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DETERMINATION OF ACTIVITY OF ^{51}Cr ON GAMMA RADIATION MEASUREMENTS

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A method of determining the activity of intensive distributed β sources on the measurement of the continuous spectrum of γ radiation, for example, the internal bremsstrahlung, is developed. The recurrent formula is used for reconstructing of a continuous spectrum, registered in a Ge detector, at distorting it in the detector. The method of precise measurements of the spectrum of ^{51}Cr internal bremsstrahlung using two point sources of low activity is described.

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INTRODUCTION

The determination of the status of neutrino oscillations with the parameter $\Delta m^2 \sim 1$ eV^2 is currently an actual task of neutrino physics. An indication of such oscillations was obtained in experiments with different neutrino sources: in the experiments LSND and MiniBooNE [1,2] with muon neutrinos from accelerator, in gallium experiments with artificial sources of electron neutrinos SAGE [3,4] and GALLEX [5,6], in the experiments with electron antineutrinos from nuclear reactors [7]. It is expected that the future experiments will confirm or disprove the existence of such oscillations and, in the case of the confirmation, will define the oscillation parameters. To achieve this, the sensitivity of new experiments should be higher than in the carried out experiments, supposed, this is provided by the high neutrino fluxes and large target mass as well as the reduction of the systematic uncertainties.

The experiments with artificial neutrino sources, produced by neutron irradiation in nuclear reactors, are considered among the proposals on the methods of search for neutrino oscillations on a short base line. The advantages of the artificial neutrino sources are a well-known neutrino spectrum, the complete absence

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of non-basic neutrino types in the source, a comparatively small size. Furthermore, the electron neutrino source emits monochromatic neutrinos; that is, the advantage in the analysis of oscillation results. Till now four experiments with sources have been performed: calibration experiments on gallium solar neutrino detectors SAGE and GALLEX with sources on the basis of ^{51}Cr and ^{37}Ar isotopes with activities of 0.4–1.8 MCi. The proposals of future source experiments on search of short base-line neutrino oscillations are associated not only with measurements of gallium detectors (currently only gallium detector SAGE at the Baksan Neutrino Observatory of INR continues the measuring), but also with other detectors (e.g., BOREXINO [8]).

One of the main sources of systematic uncertainties of the experiments with artificial neutrino sources is the error of determining the absolute activity of the source. In the three gallium calibration experiments with ^{51}Cr sources the main method of determining the source activity was the measurements of the heat released in decays (calorimetric method). The activity of an argon source in the SAGE calibration experiment was determined with approximately equal accuracy by several methods, based on the properties of ^{37}Ar as an ideal gas. All proposals of new experiments are supposed to use the solid sources, so we can expect that the main method for measuring the activity will also be calorimetric method. However, in the new experiments the error of the method can be crucial for correct interpretation of the results, so an independent method of determining the activity with a comparable uncertainty is required.

We have developed a new method for determining the activity of intense neutrino sources by measuring continuous spectra of γ radiation. Many neutrino β sources emit γ lines of certain energies. For example, ^{51}Cr source emits 320-keV photons in 10% of decays. However, detected radiation of heterogeneous distributed source under the identical geometric efficiencies can be a different intensity, depending on the relative position of the source and detector. As shown below, the uncertainty related to heterogeneous activity within the source can be suppressed by registering the photons from the source in a wide range. For example, it may be internal bremsstrahlung photons (IB) with a continuous spectrum from zero energy up to energy of decay. The IB intensity is about 10^{-4}/decay, but due to the high activity of the sources the statistical reliability of the measured IB photons spectra can be quite high.

1. DESCRIPTION OF THE METHOD OF DETERMINING THE ACTIVITY

Let γ radiation from distributed source be detected by a detector located at some distance from the source. Let us in imagination divide the source into N parts, assuming that the activity within each part is about uniform. Then in

the spectrum region with the γ-line energy registered into detector signal will be $S(E) = \sum\limits_{i=1}^{N} A_i(E) \cdot \varepsilon_i(E)$, where $A_i(E)$ — the radiation intensity of photons with energy E from the ith part of the source, $\varepsilon_i(E)$ — the detector efficiencies of detecting photons with energy E from the ith part of the source. Value $\varepsilon_i(E)$ depends on the absorption in the material of the source and its primary shielding (therefore associated with the ith position of the radiation) and the properties of the detector. The radiation intensity $A_i(E)$ can be expressed through absolute activity of the ith part of the source B_i: $B_i \equiv A_i(E) \cdot \dfrac{1}{f(E)}$, where $f(E)$ — yield of photons with energy E per decay of the source element. Obviously, the required initial source activity is the sum of activities of its parts $B_{\text{tot}} = \sum\limits_{i=1}^{N} B_i$.

Using the changed efficiencies $\varepsilon'_i(E) \equiv \varepsilon(E, x_i) \cdot f(E)$, we obtain another form of the signal recording in the detector:

$$S(E) = \sum_{i=1}^{N} B_i \cdot \varepsilon'_i(E). \tag{1}$$

One can note that in Eq. (1) signal $S(E)$ is obtained from the spectrum measuring by detector, the efficiencies $\varepsilon'_i(E)$ can be calculated from the known geometry relative to the detector location and parts of the source. Here unknowns are N values of $\{B_i\}$, we write N equations of the (1) type for N different energy ranges of detected photons $\{E_j\}$:

$$S_j = \sum_{i=1}^{N} \varepsilon'_{ij} \cdot B_i. \tag{2}$$

In the matrix form, the equations look like $S = \varepsilon' \cdot B$, and if the number of partitions of the source N is equal to the number of analyzed intervals of energies of registered photons N_j, we find the solution vector: $B = (\varepsilon')^{-1} \cdot S$.

The condition of the existence of solution is

$$\det(\varepsilon'_{ij}) \neq 0. \tag{3}$$

To avoid an information loss if $N_j > N$, the set of equations (2) can be solved by χ^2 method. In the case of fully uncorrelated errors, the function χ^2 has the form $\chi^2 = \sum\limits_{j=1}^{N_j} \left(\dfrac{S_j - \sum\limits_{i=1}^{N} \varepsilon'_{ij} \cdot B_i}{\sigma_j} \right)^2$. The searched vector $\{B_i\}$ is determined in the minimum of $\chi^2 = \chi^2_{\min}$. The intervals of allowed values of activity will be determined from fixed differences $\Delta\chi^2 = \chi^2 - \chi^2_{\min}$.

Let us make estimates of the required resolution of detector, which will be used in this task. Consider the ^{51}Cr source, its IB spectrum will be registered in the range from $\sim$300 to 750 keV (low-energy photons will be almost completely absorbed in the primary shield). Let the number of partitions for each coordinate be 3. Then $N = 3^3 = 27$. Therefore, each spectrum partition interval should have a width not greater than $\Delta E \sim (750 - 300)/27 \approx 15$ keV; i.e., the detector resolution should be not worse than $\Delta E/E \sim 15/750 \sim 2\%$. Therefore, for this task, a detector of Ge type is needed.

2. COLLIMATOR

To obtain the unknown activities $\{B_i\}$, the condition (3) should be satisfied; i.e., it is necessary to violate the symmetry of the matrix $\{\varepsilon'_{ij}\}$. Possible variant of such a violation may be the use of a collimator. Radiation from the source will reach the detector through a small hole in a thick lead wall. Symmetry violation can be achieved by direction of the collimator axis (the hole axis) away from the symmetry axis of the source. The source parts symmetric with respect to the source-detector direction will be partially shaded.

In addition, if the collimator aperture is smaller than the characteristic size of the crystal detector, the radiation through the collimator will fall in a region of the crystal detector within which the detection efficiencies of identical energies photon will be the same; i.e., the shading of the crystal detector part will change the detecting photons efficiency in proportion of the shaded region.

Finally, the use of a collimator suppresses the background, associated with the registration of the radiation reflected from the walls of the room where measurements occur.

3. COMPTON SCATTERING

Spectrum varies passing through the matter layer. Some photons undergo the Compton scattering, whereby they will be registered with less energy. Therefore, the above considerations must be supplemented. Taking into account the scattering, the signal in the detector can be written as $S_j = \sum\limits_{i=1}^{N} B_i \cdot \varepsilon'_{ij} + \Delta_j$, where Δ_j — the signal from photons, emitted with a higher energy, but registered in the energy range j. In the paper [9] it is shown that in this case spectrum of photons from the source in the detector is described by the set of equations $S_j = \sum\limits_{i=1}^{N} B_i \cdot \varepsilon''_{ij}$, coinciding with the set of equations (2), but with the altered matrix of efficiencies:

$\varepsilon''_{ij} = \sum\limits_{j'=j}^{N} \varepsilon'_{ijj'}$, where the summation is over the energy spectrum above given E_j. The $\varepsilon'_{ijj'}$ signified the values of detecting efficiencies of photons with energies E_j, which were born with energy $E_{j'}$ in the ith part of the source. Correspondingly, all of the above outputs remain valid if we replace the matrix of efficiencies.

4. RADIOACTIVE IMPURITIES

Radiation from impurities presented in the source can significantly affect the spectrum. Since the activity of the impurities is much less than the source activity, the influence of IB of impurity elements can be neglected. However, the lines of the emission spectra of such elements, undergoing scattering on the way to the detector, are detected in the IB photon energy region of the source. To correct for the effect of impurities, we can write the set of equations (2) in the form $S_j = \sum\limits_{i=1}^{N} B_i \cdot \varepsilon''_{ij} + \Pi_j$, where the part of the signal is compiled from the sum of the energy lines of the impurities photons: $\Pi_j = \sum\limits_{k=1}^{K} \left(\sum\limits_{j=1}^{N} c_i^k \cdot \varepsilon_{ijk} \right)$. Here values c_i^k — the activity of the kth impurity in the ith part of the source, ε_{ijk} — the detecting efficiency of the radiation of the kth impurity from the ith part of the source in the range of the photon energy E_j. Note that the matrix efficiencies elements for the impurities are not corrected by the value of the output emission per decay, as we do for the source radiation.

Assuming that activity of impurities is proportional to the source activity, i.e., $c_i^k = B_i \cdot p_k$, the number of extra unknowns decreases from $N \cdot K(c_i^k)$ to $N + K(p_k)$, so the set of equations is written as $S_j = \sum\limits_{i=1}^{N} B_i \cdot \left(\varepsilon''_{ij} + \sum\limits_{k=1}^{K} p_k \varepsilon_{ijk} \right)$.

5. THE DETECTOR RESPONSE

The geometry and materials of the detector also affect the registration of the investigated spectrum. The registered spectrum of monochromatic photons is transformed into a continuous spectrum, ranging from zero energy up to a maximum, corresponding to the absorption of full energy of a photon in a crystal detector. To remove from the registered in the Ge detector spectrum influence of the distortion by the detector, we have developed a procedure for recovery of the spectra.

Let monochromatic photons with energy x_1 be detected in the detector, write the spectrum of the detected radiation as

$$y_0(x) = \begin{cases} y_{01}, & x = x_1, \\ 0, & x \neq x_1. \end{cases}$$

Then the spectrum of the pulses in the detector will be $y_2(x) = y_{01} \cdot y_1(x_1, x)$, where function $y_1(x_1, x)$ will be named the detector response function, it represents spectrum pulses in the detector from the monochromatic photons with energies x_1. The recovery procedure is described in detail in [9]. If the detected photons have a continuous spectrum, then we assume that this spectrum consists of many photon lines, spaced at a distance equal to the energy interval between adjacent channels in the detector analyzer. In addition, for each photon energy (i.e., energy per pulse corresponding to each analyzer channel), there must be constructed its response function. Thus, for each photon energy (i.e., energy in a pulse corresponding to each analyzer channel) there should be its own response function. Then, the spectrum will be recovered by the recurrence formula $y_{0k} = \dfrac{y_{2k} - \sum\limits_{j=k+1}^{N} y_{1jk} \cdot y_{0j}}{y_{1kk}}$; i.e., despite the fact that the total number of points in the spectrum is N, recovery is performed sequentially from the higher energies. The reason for this is that any response function has a value of zero for energies above the energy of a full absorption. Here the following notation is used: y_{0j} — the value of the required spectrum in the channel j; $y_{1jk} \equiv y_1(x_j, x_k)$ and $y_{1kk} \equiv y_1(x_k, x_k)$. To use the given formula, it is sufficient to determine the maximum energy in the registered spectrum.

Response functions can be obtained in the measurements of radioactive sources emitting respective photon lines. Obviously, it is practically impossible to find a large number of radioactive sources emitting one photon line at an energy distance corresponding to the energy spacing between adjacent channels of the analyzer. So it is easier to obtain response functions by the Monte Carlo. We obtained response functions using the Geant4 package for the known geometry of the detector crystal.

6. THE MEASUREMENT OF THE SOURCE RADIATION SPECTRUM

To make the measurements described above, it is necessary to know precisely the spectrum of photons in the source: it is used in the definition of matrices of efficiencies ε'_{ij} and ε''_{ij} that are defined above.

If one uses the internal bremsstrahlung (IB) as continuous spectrum for determining the source activity by the method described in this paper, then one should keep in mind that the theoretical shape of the spectrum ($y(x) \sim (1-x)^2 \cdot x$, where $x = E_\gamma/Q$, Q is decay energy [10]) is correct only in some approach. Spectrum of many β decaying elements can differ from the presented shape, especially in the range of low-energy photons.

To determine the exact shape of the IB spectrum for the BEST experiment [11] on a target of 50 tons of metallic gallium with the ^{51}Cr source of

3 MCi activity, we suppose to make the measuring of such a spectrum with the pointlike source of low activity. A pulse spectrum will be taken with a Ge detector from the ^{51}Cr source of $\sim$ 20 mCi activity through the collimator. In addition, the IB photons with an energy of 320 keV are emitted in 10% of the ^{51}Cr decays. The number of events in the IB spectrum is about 300 times smaller than the number of events from 320 keV line. The spectrum recovery procedure with the use of the response functions, described above, will be applied to determine the IB spectrum. So as the measured source will be a pointlike source, i.e., there will be no absorption of radiation, after the process of the spectrum recovery the radiation of radioactive impurities will be present in the spectrum in the shape of separate lines of photon energies, which can be subtracted directly.

An absolute calibration of the spectrum (i.e., to determine the relation of the number of events in the pulse spectrum with the number of element decays in the source) will be performed with the second pointlike ^{51}Cr source of about 10^4 Bq activity. There will be two measurements with this source: first, the rate of 320 keV photons in a Ge detector with the collimator will be determined; second, the source will be placed into the narrow pit crystal detector NaI, and the total decay rate of ^{51}Cr will be determined through 320 keV line. In the context of 4π-geometry the absolute decay rate of the source can be determined with an accuracy of 0.3% (the accuracy is determined by the fact that we are neglecting the IB of the source). Thus, with the second source there will be determined the relation of the rate of registered 320 keV photons line with the source activity. And we will obtain the absolute calibration of the spectrum IB from registered 320 keV line with the first source measurements.

CONCLUSIONS

The paper describes a method developed to measure the activity of intensive distributed neutrino sources through γ radiation with continuous spectrum. It is assumed that the method will be used as an independent alternative to calorimetric measurements. Under certain conditions (sufficient statistics of the measurements, a small amount of radioactive impurities), the accuracy of the source activity measurement can be about 1%.

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