Detection of antineutrinos in the flux from two reactors

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The results of an experiment designed to observe the inverse beta-decay of the proton are presented. Antineutrinos from two reactors at distances of 32.8 and 92.3 m from the detector, respectively, were recorded. The measured inverse beta-decay cross section was found to be $\sigma = [6.19 \pm 0.2(\text{stat.}) \pm 0.3(\text{syst.})] \times 10^{-43}$ cm^2/fission. The following limits were obtained for the neutrino oscillation parameters: $\Delta^2 \leqslant 0.014$ eV^2 for $\sin^2 2\theta = 1$ (68% CL) and $\sin^2 2\theta \leqslant 0.14$ for $\Delta^2 \geqslant 1$ eV^2 (68% CL).

INTRODUCTION

The study of the internal properties of antineutrinos as elementary particles, their interaction with matter, and their use in the investigation of the structure of hadrons has been a major part of weak interaction physics during the last thirty years. At present, the question of the mass of the neutrino is an important aspect of neutrino physics. The question is being examined by direct experiments on the shape of the beta-ray spectra, neutrino-free double beta-decays, and searches for neutrino oscillations. Most of the experiments that have been carried out have not provided evidence for a nonzero neutrino mass, but there are several publications that, in our opinion, suggest that the neutrino does have a nonzero mass. These are, above all, the report[1] of an anomaly in the beta-ray spectrum of tritium, suggesting that the antineutrino has a rest mass of the order of 30 eV, the results of Simpson[2] on "heavy" neutrinos, the flux of solar neutrinos that is too low by a factor of three, which could be an indication of the existence of neutrino oscillations, and, finally, the evidence for the existence of neutrino oscillations provided by the experiments on the Bugey reactor in France,[4] and those published by the Reines group.[5]

A solution of the problem of neutrino oscillations would be important not only because it would indicate the existence of different mass states of the neutrino, but also as evidence for a departure from the conservation of lepton number,[6] which is of direct significance for the grand unification theory.

The considerable increase in the course of the last few years in the number of experiments using reactor antineutrinos has been due to the fact that, when compared with other terrestrial sources, such reactors enable us to achieve maximum sensitivity to Δ^2 (difference between the squares of neutrino masses) and, moreover, the initial flux contains only one type of particle, which makes the interpretation of the results easier. The inverse beta-decay of the proton

$$\tilde{\nu}_e + p \rightarrow n + e^+, \qquad (1)$$

is the most accessible to experimental investigation because it has the highest cross section among all possible antineutrino interactions.

The cross section for the elementary inverse beta-decay process[7] is

$$\sigma(E) = (9.41 \pm 0.09) \cdot 10^{-44} \cdot (E - 1.293) \times [(E-1.293)^2 - (0.511)^2]^{1/2},$$

where σ is the cross section in cm^2 and E is the antineutrino energy in MeV.

In the above formula, we used the recommended neutron decay constant $\tau_n = 899.7 \pm 8.9$ (Ref. 8). Since an initial energy selection of the neutrinos is not possible in reactor experiments, it is convenient to use the concept of the cross section per fission of ^{235}U (the principal fuel component used in modern reactors), i.e.,

$$\sigma_T \,\text{cm}^2/\text{fission} = \int_E \sigma(E)\, n_{\tilde{\nu}_e}(E)\, dE,$$

where $n_{\tilde{\nu}_e}(E)$ is the normalized spectrum of reactor antineutrinos. The present uncertainties in the spectra produce a spread in the calculated values of the integrated reaction cross sections for the inverse beta-decay process, as indicted in Table I.

In our work, we used the antineutrino spectrum obtained by averaging the spectra reported in Refs. 11–16. The corresponding total cross section is $\bar{\sigma}_T = (6.23 \pm 0.21) \times 10^{-43}$ cm^2/fission, where the uncertainty was deduced on the assumption that each antineutrino spectrum could be assigned the same weight. When corrections for recoil effects, weak magnetism, and single-photon exchange[17] are taken into account, the calculated total cross section for inverse beta-decay in the case of an equilibrium antineutrino spectrum becomes

$$\bar{\sigma}_T = (6.11 \pm 0.21) \cdot 10^{-43} \text{ cm}^2/\text{fission}.$$

INTEGRATING NEUTRINO DETECTOR (IND). PRINCIPLE OF THE EXPERIMENT

IND is a plexiglass parallelepiped ($80 \times 80 \times 97$ cm) which is also the hydrogen-containing target (total number of protons $N_p = 2.78 \times 10^{28}$) and moderator of neutrons produced in reaction (1). A neutron is slowed down to thermal energy and is effectively absorbed in one of the 105 pro-

TABLE I. Integrated cross sections (calculated).

$\sigma \times 10^{+43}$, cm^2/fission	$\sigma \times 10^{+43}$, cm^2/fission
8.11 (Ref. 9)	6.23 (Ref. 13)
7.38 (Ref. 10)	6.16 (Ref. 14)
6.53 (Ref. 11)	6.10 (Ref. 15)
6.27 (Ref. 12)	6.07 (Ref. 16)

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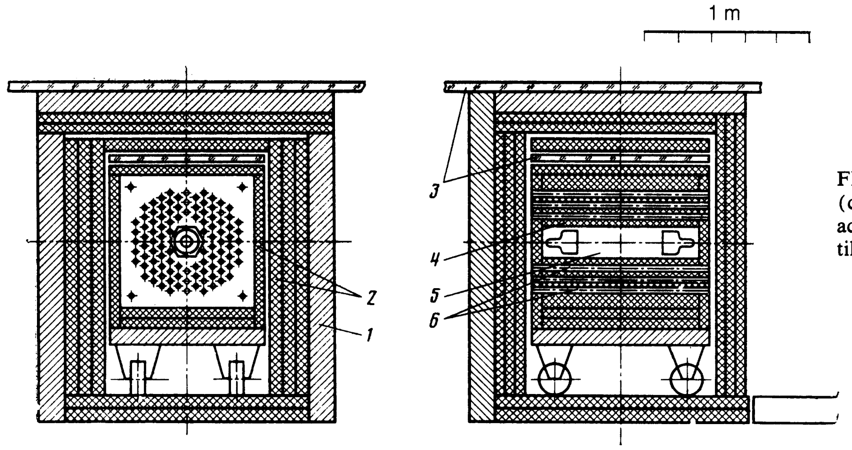

FIG. 1. External view of the detector; 1—gamma ray field (copper), 2—neutron shield (borated polyethylene), 3—active shield, 4—moderating target (plexiglass), 5—scintillation section, 6—^{3}He neutron counters.

portional ^{3}He neutron counters inserted into the moderating target (Fig. 1). This produces the following reaction in the counter:

$$n+{}^3\text{He}\rightarrow{}^3\text{H}+p+765\ \text{keV}. \quad (2)$$

When 765 keV of energy is released, it is concluded that a neutron has been detected. The IND is sensitive only to one secondary particle from reaction (1), i.e., the neutron. The energy threshold for the detection of the antineutrino is the physical threshold for the inverse beta-decay process ($E_{\text{th}} = 1.8$ MeV).

Figure 2 shows the differential pulse-height spectrum of signals from all the 105 IND neutron counters. The peak at 765 keV is due to thermal-neutron capture in reaction (2) and the continuous plateau is due to alpha-particles emitted by the metallic bodies of the counters, which contain a certain number of alpha-active elements. The left-hand part of the plateau is somewhat higher than the right (relative to the peak). This is due to the wall effect [the ranges of the products of reaction (2) do not completely fit into the working

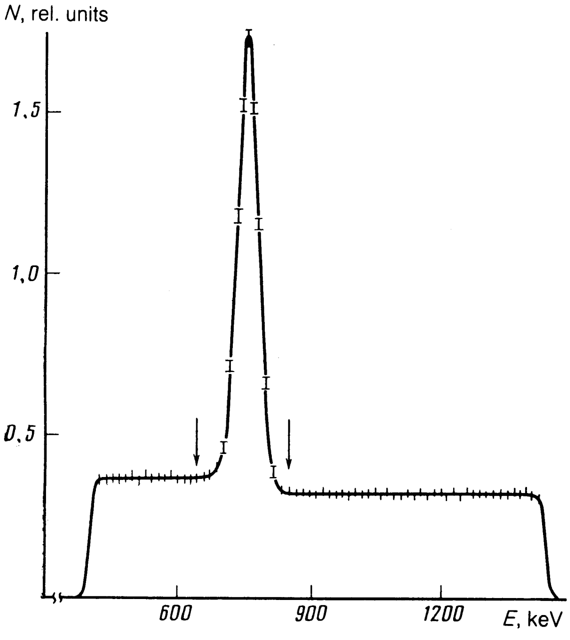

FIG. 2. Differential pulse-height spectrum produced by IND. Arrows define the neutron detection window.

volume of the counter]. The arrows mark the neutron detection window. The smooth shape of the alpha-particle spectrum enables us to extrapolate the alpha-particle background from the region near the neutron peak to the region under the peak and thus correctly take into account this component of the background.

The IND is surrounded by a passive shield consisting of at least a 30 cm thickness of borated polyethylene. It is also surrounded on four sides by a $\sim$10-cm layer of electrolytic copper, which reduces the external neutrino flux by a factor of more than 50. The IND is shielded from cosmic-ray mesons by covering it at the top with scintillation plates having a total area of about 10 m^2. The amount of matter above the detector corresponds to several tens of meters of water equivalent.

The antineutrino detection efficiency of IND is wholly determined by the neutron detection efficiency: $\varepsilon = \varepsilon_0(1-\eta)$, where ε_0 is the neutron absorption probability of ^{3}He and η represents the wall effect.

The quantity η can be measured with good precision in a thermal neutron beam, but ε_0 cannot be found experimentally because there is no source that completely simulates the neutron spectrum from inverse beta-decay. The neutron absorption probability was therefore determined for the IND by the Monte Carlo method, in which the coordinates of the point of creation, the neutrons, their energy, the direction of emission, the scattering angles, and so on, were defined by random sampling. The calculation was performed using 21-group nuclear-physics constants in a program simulating processes occurring in heterogeneous reactors.[18] It was assumed that the neutrons were created uniformly throughout the target and the external hydrogen-containing shield (borated polyethylene). A special analysis was carried out of the effect of initial anisotropy in the emission of neutrons in reaction (1). This was done by simulating neutron absorption in the counters with the initial direction of the neutron flux, respectively, parallel ($\leftrightarrow$) and transverse ($\updownarrow$) to the counters. These calculations showed that the difference between the corresponding efficiencies among themselves and when compared with isotropic neutron emission (ε_{is}) was small in comparison with the uncertainty introduced by the method itself: $\varepsilon_{\leftrightarrow} = 33.7\%$, $\varepsilon_{\updownarrow} = 34.3\%$, $\varepsilon_{\text{is}} = 33.9\%$.

The program was checked by comparing the calculated and measured neutron detection efficiencies $\varepsilon_p^{\text{Cf}}$ and $\varepsilon_e^{\text{Cf}}$ for a ^{252}Cf source placed inside the IND. To avoid the necessity

TABLE II. Luminosity of different detectors.

Type of detector	Differential (Ref. 4)	Integrated (Ref. 19)	Integrated (Ref. 20)	Integrated, IND
Luminosity $\overline{\varepsilon N}_p\,(10^{27})$	5.4	5.0	6.2	8.7

for absolute source intensity calibration, we used a "start method" in which we started with the first neutron and measured the distribution of the number of recorded neutrons in a given time window T after the "start." This distribution uniquely determined $\varepsilon_e^{\rm Cf}$, which was found to be 63.7%. The calculated value was 65.3%. As can be seen, the two agree to within 2.5%. The 3% level was taken to be the systematic error in the neutron detection efficiency. The efficiency of detection of neutrino-proton interactions in the IND, including the wall effect η, is thus found to be $\varepsilon = 31.1 \pm 0.9\%$.

An important parameter of the detector is its luminosity $\overline{\varepsilon N}_p$ which, other things being equal, determines the efficiency of antineutrino detection for each particular detector. Table II lists the values of this parameter for different detectors.

The principal feature of our experiment is that the detector recorded antineutrinos from two reactors located at distances $R_1 = 32.8$ m and $R_2 = 92.3$ m from it, respectively. When the neutrino oscillation parameters were determined, this enabled us to use the method of two distances, which had the significant additional advantage of constant background.

EXPERIMENTAL RESULTS

The IND was exposed for about 1200 days, during which we recorded about 10^5 antineutrino-proton events. Table III lists the results only for the one-reactor regimes, when only one of the two reactors was working and when both reactors were shut down (background measurements).

Detailed analysis of the IND background showed that practically the entire neutron background of this detector was due to ^{252}Cf decays. A small amount of ^{252}Cf nuclei (about 10^7) entered the detector when it was used in a previous experiment on the fission parameters of this element. In each of the series of measurements, we recorded events in which the number of neutrons within the time interval of 270 μs (four neutron lifetimes in the system) was between one and four. Figure 3 shows the rate of events with several ($\geqslant 2$) neutrons as a function of time from the beginning of the experiment. The straight line was optimized by the χ^2 method and represents the function $N = N_0 \exp(-t/\tau_{\rm Cf})$ with $\tau^{\rm Cf} = 1390 \pm 5$ d (Ref. 21). Optimization with respect to the two independent parameters N_0 and τ yields $\tau = 1356 \pm 59$ d with $\chi^2 = 0.59$. The satisfactory agreement between the decay constant $\tau^{\rm Cf}$ and the measured τ confirms the presence of the ^{252}Cf nuclei in the detector. Naturally, the detector records events involving several neutrons, but only for those ^{252}Cf nuclei that are located in its central part. On the other hand, contamination of the peripheral part of the system provides mostly contributions to single-neutron events. Actually, the count rate corresponding to single-neutron events was found to decrease systematically in the course of the experiment. Figure 3 also shows the results of measurements in the $(-\ +)$ regime for which the principal contribution to the neutron count rate was determined by the background. The χ^2 analysis of all the measurement regimes yielded a background level due to ^{252}Cf at the beginning of the experiment, as follows: $N_{\rm Cf} = 167.3 \pm 8.3$ events during one standard series of measurements. The decay coefficients of californium (α) listed in Table III represent the intensity of the neutrino background component averaged over the duration of the measurements:

$$\alpha = \Big(\sum_k \Delta T_k\Big)^{-1} \sum_k \Delta T_k \exp(-t_k/\tau),$$

where t_k is the time during the k th series of measurements, measured from the beginning of the experiment, and ΔT_k is the duration of the k th series.

To calculate the effect due to each reactor, the initial data (Table III) were arranged in the form of the following set of linear equations:

$$\begin{aligned} 1.049N_1 + 0.61N_{\rm Cf} + N_c &= 389.9 \pm 7.2,\\ 1.032N_2 + 0.61N_{\rm Cf} + N_c &= 163.2 \pm 2.7,\\ 0.68N_{\rm Cf} + N_c &= 141.8 \pm 5.9, \end{aligned} \qquad (3)$$

where N_1 and N_2 are the effects due to the first (nearer) and second (further) reactors in one standard series of measurements, scaled to the same output power, and N_c is the constant component of the background.

Solution of this set of equations yields

TABLE III. Experimental results.

Regime No.	Reactor regime		Number of neutrino events $A_i \pm A_i$ per series of measurements	Mean decay constant of ^{252}Cf
1	+	−	389.9 ± 7.2	0.61
2	−	+	163.2 ± 2.7	0.61
3	−	−	141.8 ± 5.9	0.68

Footnote. The plus sign signifies that the reactor is turned on, and minus that it is shut down. The first column of these signs refers to the nearer reactor and the second to the more distant reactor.

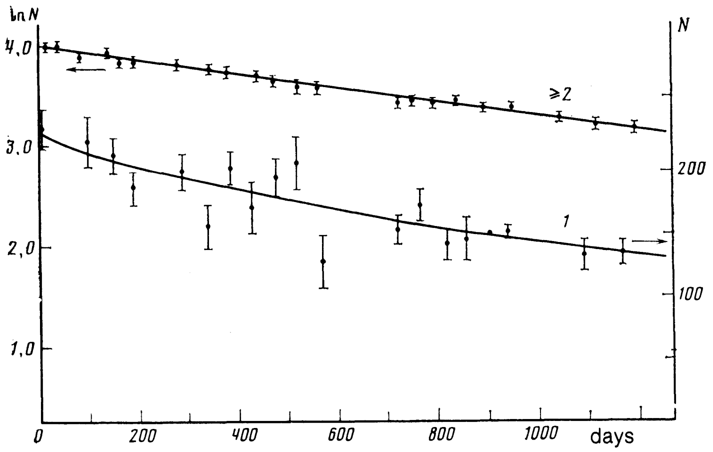

FIG. 3. Event count rate as a function of time for events with one and several neutrons, respectively.

$$N_1=248.0\pm8.9,\quad N_2=31.9\pm6.3,\quad N_c=28.4\pm8.2,$$
$$K_{exp}=N_2/N_1=0.129\pm0.022.$$

If we impose the additional relation $(R_1/R_2)^2 = 0.127$ (R_1 and R_2 are the effective distances between the detector and corresponding reactor), which represents the inverse square reduction in the antineutrino flux in the absence of oscillations, we can use the entire accumulated statistics to determine N_1. The set of equations given by (3) then contains a degree of redundancy and its solution, based on χ^2 minimization, yields the following results: $N_1 = 247.6 \pm 8.0$, $N_c = 28.9 \pm 5.9$, and $P = 93.2\%$ (degree of agreement). We can then use this solution to find the integrated inverse beta-decay cross section per fission of ^{235}U, corrected for the composition of the fuel. The result is

$$\bar{\sigma}_{exp}=[6.19\pm0.20\,(\text{stat.})\pm0.3\,(\text{syst.})]\cdot10^{-43}\ \text{cm}^2/\text{fission}.$$

The systematic uncertainty includes uncertainties in the luminosity of the detector ($\sim3\%$), the reactor power ($\sim3\%$), and the effective distance ($\sim1\%$).

This result is in good agreement with the calculated value

$$\bar{\sigma}_T=(6.11\pm0.21)\cdot10^{-43}\ \text{cm}^2/\text{fission}.$$

Table IV lists the results of other experiments, in which the inverse beta-decay cross section was measured.

ESTIMATES OF THE PARAMETERS OF NEUTRINO OSCILLATIONS

The search for neutrino oscillations can be made in two ways: by comparing the measured cross section with calculated values and by comparing effects at different distances from the reactors. We used both methods.

When oscillations are present, $\bar{\sigma}_{exp}$ depends on the distance R between the reactor and detector:

$$\bar{\sigma}_{exp}=\bar{\sigma}_T[1-\sin^2 2\theta I(R)],$$

$$I(R)=1/\bar{\sigma}_T\int_E\sigma(E)\,n_{\tilde{\nu}_e}(E)\sin^2\left(1.27\frac{\Delta^2}{E}R\right)dE,$$

and θ is the mixing angle for the different mass states of the neutrino. These formulas are derived in all treatments of oscillations. We note that the oscillations term $I(R)$ tends to $\frac{1}{2}$ as $\Delta^2\to\infty$. In practice, this value of $I(R)$ was reached in our experiment for $\Delta^2\geqslant1$ eV.^{2}

The values of N_1 and N_2, obtained by solving (3), lead to the following cross sections:

$$\sigma_{exp}^{(1)}=[6.20\pm0.22\ (\text{stat.})\pm0.30\ (\text{syst.})]\cdot10^{-43}\ \text{cm}^2/\text{fission},$$

$$\sigma_{exp}^{(2)}=[6.30\pm1.25\ (\text{stat.})\pm0.30\ (\text{syst.})]\cdot10^{-43}\ \text{cm}^2/\text{fission}.$$

The corresponding limits (curves 1 and 2) are shown in Fig. 4. The region of allowed neutrino oscillation parameters lies to the left and below the curves. When the oscillation parameters were estimated by the other method, we compared the quantities

$$K_{exp}=\frac{N_2}{N_1}\left(\frac{R_2}{R_1}\right)^2$$

and

$$K_{theor}=\frac{1-I(R_2)\sin^2 2\theta}{1-I(R_1)\sin^2 2\theta}.$$

This ratio is not very sensitive to the shape of the antineutrino spectrum, which was verified for the two spectra exhibiting the maximum difference.[9,16]

For maximum mixing ($\sin^2 2\theta = 1$), the values of K_{theor}

TABLE IV.

Experiment	(Ref. 22)	(Ref. 19)	(Ref. 20)	(Refs. 20–25)	This paper
$\bar{\sigma}\times10^{43}$, cm^2/fission	5.8	6.24	5.97	$\sim$6.1	6.2

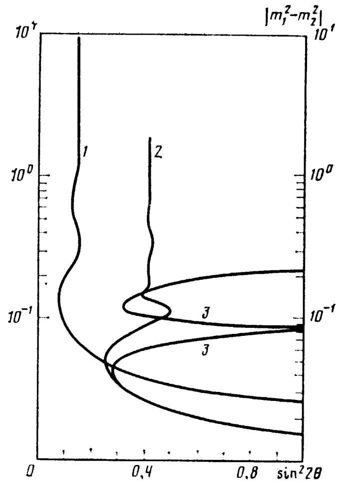

FIG. 4. Experimental limits on neutrino oscillation parameters obtained in this research.

for these two spectra differ by only about 2%. It follows that the main uncertainty involved in the comparison of $K_{\rm exp}$ with $K_{\rm theor}$ is due to the experimental uncertainty. The limits on the oscillation parameters obtained by this method are indicated in Fig. 5 (curves 3). The confidence limit (CL) for all the curves in this figure is about 68%.

Figure 5 shows the results obtained in experiments on neutrino oscillations, performed on the reactors at Gösgen,

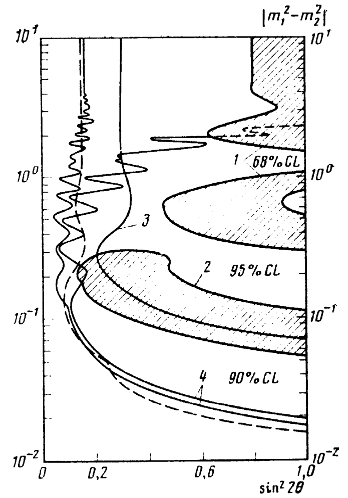

FIG. 5. Comparison of the limits on neutrino oscillation parameters: 1—Ref. 5, 2—Ref. 4, 3—Ref. 10, 4—Ref. 25, broken curve—present work.

Bugey, and Rovno. It is clear from the figure that the limits obtained in our experiments are in good agreement with the results obtained at Gösgen, which substantially reduces the reliability of the positive conclusions drawn from the Bugey experiment.

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[1]V. S. Kozik, V. A. Liubimov, E. G. Novikov, *et al.*, Phys. Lett. B **94**, 266 (1980).
[2]J. J. Simpson, Phys. Rev. Lett. **54**, 1891 (1985).
[3]J. K. Rowley, B. T. Cleveland, and R. Davis Jr., Solar Neutrinos and Neutrino Astronomy, AIP Conf. Proc., 1985, Vol. 126, p. 1.
[4]J. E. Cavaignac, A. Hoummada, D. H. Koang, *et al.*, Phys. Lett. B **148**, 387 (1984).
[5]F. Reines, H. W. Sobel, and E. Pasierb, Phys. Rev. Lett. **45**, 1307 (1980).
[6]B. M. Pontecorvo, Zh. Eksp. Teor. Fiz. **33**, 549 (1957) [Sov. Phys. JETP **6**, 429 (1958)].
[7]C. S. Vu and S. A. Moszkowski, *Beta-Decay* [Russian transl. Atomizdat, M., 1970, p. 220], Wiley, 1966.
[8]J. Byrne, J. Morse, K. F. Smith, *et al.*, Phys. Lett. B **92**, 274 (1980).
[9]F. Avignone and Z. D. Greenwood, Phys. Rev. C **22**, 594 (1980).
[10]V. I. Kopetskin, Yad. Fiz. **32**, 1507 (1980) [Sov. J. Nucl. Phys. **32**, 780 (1980)].
[11]P. Vogel, G. K. Schenter, F. M. Mann, *et al.*, Phys. Rev. C **24**, 1543 (1981).
[12]F. Feilitzsch, A. A. Hahn, and K. Schreckenbach, Phys. Lett. B **118**, 162 (1982).
[13]J. K. Dickens, Phys. Rev. Lett. **46**, 1061 (1981).
[14]B. R. Davis, P. Vogel, and F. M. Mann, Phys. Rev. C **19**, 2259 (1974).
[15]H. V. Klapdor and J. Metzinger, Phys. Lett. B **112**, 22 (1982).
[16]K. Schreckenbach, H. R. Faust, F. Felitzsch, *et al.*, Phys. Lett. B **99**, 251 (1981).
[17]S. A. Fayans, Yad. Fiz. **42**, 929 (1985) [Sov. J. Nucl. Phys. **42**, 590 (1985)].
[18]E. A. Gonin and A. V. Maiorov, ANT. Ser. Fiz. Tekh. Yad. Reaktor. No. 8(21), 62 (1981).
[19]A. I. Agonin, A. A. Borovoĭ, Yu. L. Dobrynin, *et al.*, Pis'ma Zh. Eksp. Teor. Fiz. **41**, 355 (1985) [JETP Lett. **41**, 435 (1985)].
[20]S. N. Belen'kiĭ, Yu. A. Dobrynin, L. A. Mikaelyan, *et al.*, Yad. Fiz. **42**, 894 (1985) [Sov. J. Nucl. Phys. **42**, 567 (1985)].
[21]International Nuclear Data Committee, INDC(IDS)-149/NE, 1983.
[22]H. Kwon, F. Boehm, A. A. Hahn, *et al.*, Phys. Rev. D **24**, 1097 (1981).
[23]J. L. Vuilleumier, F. Boehm, J. Egger, *et al.*, Phys. Lett. B **114**, 298 (1982).
[24]K. Gabathuller, F. V. Feilitzsch, J. L. Gimlet, H. Kwon, R. L. Mössbauer, J. L. Vuilleumier, G. Zacek, and V. Zacek, Phys. Lett. B **138**, 449 (1984).
[25]V. Zacek, G. Zacek, F. Boehm, *et al.*, Phys. Lett. B **164**, 193 (1985).

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