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Development of high-resolution photographic materials of the National Research Center „Kurchatov Institute“ for nuclear research

© *R.V. Ryabova,*[1] *A.Ya. Balysh,*[1] *A.N. Ponomarev,*[1] *E.P. Senchenkov*[2]

[1] National Research Center „Kurchatov Institute“,
123182 Moscow, Russia
[2] Moscow State University,
119899 Moscow, Russia
e-mail: danviking@yandex.ru

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In the course of the program for the development of high-resolution photographic materials for research in neutrino physics, the possibility of obtaining a nuclear emulsion with a resolution that exceeds the known materials by 5 times has been shown. The sensitivity in such materials is maintained at a high level, sufficient for the registration of nuclear radiation. With an increase in the concentration of silver halide up to 80 wt.%, nuclear photographic materials can be used to solve many physical problems

Keywords: high-resolution photographic materials, nuclear research, silver halide concentration.

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Introduction

The nature of neutrinos — a fundamental problem in the physics of weak interactions. Are neutrinos their own antiparticles, while violating the laws of the lepton charge, obeying the so-called Majorana description, why the masses of neutrinos are so small compared to the masses of other leptons and what their absolute values are, what the hierarchy of masses really looks like — this is an incomplete list of problems that physicists are trying to solve.

The search for a neutrinoless mode of double beta decay — the only experiment to date that can provide answers to many of these questions is being carried out in many laboratories around the world. The detection of such a decay would provide important information for the development of the theory of fundamental particles and the construction of astrophysical and cosmological models. The whole variety of double beta decay experiments can be conditionally divided into 2 types — calorimetric and track (recently, a combination of both techniques has been used in the track approach). A simple approach is based on precision measurement of the total energy of two electrons, a more complex one is the study of electron tracks. In the latter case, the experiment gives a significantly greater amount of information about the decay — the amount of energy of each electron, (the departure of electrons from one point), information about the charge of the particle and the magnitude of the path. The present development of the nuclear emulsion is aimed at studying the processes of double beta decay, i.e. the decay of the nucleus, the size of which is $\sim 10^{-12}-10^{-13}$ see, with the departure of electrons from it. Since the grain size of the emulsion is much larger than the size of the nucleus, in practice, the departure of electrons corresponds to the departure from one point. All this makes it possible to identify the event with much greater certainty as a double beta decay against the background of a large number of simulating processes. As a rule, the calorimetric technique is used in cases where the material of the double beta decay source is simultaneously the detector material (germanium detectors, various scintillators, xenon cameras). However, a number of isotopes that are very promising for the study of double beta decay are quite difficult (or practically impossible) to use as detectors. In this case, there is no alternative to the track technique. A detailed description of the current state of experiments on the search for neutrinoless double beta decay can be found in numerous reviews (see, for example, [1,2])

Nuclear emulsions were one of the first detectors used to search for double beta decay of [3]. However, due to the low speed of image analysis — the main disadvantage of emulsion detectors — over time, they began to be replaced by techniques based on time-projection cameras [4–6], with the help of which the half-lives of the two-neutrino mode of double beta decay of a number of isotopes were obtained for the first time.

Nevertheless, the development and automation of image processing techniques currently allows us to return to the use of nuclear emulsions to study double beta decay. It is known that nuclear emulsions have excellent angular resolution. This quality can be used to distinguish neutrinoless double beta decay, in which two electrons appear in the final state, from two-neutrino decay (two electrons and two neutrinos appear). The key to solving this energy resolution problem is to reduce the size of silver halide grains [7,8]. A similar problem is being investigated, for example, in the study on the search for dark matter at the University of Nagoya, Japan [9,10]. However, there we are talking about the registration of short-lived particles. This study is devoted to the possibility of creating an emulsion with a small grain size while maintaining their ability to register nuclear radiation.

1. Experimental procedure

The requirements for nuclear photographic emulsions for the study of double beta decay are much higher than for emulsions intended for the study of dark matter. In addition to the increased requirements for the resolution of photographic emulsions and high sensitivity to the registration of nuclear radiation, high requirements are imposed on the degree of monodispersity of photographic emulsions. The objective of this study is to develop and create a photographic material based on silver halide salts for nuclear research with a resolution of (R) exceeding R of known nuclear photographic materials by a factor of 5−6 and sufficient sensitivity to register nuclear radiation. It is necessary to obtain a photographic emulsion with microcrystal sizes of $0.05\,\mu$m, with a high concentration of silver halide in the layer up to 80 wt.% and sufficient sensitivity to nuclear radiation. The study was divided into 2 stages.

1. Obtaining a high-resolution photographic emulsion with a microcrystal size of $0.05\,\mu$m and sensitive to nuclear radiation.

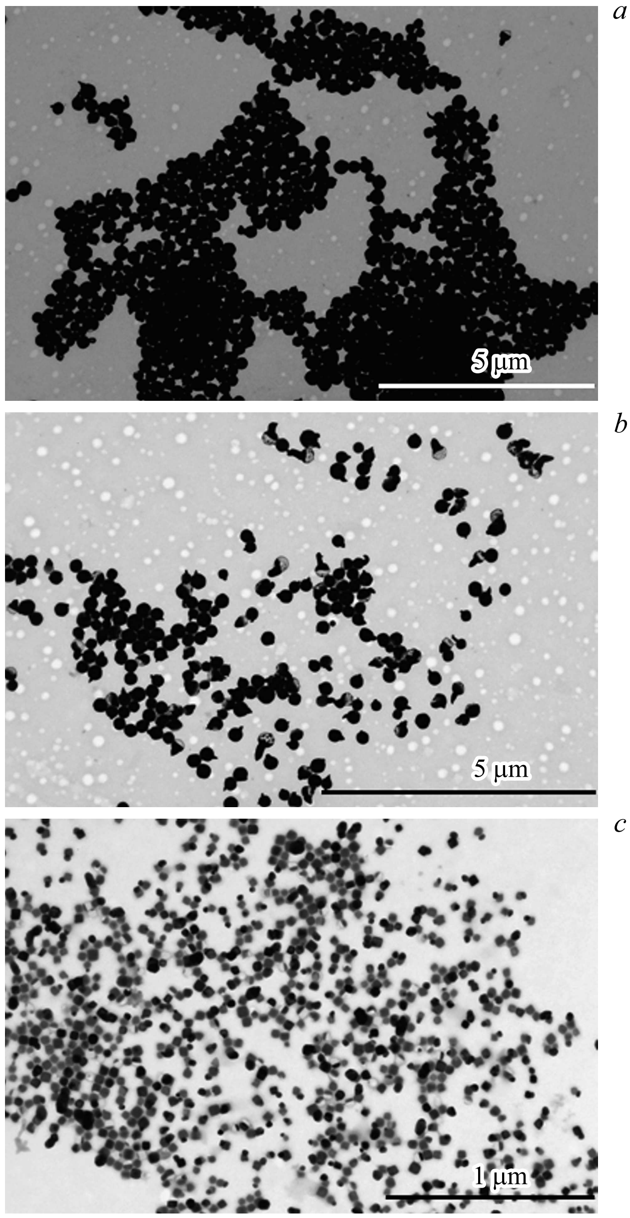
2. Concentration of the photographic emulsion in order to obtain further photo layers with a silver halide content of at least 80 wt.%.

This article presents the experimental results of the first stage of the work.

Why is the size of microcrystals chosen $0.05\,\mu$m, and not less' According to the theory of Gurney and Mott [14], the process of formation of a latent photographic image consists of two stages: electronic and ionic. An essential factor for the formation of a latent image is the presence of interstitial silver ions in crystals. According to study data [12], as well as experimental work data [13,14] the number of interstitial silver ions at room temperature in 1 cm^3 of silver bromide is equal to $\sim 8 \cdot 10^{14}$ ions. In the study [15], calculated data on the concentration of interstitial silver ions in silver halide crystals with diameters of 0.02 and $0.03\,\mu$m are presented: the number of interstitial silver ions is extremely small and amounts to ~ 0.6 and ~ 2 silver ions per microcrystal, even taking into account the near-surface zone, in which there are more interstitial silver ions than in the entire volume of the crystal. This circumstance explains, first of all, the low sensitivity of crystals of such sizes and even the chemical sensitization to which the photographic emulsion is subjected will not be able to increase the sensitivity of such fine-grained emulsions due to the small surface of the grains.

Optical densities and exposure time of Pereslavl, Japanese and RDE's photographic plates „KI“ irradiated with WI_{207} and developed in developer D-19

Name photographic plates	Time exposure, h	Optical density images
Pereslavl nuclear photographic plates	2 48	~ 0.30 > 3 str 0.6.0.
Japanese nuclear photographic plates	2 48	~ 0.30 > 3 str 0.6.0.
Photographic plates RDE „KI“	48	~ 0.3



Photos of microcrystals of nuclear photographic emulsions of Pereslavl (a), Japanese ones (b) and RDE „Kurchatov Institute (KI)“ (c), performed on a microscope of the Lomonosov Moscow State University.

As for the sizes of crystals in $0.05\,\mu$m, calculations show that the number of interstitial silver ions in comparison with crystals in 0.02 and $0.03\,\mu$m increases by more than $2-3$ times and amounts to ~ 5 ions in the crystal.

Nuclear photographic plates of the Pereslavl Chemical Plant and Japanese nuclear photographic plates were used as materials for comparison.

The technological process for obtaining nuclear photographic emulsions with high resolution was based on the technological regulations for obtaining high-resolution photographic materials for holography in oncoming beams with the necessary changes in the processes of synthesis and sensitization of photographic emulsions [15]. This technological regulation did not provide the necessary concentration of silver halide in the developed photographic materials (up to 80 wt.%). We can only talk about obtaining crystals of certain sizes and their sensitivity. The obtained photographic materials were irradiated with a source Wi_{207}.

2. Discussion

The size and shape of microcrystals were studied in the Laboratory of Electron Microscopy of the Lomonosov Moscow State University. A comparative study of the developed photographic materials of the RDE „Kurchatov Institute" with well-known photographic materials of the Pereslavl Chemical Plant and Japanese nuclear materials was carried out. Encouraging results have been obtained on the size of microcrystals and their sensitivity.

The figure shows photos of grains: Pereslavl nuclear emulsion (a), Japanese nuclear emulsion (b), photographic emulsions RDE „Kurchatov Institute" (c).

It follows from the figures that the sizes of microcrystals of photographic emulsions of the Pereslavl plant and the Japanese ones are very close and are $\sim 0.3-0.4\,\mu$m in diameter. Sizes of crystals of RDE „KI" are $\sim 0.05\,\mu$m.

The concentration of halide silver is ~ 80 wt.% in the Pereslavl and Japanese emulsions, in the emulsion of RDE „KI" so far only ~ 20 wt.% and further work is to be done to increase the halide silver in this emulsion.

The table shows the values of optical densities and exposure time of photographic plates irradiated with Wi_{207} and developed in the developer D-19.

The low density on the plates of the RDE „KI", as mentioned above, is primarily due to the insufficient content of silver halide in the photographic plates.

Conclusion

Summing up the results of the study performed, we can talk about the possibility of obtaining nuclear photographic emulsions with the sizes of microcrystals $\sim 0.05\,\mu$m, sensitive to nuclear radiation, which will certainly increase the resolution of photographic materials and allow them to be used for studying double beta decay, dark matter and other purposes.

The study on increasing the concentration of silver halide in the RDE „KI" photographic materials will be continued and described in the following publications.

Conflict of interest

The authors declare that they have no conflict of interest.

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