Nuclear emulsion with molybdenum filling for observation of $\beta\beta$ decay

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Abstract

The usage of nuclear emulsion with molybdenum filling for observation of $\beta\beta$ decay are shown to be possible. Estimates for 1 kg of ^{100}Mo with zero background give the sensitivity for the $0\nu\beta\beta$ decay of ^{100}Mo at the level of $\sim 1.5 \cdot 10^{24}$ y for 1 year of measurement.

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Nuclear emulsion was first used as a simple counter of electrons to search for double beta decay in 1952 [1]. In 1987−1990 an experiment was performed searching for the $\beta\beta$ decay of ^{96}Zr and ^{94}Zr using the nuclear emulsion BR-2 and the best limits on the $\beta\beta$ decay of ^{96}Zr and ^{94}Zr were obtained for these isotopes [2, 3, 4, 5, 6]. As a result of those studies it became obvious that a full-scale $\beta\beta$ decay experiment would require an automatic scanning and much higher (by several orders of magnitude) scanning rates. In recent years significant progress has been made to automate the procedure and to increase nuclear emulsion scanning rates. These significant technical advance has been made possible by the OPERA experiment [7] and the creation of a fully automated PAVIKOM facility [8] at the Lebedev Physical Institute. This triggered several proposals to search for $\beta\beta$ decay [9] and dark matter [10] using nuclear emulsions. The main advantage of this approach in $\beta\beta$ decay studies is the visualization of candidate events and the possibility to measure all decay characteristics: the total energy, the energy of single electrons and the angle between the two electrons.

We have conducted a special investigation to elucidate the possibility of using nuclear emulsions in full-scale $\beta\beta$ decay experiments. A nuclear emulsion with very fine powder of natural molybdenum as a filler (average size of granules, $\sim 2 − 4$ μm) was used. The method was refined using commercial powder to be replaced subsequently by a pure ^{100}Mo source. Estimates indicate that molybdenum should not "spoil" the emulsion and with an optimal amount of fine powder, would not significantly interfere with scanning and measurements in emulsion layers.

The molybdenum powder was introduced into nuclear emulsion during its production at the SLAVICH Ltd (Pereslavl-Zalessky, Russia). Ten plates, 9 cm by 12 cm in size, had been fabricated with a 75 μm thick emulsion layer of dry substance into which 1.43 g of molybdenum powder ($\sim 6\%$ by weight of dry emulsion) was added. The plates were developed by a standard method at the JINR (Dubna, Russia). A KSM microscope was used to scan the plates, to measure the size of powder particles and to localize them in the emulsion layer. Fig. 1 shows a micrographs of molybdenum particles in the emulsion layer, and Fig. 2 presents their distribution by size. These data indicate that $\sim 80\%$ of the powder particles are less than 8 μm. The shaded part of the histogram in Fig. 2 corresponds to the powder particles near the bottom of the plate. Fig. 3 shows the distribution of particles as a function of the depth of the emulsion layer. The dashed line indicates the number of particles less than 8 μm in size in the 10 μm layer at the bottom

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of the plate. Thus, a major excess of particles at the bottom of the plate can be explained by the precipitation of particles greater than 8 μm during the emulsion coating process. The results presented in this figure suggest that there is a slight gradient in the distribution of molybdenum particles along the depth of the emulsion layer. Most likely, however, it will not interfere with the search for $\beta\beta$ decay in the experiment. A visual assessment shows that the amount of molybdenum can be increased by a factor of $\sim (1.5 - 2)$. This increase would make it possible to reduce the amount of emulsion in the experiment by the same factor.

Let us try to estimate the amount of emulsion required for a full-scale experiment. Assuming that the volume of the dry emulsion in our study is 8.1 cm^3, for 1 g of molybdenum the required volume of dry emulsion is 5.6 cm^3. For a full-scale experiment, it is advisable to use ~ 1 kg of molybdenum in 5.6 liters (21.3 kg) of dry emulsion. It is known that 11.5 kg of gel is required to prepare 1 liter of dry emulsion (Ilford (Great Britain) or ET-7D (Japan)). Hence, we have:

• 1 kg of molybdenum in a $\beta\beta$ decay experiment requires 65.5 kg of gel, which would yield 5.6 liters of dry emulsion or 860 plates (9x12x0.06) cm^3 in size;

• if the content of molybdenum in emulsion is increased by a factor of 1.5-2 then $\sim (570 - 430)$ emulsion layers with a thickness of ~ 600 μm is enough to assemble $10 - 12$ emulsion chambers;

• the optimal size for granules is $\sim 2 - 5$ μm (if necessary, the molybdenum powder can be sieved before it is added to the gel);

• the scanning rate at one PAVIKOM unit is $\sim 1 - 2$ plates per day, which should make it possible to complete scanning within one year.

In this case, with a zero background and one-year measurements we can achieve a sensitivity to 0ν-decay of ^{100}Mo at the level of $\sim 1.5 \cdot 10^{24}$ years. This sensitivity is comparable with the result of the NEMO-3 experiment, $T_{1/2}(0\nu) > 1.1 \cdot 10^{24}$ years [11] (for 7 kg of ^{100}Mo in 3.7 years of measurements).

The success of the experiment largely depends on the accuracy of measuring the electron energy in the nuclear emulsion. The energy of electrons is determined by their ranges in the emulsion chamber. The coordinates of each grain are measured, and the range is calculated as a sum of segments of a broken line. As the energy of particle with unit charge depends on its range as $E \sim R^{0.58}$ the representation of its trajectories by a broken line
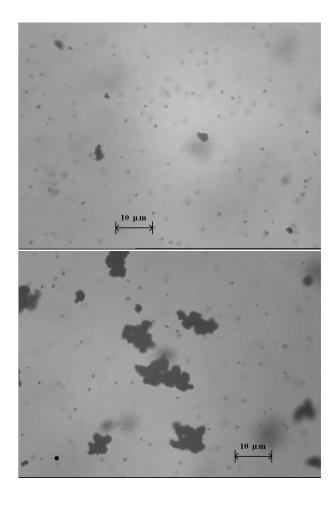
Figure 1: Micrographs of the emulsion with Mo powder near the top of the plate and at the bottom. Definition in depth is 1 μm.
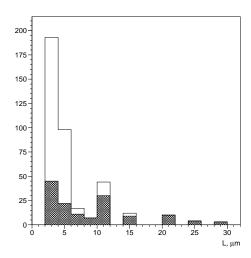
Figure 2: The distribution of Mo granules versus their sizes L in the emulsion plate. The shaded histogram corresponds to Mo granules precipitating to the bottom layer of 10 μm during gel polymerization.
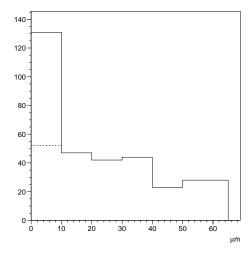

Figure 3: The distribution of Mo granules from the bottom to the top of the emulsion plate after development. The dashed line corresponds to the number of Mo granules up to 8 μm observed in 10 μm bottom layer.

with the emulsion sensitivity of ~ 30 grains/100μm yields an error of no more than $2 - 3\%$. Other sources of uncertainties [12, 13] come from a) the straggling, $\sim 3\%$; b) a correction for bremsstrahlung, $\sim 1\%$; c) layer-to-layer transitions (depend on angles), $\sim 3\%$. The total error is expected to be $\sim 6\%$.

The first stage of a full-scale experiment will involve an exposure with 100 grams of ^{100}Mo. This will enable us to verify the method, to study possible sources of background and to observe ~ 4000 $(2\nu\beta\beta)$ decays of ^{100}Mo for one month of exposure which will also be an important experimental result on its own. The experiment will be carried out under low-background conditions with an exposure time of several months. In order to accomplish this the nuclear emulsion should have an insignificant regression of a hidden image, and the sensitivity of emulsion layers should be checked periodically.

Promising elements for the double beta decay search, besides molybdenum (^{100}Mo), are also ^{82}Se, ^{150}Nd, ^{96}Zr, ^{130}Te, ^{116}Cd, and ^{48}Ca.

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