Experiment BEST-2 with a source of $^{65}$Zn on gallium target for the search of neutrino oscillations on a short baseline

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Abstract. The proposal for an experiment on a 2-zone gallium target of a solar Gallium-germanium neutrino telescope at the Baksan neutrino observatory of the INR RAS with a $^{65}$Zn source for short baseline neutrino oscillations search is considered. The possibilities of determining the parameters of oscillations, the necessary characteristics of the neutrino source, the possibility of its production and its use are described. The expected results of measurements with a $^{65}$Zn source are compared with the results expected in the experiment BEST with the $^{51}$Cr source.

1. Introduction

Experimental indications of the existence of the fourth type of neutrino gave rise to a number of proposals to test this hypothesis [1-4]. Neutrinos of the fourth type do not interact with matter and are formed as a result of oscillations of "ordinary" neutrinos. Oscillations with a large value of $\Delta m^2 \sim 1$ eV$^2$ can explain the results of accelerator experiments LSND [5] and MiniBooNE [6], calibration measurements of gallium detectors of solar neutrinos SAGE and GALLEX with intensive artificial neutrino sources $^{51}$Cr and $^{37}$Ar [7-10] and measurements of electron antineutrino fluxes from nuclear reactors on a short baseline (< 100 m) [11].

2. On gallium experiments and BEST

In gallium measurements, electron neutrinos from a source interact with $^{71}$Ga nuclei: $\nu_e + ^{71}Ga \rightarrow ^{71}Ge + e^-$. Measurements are cyclical, each cycle, called “run”, consists of the exposure (irradiation) of a target by a neutrino flux from the source, extraction of the accumulated in the target $^{71}$Ge atoms and subsequent counting of their number. The number of $^{71}$Ge atoms is calculated by their decay in a proportional counter, the half-life of $^{71}$Ge is 11.43 days.

In experiments, artificial neutrino sources were placed in the center of a cylindrical target. Neutrino oscillations change the probability of neutrino capture in gallium at different distances L from the source: $P_{ee} = 1 - \sin^2 2\theta \cdot \sin^2 \left( \frac{1.27 \cdot \Delta m^2 \cdot L}{E} \right)$. The oscillation parameters $\sin^2 2\theta$ and $\Delta m^2$ are unknown and should be determined in future experiments. In the gallium measurements were used sources of monochromatic neutrinos (of energies: 0.75 MeV in $^{51}$Cr source and 0.81 MeV in $^{37}$Ar.
source), and for the relatively small size of the source the neutrino capture rates varies as a cosine of the distance. In the BEST experiment [12], which is currently being prepared on the basis of the gallium detector of solar neutrinos SAGE, the gallium target is divided into 2 parts (zones), the inner spherical and the outer cylindrical, which provides the same average path length (55 cm) of the neutrino from the source, placed in the common center.

An indication of the oscillations will be a significant difference in the neutrino capture rates in the two target zones and a general suppression of the capture rate relative to the value expected in the absence of oscillations.

For the BEST experiment, a $^{51}$Cr source with activity of 3 MCi ($10^{17}$ Bq) with an active volume of about 0.6 l will be produced. The expected number of neutrino captures in each of the two target zones in the absence of oscillations is about 1650. The statistical error of the result in one zone of the target will be 3.7%, and with the expected systematic error of 2.6%, the total measurement error will be 4.5% for each zone of the target and 3.7% for the entire target.

There are several advantages of gallium measurements: the use of a source of monochromatic neutrinos for which the cross sections of interactions are well known; the small size of the source and the well-known intensity of the neutrino flux; the simplicity of analysis and interpretation of results.

3. BEST-2

A natural extension of the experiment BEST with a chromium source can be the gallium experiment BEST-2 [13], which can be performed in the same geometry but with a different source with neutrinos of different energy. A proper source for this purpose could be $^{65}$Zn. The $^{65}$Zn isotope decays with emission of neutrino with an energy of 1.35 MeV. The neutrino capture cross section on Ga is about 3 times larger than that of chromium source. Therefore, while the half-life of the $^{65}$Zn source (244.1 d) 8.8 times longer than that of the chromium, to obtain the statistics of events in the experiment BEST-2, comparable with the statistics in the experiment BEST, the activity of the $^{65}$Zn source can be significantly less than $^{51}$Cr activity (3 MCi).

![Figure 1](image_url)  
**Figure 1.** Dependence of the number of events $N$ on the number of exposures $m$ for experiments with $^{51}$Cr and $^{65}$Zn sources. The duration of the exposure of $t_1$ is different for different $m$, to obtain the maximum number of events $N$.  

4. The activity of $^{65}$Zn source

The activity of the $^{65}$Zn source should ensure the event statistics in the BEST-2 experiment comparable to the statistics in the BEST experiment, i.e., in the absence of oscillations, about 1650 $^{71}$Ge atoms extracted from gallium should be expected in each target zone.

In figure 1 it is shown what relative statistics can be expected in the BEST and BEST-2 experiments when $m$ irradiations of the same time are carried out. The irradiation time $t_i$ is selected each time to provide the maximum number of atoms extracted from the target. As one can see in the figure, in the experiment with a chromium source, the statistics practically ceases to increase after $m \sim 10$ irradiations. At the same time, in the case of a zinc source, a significant increase in statistics can be expected even after $m \sim 100$ irradiations.

If we limit ourselves to $m = 10$ irradiations, like in the BEST experiment, the minimum activity of $^{65}$Zn should be 0.33 MCi for the duration of each irradiation $t_i = 30$ days.

![Graph](image)

**Figure 2.** The curves of the accumulation of the number of $N_{65}$ activity of $^{65}$Zn in the thermal neutron flux $\Phi = 1 \times 10^{14}$ cm$^{-2}$sec$^{-1}$ for the zinc target with a mass of 20 kg 94% enrichment in the isotope $^{64}$Zn. (1) – without taking into account $^{65}$Zn burnout; (2) – taking into account $^{65}$Zn burnout.

5. Production of the source

$^{65}$Zn can be produced by the capture of thermal neutrons by nuclei of the isotope $^{64}$Zn. Natural abundance of $^{64}$Zn is 48.6%, but for neutron irradiation, zinc enriched in the isotope $^{64}$Zn to 94% will be used. This zinc is a by-product in the manufacture of materials used in nuclear reactors that are depleted by the $^{64}$Zn isotope.

Figure 2 shows how the activity of $^{65}$Zn increases under irradiation of 20 kg of $^{64}$Zn-enriched zinc in the thermal neutron flux $\Phi = 10^{14}$ cm$^{-2}$sec$^{-1}$. The curve (2) is drawn taking into account thermal neutron capture by $^{64}$Zn nuclei ($\sigma_{64} = 0.787$ b, $\sigma_{65} = 64$ b).
Production of the source can be carried out on at least three nuclear reactors operating on the territory of the Russian Federation [13]: MIR (JSC «SSC SRIAR», Dimitrovgrad, Ulianovsk region), IVV-2M (JSC «IRM», Zarechny, Sverdlovsk region) and L-2 (FSUP «PU «Mayak», Ozersk, Chelyabinsk region).

In the reactor, the zinc target can be placed in the form of either metallic zinc ($\rho = 7.13$ g/cm$^3$) or ZnO oxide ($\rho = 5$ g/cm$^3$). The activity from 0.33 to 0.5 M Ci can be achieved in all three reactors under thermal neutron irradiation of 30-40 kg of metallic zinc (up to 5.7 l) or 32-43 kg of ZnO (up to 8.7 l) for a period from 150 days to 2 years.

6. **Size of the source**

The source size is important because, first, the source should be placed in the center of the gallium target in the experimental geometry of the BEST, and, secondly, the size of the source affects the quality of the determination of the oscillation parameters.

In the geometry of the BEST experiment, the source should be placed in the center of the 2-zone gallium target through a pipe with an internal diameter of 21 cm. Therefore, taking into account the outer shell protecting the personnel, the diameter of the cylindrical source should not exceed 16 cm. The height of the source of 8 liters volume in this case will be 40 cm. For comparison, the active part of the $^{51}$Cr source in the BEST experiment with a volume of 0.6 l will have dimensions $8.6 \times 9.5$ cm.

Increasing the size of the source in the BEST-2 experiment results decrease of sensitivity to determination of oscillation parameters. Figure 3 shows the dependence of ratio of the neutrino capture rates in the two zones of the target on the parameter $\Delta m^2$ for the experiments BEST and BEST-2 with specified dimensions of the sources $^{51}$Cr and $^{65}$Zn. The amplitude of the oscillation $\sin^2 2\theta = 0.30$ determines a linear scale on the y-axis.

In spite of the size of the source $^{65}$Zn is larger, the value of the first minimum and maximum is $\approx 15\%$ less than that of the chromium source. Thus, limiting the $^{65}$Zn source activity, which is directly related to its size, slightly reducing the sensitivity of the BEST-2 experiment to the definition of the oscillation parameters.

![Figure 3](image-url)

**Figure 3.** Dependencies of ratios of the expected rates of the neutrino capture in two zones of target ($R_{in}/R_{ext}$) on the oscillation parameter $\Delta m^2$ and amplitude of oscillation $\sin^2 2\theta = 0.30$ for the sources of $^{51}$Cr and $^{65}$Zn.
In a single experiment – BEST or BEST-2 – with a significant difference in the capture rates in the two target zones, $\Delta m^2$ will always be the best fit value corresponding to the first minimum or maximum of the curves shown in figure 3. As one can see in the figure, at different neutrino energies from $^{51}$Cr and $^{65}$Zn sources, the first minima and maxima are in the opposite phase. Therefore, the combined analysis of data of experiments with two sources can indicate the best fit value of $\Delta m^2$ in an arbitrary region from 0 to about 5-7 eV$^2$, except for the values in which the capture rates in both zones are equal.

7. Conclusion

The paper considers the possibility of the BEST-2 experiment with an artificial neutrino source $^{65}$Zn as a natural continuation of the BEST experiment with a source $^{51}$Cr to determine the parameters of neutrino oscillations on a short baseline. At the source activity of $^{65}$Zn of the order of 0.33 MCi, the sensitivity of the experiments to neutrino oscillations is approximately equal. Carrying out both experiments on a 2-zone gallium target with $^{51}$Cr and $^{65}$Zn sources expands the possibilities to determine the oscillation parameters.

The possibilities of $^{65}$Zn source producing by zinc irradiation in the thermal neutron fluxes of the three nuclear reactors currently operating in the Russian Federation are considered.

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