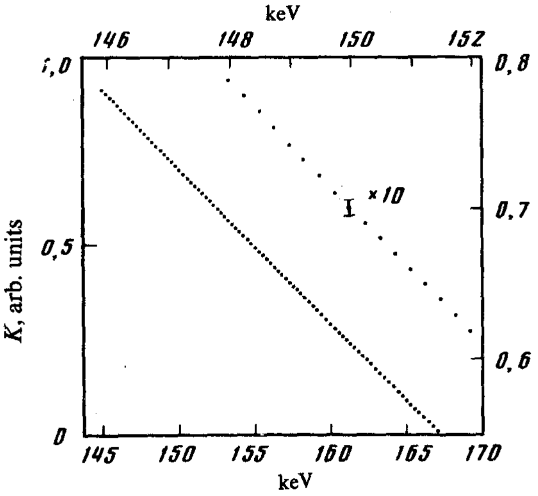

FIG. 1. Curie plot $K = [W_x(p)/p^3F \times (Z,E)]^{1/2}$ based on the data from energy interval II (145–170 keV). The region 148–152 keV has been singled out (the scales at the top and the right correspond to this smaller interval). The error is magnified by a factor of 10.

$|U_{e1}|^2 + |U_{e2}|^2 = 1$. The parameters E_0, M_{ν_2}, $|U_{e2}|^2$, α, α', and C are found by minimizing the functional

$$\chi^2 = \sum_{n=1}^{N} \chi_n^2, \quad \chi_n = [W_x(p_n) - W_e(p_n)]/\sigma_n, \tag{2}$$

where σ_n is the error of the experimental value of $W_x(p_n)$. In a combined analysis of all the experimental data (I + II), the massless fit turned out to be the best ($\chi^2 = 201$, with 190 degrees of freedom). As a result, we find the following parameter values: $\epsilon_0 = E_0 - M_e c^2 = 167268 \pm 4$ eV, $|U_{e2}|^2 = 0 + 1.1 \times 10^{-3}$, $\alpha = (2.40 \pm 0.03) \times 10^{-6}$ eV^{-1}, and $\alpha' = (1.33 \pm 0.02) \times 10^{-11}$ eV^{-2}.

The points in Fig. 2 show the χ_n distribution from (2) with the parameters from the optimum fit. The solid line in this figure corresponds to the case with $M_{\nu_2} = 17.1$ keV/c^2 and $|U|^2 \equiv |U_{e2}|^2 = 0.03$, within the error margin of the present experiment. The data for the two intervals, I and II, are shown separately in Fig. 1 only for

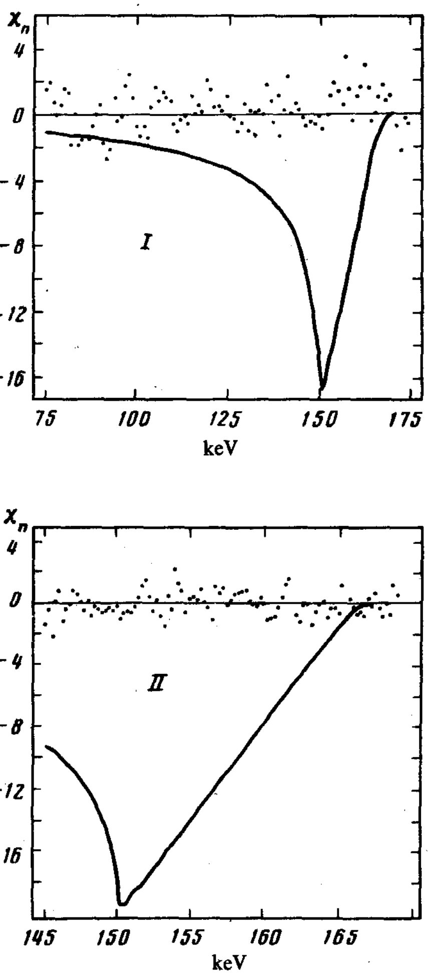

FIG. 2. Distribution of the values of χ_n of the experimental points with respect to the theoretical curve with the parameters of the best fit in the two intervals, I and II. The solid lines in these figures correspond to the case with $M_{\nu_2} = 17.1$ keV/c^2 and $|U|^2 = 0.03$, within the errors of the present experiment.

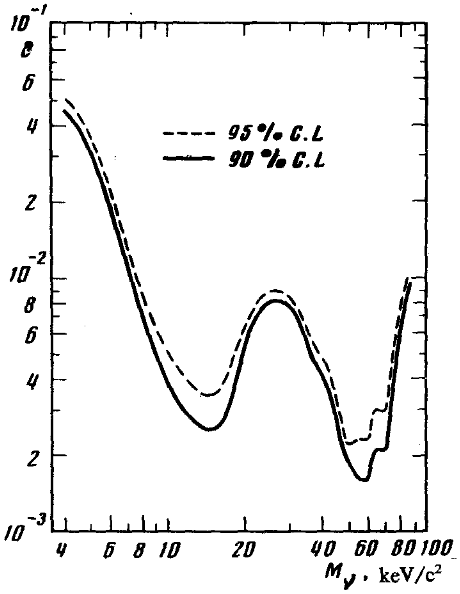

FIG. 3. Upper limits on $|U|^2$ for the neutrino-mass region 5–80 keV/c². Solid line—With a confidence level of 90%; dashed—95%.

convenience. To test the experiment of Ref. 6, we fitted the data to a theoretical spectrum with the fixed values $M_{\nu_2} = 17.1$ keV/c² and $|U|^2 = 0.03$, leaving the other parameters adjustable. As a result, we found $\chi^2 = 1602$. With 192 degrees of freedom, it means that the result reported in Ref. 6 contradicts our measurements at a level ~70 standard deviations. At the fixed value $M_{\nu_2} = 17.1$ keV/c² we have $|U|^2 = (0.64 \pm 0.85) \times 10^{-3}$ according to our data; this figure corresponds to an upper limit $|U|^2 < 0.0017$ at a 90% confidence level.

Working from the β spectrum of ^{35}S, we found limits on the neutrino mixing ratios in the mass region 5–80 keV/c². The results are shown in Fig. 3, where the solid and dashed lines correspond to the upper limits for $|U|^2$ with respective confidence levels of 90% and 95%. These limits were found by scanning $|U|^2$ at fixed values of M_{ν_2}. In this case the uncertainty level in $|U|^2$ is at a maximum, and the upper limits are drawn most cautiously.

We estimate the end-point energy for the β decay of ^{35}S to be $\epsilon_0 = 167\,288 \pm 4 \pm 30$ eV. The first of these errors is statistical, and the second systematic. A shift of 20 ± 30 eV of the fitted value of ϵ_0 is caused by the asymmetry of the optics (10 ± 10 eV), the energy loss in the source material, and the spectrum of ^{35}Cl states in the methionine (10 ± 10 eV). The uncertainty in the calibrated energy measurements is ± 10 eV.

We wish to thank L. B. Okun' for stimulating discussions.

After completing this study, we learned that similar results have been obtained at Princeton by T. Altzizoglon *et al.*

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