Analysis of published data of electron capture in $^7$Be in the search for a heavy neutrino in the mass range under 800 keV

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We present reanalysis of the experimental data of electron capture in $^7$Be embedded in Ta which have been published by other authors. Our goal is to set upper limits on a mixture of electron neutrino with a possible right handed heavy neutrino in the 150–800 keV mass range. In the published experiment a $^7$Li recoil energy spectrum in the 20–200 eV range was measured. In case of electron capture with emission of a heavy neutrino, the recoil spectrum should be shifted to the lower energies. We search for an additional Gauss-shaped structure with the same energy width as the main K-shell transition peak. For this we digitize the published spectrum curve, find the energy resolution, calculate the moving sum of the events along the spectrum in the energy interval of about 3 sigma of energy resolution. Then we use the statistical error of this sum to exclude at some level the appearance of an additional peak. Finally, we present the upper limits at a 95% confidence level on electron neutrino – heavy neutrino mixing element, $U^2$, in the mass matrix. New upper limits are at least one order of magnitude lower than the existing data in 300–800 keV mass range.

1. Introduction. Neutrinos are massive and this property cannot be accommodated in the Standard Model. The simplest mechanism to provide neutrino with mass assumes the existence of new particles - right handed ("sterile") neutrinos. Their number, masses and mixing angles with left handed ("active") neutrinos, apart from the existing observational restrictions, are free parameters of the theory [1]. Sterile neutrino in the keV mass range is one of the best motivated dark matter particle candidates. Therefore, studies of the sterile neutrino mass may probe a new physics. Currently there have been many attempts to search for such heavy neutrino directly in the laboratory [1]. Nucleus β-decay and electron K-capture are prominent channels to search for a heavy neutrino component [2], [3].

Electron capture in $^7$Be is a two body decay with emitted neutrino and recoil $^7$Li nucleus. Almost 20 year ago micro calorimeters were used to detect recoil $^7$Li nucleus where $^7$Be was implanted into HgTe chips [4]. High statistics data for electron capture from $K$- or $L$-shells in $^7$Be have recently been published [5]. In this paper the authors used Ta-based superconducting tunnel junction (STJ) detectors to measure a recoil nucleus in the 10–200 eV energy range. We decided to use these data for estimation of the possible admixture of a heavy neutrino in contrast to emission of the standard electron neutrino. After some steps taken to re-treat the published spectra, we extract upper the 95% CL limits for a such heavy neutrino in the mass range 150–800 keV.

2. Features of $^7$Be decay. $^7$Be decays by electron capture from $K$- or $L$-orbit to $^7$Li ground or first excited state with $Q$ value of about 862 keV. Thus, it has four possible channels:

- with a 89.5% probability the decay is to $^7$Li ground state and a neutrino with the total energy of 862 keV is emitted and the residual recoil nucleus gets 57 eV kinetic energy;
- with a 10.5% probability the decay may go to $^7$Li excited state and the neutrino total energy is 384 keV. This decay is quickly followed by a wide angle gamma emission with energy of 478 keV. The recoil nucleus energy spectrum becomes wide;
- the capture from $K$-shell to the exited state is followed by gamma emission.

As a result, the recoil nucleus spectrum has two similar parts: a prominent $K$ line peak at 112 eV with a wide
distribution from 55 eV to 112 eV centered at about 80 eV when the decay goes to the excited state, and $L$ line peak at 57 eV and a relevant wide distribution centered at about 30 eV for decays to the excited state. These features were clearly seen in papers [4] and [5].

The letter paper has an additional feature: $K$-line peak is not at 112 eV but roughly at 107 eV. The authors of paper [5] consider a list of in-medium effects to describe the whole energy spectrum including electron escape and shake-up and shake-off in daughter $^7$Li atom (see the paper for all explanations). They also state that the observed difference could be due to in-medium effects of Li in Ta. Indeed, this shift of about 4-5 eV could be attributed to the difference in $^7$Be source preparation and detector materials. As already mentioned, the additional 55 eV should come from the Auger electron energy. According to the results and calculations in Ref. [6] the intensity and energy of this transmission depend on chemical bonding of $^7$Li.

3. Procedure. One of the main motivations for our work comes from the plot of residuals after applying calibration and describing the spectrum distribution [5]. Recoil spectrum of $^7$Li does not have any statistically significant features and the single channel residuals in most cases do not exceed two sigmas. Thus, our task was to transfer a high statistics spectrum to estimation of the upper level for a possible heavy neutrino admixture.

We assume that the detector response can be described by a finite resolution with Gaussian shape, the width of which does not depend on recoil energy. Formally, an additional 55 eV should come from the Auger electron energy. According to the results and calculations in Ref. [6] the intensity and energy of this transmission depend on chemical bonding of $^7$Li.

We estimate a possible systematic error by assumption that the energy resolution or the shape of the peak are known with 10% uncertainty, say, with be $\pm 0.3$ eV for sigma of the Gauss peak. This systematic translates to about 5% of CL.

The procedure described above, actually, gives the sensitivity limit based on the accumulated statistics. In a real experiment, the search for a small peak will meet an additional problem: it is difficult to find a such peak in vicinity to a large Gauss-like one. Some procedure or peak-finding algorithm should be applied. In Fig. 1 we plot two vertical dashed lines which define the central region between $L$ and $K$ peaks where the sensitivity limit estimation is valid. For energy regions at about 57–63 eV and 99–107 eV we did an additional simulation to find the actual limits. To do this, we:

- simulate a small Gauss-like peak on shoulder of the large peak. The width of the simulated peak is equal to the energy resolution or $3$ eV;
- sum two distributions;
- fit this sum by a single normal distribution function;
- calculate residuals between the sum and the fit;
• compare the total absolute value of the residuals with an estimation of statistical fluctuation in this region;

• at particular position of the small peak find its minimal recognizable magnitude.

This gives an additional conservative confidence level for a small peak in vicinity to the large one.

4. Results. In Fig. 1 we plot the reconstructed energy spectrum released by a $^7\text{Li}$ recoil atom, solid curve. The plot of the residuals in [5] does not have any statistically significant features, thus, as already mentioned, we do not actually search for an additional peak, but made a statistical analysis of the spectrum to exclude any possible additional component. The dotted line in Fig. 1 represents a double statistical error (actually, 1.95 error to get later a 95% confidence level) for the moving sum over about 3 sigma energy interval. The results were extracted from $K$-line data between 55 eV and 107 eV. For electron capture from the $K$-shell to the $^7\text{Li}$ ground state the neutrino with zero mass produces a peak at 107 eV in the measured spectrum. The largest possible heavy neutrino mass of 862 keV should form events around energy of Auger electron or close to 50 eV. Thus, calculating relation between the energy positions of the dotted line in Fig. 1 and the possible heavy neutrino mass and taking into account the statistical significance, we get upper 95% CL limits, $U^2$, for probability to find a heavy neutrino versus its mass, Fig. 2, solid line. Limits at the regions 150–300 keV and at 750–800 keV are obtained by simulation close to $L^-$ and $K$-peaks as described. At the same figure we plot all existing published data. New limits are at least one order of magnitude lower.

Figure 1: Figure 1. Solid line – our reconstructed energy spectrum from Ref. [5]; dotted line – double statistical error in the moving interval in search for a sign of heavy neutrino, see text. In the region between two vertical dashed lines a such statistical search is still valid.

Figure 2: Figure 2. Upper 95% CL limits, $U^2$, for probability to find a heavy neutrino versus its mass. Thin solid numbered lines are for published data: 1 – [2], 2 – [3], 3 – [7], 4 – [8].

To conclude, we present our estimation of limits on search for a heavy right-handed (sterile) neutrino. We use the published high statistics data from reference [5] where they measured electron capture in $^7\text{Be}$. Electron capture in $^7\text{Be}$ is a two body decay with emitted neutrino and recoil $^7\text{Li}$ nucleus. Neutrino mass defines the maximum energy released by $^7\text{Li}$. After performing statistical analysis of the measured spectrum we get an upper 95% CL in the mass range 150–800 keV. These limits are at least one order of magnitude lower than the existing published data.

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