Measurement of $\beta\beta$ Decay-Simulating Events in Nuclear Emulsion with Molybdenum Filling

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Abstract

The measurement of positron–nucleus collisions was used to estimate the possibility of suppressing background events that simulate $\beta\beta$ decay in the emulsion region adjacent to molybdenum conglomerates. The range of the escape of two relativistic particles from the interaction was found to be $<d> = (0.60 \pm 0.03) \mu m$, which approximately corresponds to the grain size of developed nuclear emulsion. No correlation of the values of $d$ with the angle between two relativistic particles was observed. It was shown that it was possible to exclude $\beta\beta$ decay background from electrons emerging in the decay of elements of naturally occurring radioactive chains. The background from $\beta$ decays of $^{90}\text{Sr}$ and $^{40}\text{K}$ available in emulsions around Mo conglomerates was determined by the ratio of the volume ($\sim d^3$) to the total volume of emulsion and was found to be $1.5 \cdot 10^{-2}$. It was shown that the backgrounds from $^{40}\text{K}$, $^{90}\text{Sr}$ and natural radioactivity could be significantly suppressed and would not limit the sensitivity of the experiment with 1 kg $^{100}\text{Mo}$.

Nuclear emulsion as a detector of electrons emerging in $\beta\beta$ decay has been used in a number of experiments [1, 2]. The papers [2] present the result of an emulsion experiment to search for $\beta\beta$ decay of $^{96}\text{Zr}$, which obtained the best (at that time) limit on the $2\nu\beta\beta$ decay of $^{96}\text{Zr}$. Using emulsion chambers layered with $\beta\beta$ decay source foils was discussed in [3]. We proposed an experiment [4] which made use of a nuclear emulsion with molybdenum ($^{100}\text{Mo}$) filling for $\beta\beta$ decay observation. The main advantage of this technique is the visualization of events and the possibility to measure all decay characteristics: total energy, energy of every electron and a decay angle between electrons.
The energy of electrons is determined by their path range from the site of escape from Mo conglomerate up to the complete stop, where the path has a characteristic form in emulsion. In our experiment, fine powder (Mo, 2–4 µm) was mixed with nuclear emulsion during its preparation. Details of preliminary tests and estimates of expected results of using nuclear emulsions with $^{100}$Mo filling were published in [4].

The present work provides the results of assessing the possibility of excluding some backgrounds that simulate $\beta\beta$ decay in the configuration of the experiment proposed in [4]. Figure 1 shows a real micrograph of conglomerates (stuck-together grains) of fine-grain commercial Mo powder in nuclear emulsion and a simulation of the escape of two electrons with various energies from Mo. If these two electrons escape as the result of $\beta\beta$ decay of the $^{100}$Mo nucleus, they should escape from one point. Several other factors make the observation of the escape of two electrons possible.

- As the exposure of emulsion chambers with $^{100}$Mo is assumed to be prolonged, and nuclear emulsion has no temporal resolution, a successive not simultaneous escape of two electrons from a conglomerate would be registered as a candidate for a $\beta\beta$ decay of $^{100}$Mo.
- Such events can be $\beta$ decays of various isotopes occurring in Mo as impurities due to the insufficient purification of $^{100}$Mo, and a $\beta$ decay of $^{40}$K ($T_{1/2} = 1.28 \cdot 10^3$ years; $Q_\beta = 1.312$ MeV), which is present in gelatine near the conglomerate. The endpoint of the $\beta$ spectrum of $^{40}$K is 1.31 MeV. That is, the maximum energy of two $\beta$ events (from two different decays of $^{40}$K) can reach 2.62 MeV. At not so good an energy resolution such events may with some (small) probability simulate events from neutrinoless double beta decay of $^{100}$Mo.

- Background events can occur in the decay of $^{90}$Sr close to a Mo conglomerate. Strontium decays to yttrium ($^{90}$Sr$_{38} \rightarrow ^{90}$Y$_{39} + e^- + \bar{\nu}_e (T_{1/2} = 28.8$ years; $Q_\beta = 0.549$ MeV)), which, in turn, rapidly decays to (stable) zirconium ($^{90}$Y$_{39} \rightarrow ^{90}$Zr$_{40} + e^- + \bar{\nu}_e (Q_\beta = 2.28$ MeV)). This chain of two successive decays will look in emulsion as a $\beta\beta$ decay. The maximum possible energy of two
Figure 2: Distribution of the value of $d$, a minimum distance between two tracks formed by particles escaping from the collision point of a positron and an emulsion nucleus.

electrons of this chain is 2.829 MeV, whereas for $^{100}$Mo it is 3 MeV. In the case of an insufficient energy resolution these events can contribute to the effect.

To assess the possibility of excluding $\beta\beta$ decay-simulating events we used positron-nucleus interactions, where relativistic particles have escaped from the collision point at different angles. In those measurements we arbitrarily chose pairs of relativistic particles with an angle $\phi$ between them, and determined how exactly they intersected in the region of the interaction vertex. The calculations used the spatial coordinates of two emulsion grains on each track, i.e. the nearest to the interaction vertex and then the next up to the fourth grain. The length of the measuring base for electrons is limited due to their low energy, and, as a consequence, strong scattering. The effect of scattering on the accuracy of determining the intersection of electron tracks is estimated by the data of [5].

Due to errors in the measurement of the coordinates of grains on particle tracks and to scattering the straight lines drawn through these points do not intersect but are skew. Therefore, a minimal distance between these lines is taken to be the "intersection point" $d$. Figure 2 shows the distribution of the values of $d$. The mean value of $<d> = (0.60 \pm 0.03) \mu$m and its spatial position within the limits of angle $\phi$ does not exceed the size of the conglomerate, and 80% of the values of $d$ is concentrated in the region of $\sim 1 \mu$m relative to the collision point. Figure 3 shows the dependence of $d$ on angle $\phi$. As seen from the data of Figs. 2 and 3, $<d>$ has the size of approximately one developed grain of nuclear emulsion, and no correlation between $d$ and angle $\phi$ is observed.

For assessing the background suppression we considered Mo conglomerates
to have a round shape, $< R_{congl} > \sim 3 \, \mu m$, and the "dangerous" zone around them to have the size of $\sim d$ (0.6 $\mu m$). In this case, the number of $^{40}K$ and $^{90}Sr$ decays in the "dangerous" zone near all conglomerates for exposure with 1 kg of $^{100}Mo$ (5.6 litres of emulsion, $n_{congl} \approx 10^{12}$) will be suppressed by a factor of $\sim 1.5 \cdot 10^{-2}$ of the total number of decays in emulsion. A real number of background events depends on the content of potassium and strontium in gelatine. After the purification of potassium in gelatine up to $\sim 10^{-8}$ g/g the number of $^{40}K$ decays in the "dangerous" zone will be $\sim 0.7 \cdot 10^{-5}$ decays/year per conglomerate, and the probability of observing two electrons, $\sim 5 \cdot 10^{-11}$. This value should be further reduced to account for the probability of the escape of two electrons from one point (a region equal to $< d >$), $\sim 0.1$. As the result, the number of $\beta\beta$ events due to $^{40}K$ will be $\sim 5$ per year of exposure with 1 kg $^{100}Mo$. Much less than 1 event will get into the energy range of $(3 \pm 0.3)$ MeV.

A more profound purification of gelatine from impurities is possible.

In the case of strontium, both electrons escape from one vertex, and this event may simulate a $\beta\beta$ decay. About $10^3$ decays will occur in the "dangerous" zone at a $^{90}Sr$ activity in gelatine at a level of 1 mBq/kg per year of measurements with 1 kg of $^{100}Mo$. The contribution of two-electron events to the energy range of $> 2.8$ MeV will be less than 1 event (at an energy resolution of 10%). Besides, it should be borne in mind that in this case we would deal with "asymmetric" events (maximal energies of electrons would be $\sim 0.6$ and $\sim 2.2$ MeV). This can also be used to reduce the background from $^{90}Sr$, because in a neutrinoless double beta decay (a widespread mechanism) the most probable distribution of electron energy in a pair is "symmetric" (see the discussion of a similar situation in [6]).
Figure 4: A "star" observed in emulsion in successive α decays of thorium-series elements.

- Nuclear emulsion always has impurities of natural radioactive elements of the thorium, uranium (radium) and actinium series. In a typical (not extreme) case, 1 cm³ emulsion contains ~ 20 decays forming (3–5)-ray stars consisting of α particles (1 atom of thorium per ~ 10⁸ atoms of emulsion). It would seem that electron decays of these elements occurring in gelatine near Mo conglomerates may form a background which would simulate a ββ decay of ¹⁰⁰Mo. What does occur in reality, however, is that a chain of decays of the three series of natural radioactivity always begins with the successive emission of (3–5) α particles, and only after that elements which are sources of β and γ radiation occur. In emulsion with a high efficiency, 3–5-ray α stars are observed (Fig. 4) and even the diffusion of radon (Rn), which emerges in the radium series, is measured. The work [7] presents the spectra of α particle path lengths in nuclear emulsion, which emerge in the decay of the nuclei of natural radioactive elements. These path lengths of 10–50 µm (α energy, 3–9 MeV) are well observed in emulsion and the efficiency of their registration is ≈ 100%. Such "double" events (a Mo conglomerate and an α star) make it possible to determine and exclude a background electron with a high probability. If a thorium star proves inside a conglomerate, it can be observed too, because the path range of α particles considerably exceeds the size of Mo conglomerate.

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