On possibility to detect light sterile neutrino in beta- and neutrinoless double beta-decays of nuclei

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A (3+3)-neutrino model is used to describe the effects of sterile neutrinos in beta-decay and neutrinoless double beta-decay of nuclei.

This model includes three active neutrinos ν_α (α = e, μ, τ) and three new sterile neutrinos in the assumption of Majorana nature of neutrino.

These new neutrinos are: a sterile neutrino ν_s, a hidden neutrino ν_h and a dark neutrino ν_d.

Appearance and survival probabilities for active neutrinos with contributions of sterile neutrinos are obtained for explanation of all available data on neutrino anomalies at small distances

There are experimental indications on neutrino fluxes anomalies, which can not be explained with Modified Standard Model (MSM) with only three massive active neutrinos

Short Base Length (SBL) anomalies

$$\Delta m^2 (eV^2) \frac{L}{E_\nu} \approx 1$$

L is the distance from neutrino source (m)

E_ν is the neutrino energy (MeV)

Accelerator anomaly

LSND and MiniBooNE anomaly: an excess of the electron antineutrinos in beams of muon antineutrinos in comparison with the expected value according MCM

LSND Collaboration,

C. Athanassopoulos et al., Phys. Rev. Lett. 77, 3082 (1996)

MiniBooNE Collaboration, A.A. Aguilar-Arevalo et al., Phys. Rev. Lett. 161801 (2013)

Reactor anomaly

Deficit of reactor electron antineutrinos at short distances

Gallium or calibration anomaly

Deficit of electron neutrinos from a radioactive source occurred at calibration of detectors for the SAGE and GALLEX experiments

SBL anomalies
may be explained by means of existence of new sterile neutrinos, which do not interact directly with the SM gauge bosons.

The characteristic mass scale of these light SNs is ~1 eV. Now intensive searches are carried out for light SNs or eV-sterile neutrinos. It is expected that in the coming several years it will be possible to confirm or reject their existence

Standard Model

Three types of massless neutrino

$$\Psi_{L,\alpha} \qquad \alpha = e, \mu, \tau$$

Modified Standard Model (MSM)

$$\psi^{\alpha} = U^{\alpha}{}_{i}\, \psi^{i}, \qquad U_{PMNS} = U = VP,$$

$$P = \mathrm{diag}\{1,\ \exp(i\alpha),\ \exp(i\beta)\},$$

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Experimental data on neutrino oscillations characteristics

$$\sin^2\theta_{12} = 0.297^{+0.017}_{-0.016}, \quad \sin^2\theta_{23} = \begin{cases} NH: 0.437^{+0.033}_{-0.020} \\ IH: 0.461^{+0.030}_{-0.033} \end{cases},$$

$$\sin^2\theta_{13} = \begin{cases} NH: 0.0214^{+0.0011}_{-0.0009} \\ IH: 0.0218^{+0.0009}_{-0.0012} \end{cases}, \quad (1\sigma \text{ level})$$

$$\Delta m^2_{21}/10^{-5}\,\mathrm{eV}^2 = 7.37^{+0.17}_{-0.16}, \quad \Delta m^2/10^{-3}\,\mathrm{eV}^2 = \begin{cases} NH: 2.50^{+0.04}_{-0.04} \\ IH: -\left(2.46^{+0.05}_{-0.04}\right) \end{cases}$$

$$\Delta m^2 = m_3^2 - (m_1^2 + m_2^2)/2$$

Generalized mixing of active and sterile neutrinos

For the compactness of the formulas, we introduce the symbols h_s and $h_{i'}$ for additional left flavor fields and additional left mass fields, respectively. As s we will use a set of indices that allocate ν_s, ν_h and ν_d fields among h_s, and as i' we will use a set of indices 4, 5 and 6. The 6×6 mixing matrix U_{mix} can then be expressed through 3×3 matrices R, T, V and W as follows

$$\begin{pmatrix} \nu_a \\ h_s \end{pmatrix} = U_{\text{mix}} \begin{pmatrix} \nu_i \\ h_{i'} \end{pmatrix} \equiv \begin{pmatrix} R & T \\ V & W \end{pmatrix} \begin{pmatrix} \nu_i \\ h_{i'} \end{pmatrix}, \qquad (1)$$

where $R = U_{\text{PMNS}} + \Delta U_{\text{PMNS}}$. The matrix ΔU_{PMNS}, as well as the matrix T in equation (1) should be small as compared with the matrix U_{PMNS}, thus $\Delta U_{\text{PMNS}} = -\epsilon U_{\text{PMNS}}$, where ϵ is a small value, which can be represented as $\epsilon = 1 - \varkappa$ so $R = \varkappa U_{\text{PMNS}}$. ($U_{\text{PMNS}} \equiv U$ below).

Generalized mixing of active and sterile neutrinos

We define T as $T = \sqrt{1-\varkappa^2}\,a$, where a is an arbitrary unitary 3×3 matrix. $U_{\rm mix}$ can be written as

$$U_{\rm mix} = \begin{pmatrix} R & T \\ V & W \end{pmatrix} \equiv \begin{pmatrix} \varkappa U & \sqrt{1-\varkappa^2}\,a \\ \sqrt{1-\varkappa^2}\,bU & \varkappa c \end{pmatrix}, \qquad (2)$$

where b is also an arbitrary unitary 3×3 matrix, and $c = -ba$. Under these conditions $U_{\rm mix}$ will be unitary. We consider only some particular cases for $U_{\rm mix}$ and use the matrices a and b:

$$a = \begin{pmatrix} \cos\eta_2 & \sin\eta_2 & 0 \\ -\sin\eta_2 & \cos\eta_2 & 0 \\ 0 & 0 & e^{-i\kappa_2} \end{pmatrix}, \quad b = -\begin{pmatrix} \cos\eta_1 & \sin\eta_1 & 0 \\ -\sin\eta_1 & \cos\eta_1 & 0 \\ 0 & 0 & e^{-i\kappa_1} \end{pmatrix}, \qquad (3)$$

Generalized mixing of active and sterile neutrinos

where κ_1 and κ_2 are mixing phases for AN and SN, whereas η_1 and η_2 are their mixing angles. The matrix a in the form (3) was proposed in Ref. 4. In order to make our calculations more specific, we use the following test values for new mixing parameters:

$$\kappa_1 = \kappa_2 = -\pi/2, \quad \eta_1 = 5^\circ, \quad \eta_2 = \pm 30^\circ, \tag{4}$$

and assume that the small parameter ϵ satisfies at least the condition $\epsilon \lesssim 0.03$. The mixing matrix in the form of equation (2) is more general in comparison with the mixing matrix $\widetilde{U}$ that was proposed and used in Ref. 4, so there are more possibilities to describe the various contributions of SN.

The neutrino masses are given by a normally ordered set of values $\{m\} = \{m_i, m_{i'}\}$. For AN we use the neutrino mass estimations, which were proposed in Refs. 4,26,30 for NH-case (in units of eV) and which do not contradict to the known experimental data:

$$m_1 \approx 0.0016, \quad m_2 \approx 0.0088, \quad m_3 \approx 0.0497\,. \tag{5}$$

Neutrino masses will be set on the base of existing experimental data and limits for

Δm^2 , effective masses in beta and neutrinoless double beta decay and mixing parameters of active and sterile neutrinos

Both active and sterile neutrinos are treated as Majorana particles

{m(eV)}={0.0016, 0.0088,0.0497,1.05,0.63,0.27}

Transition probability

$P(\nu_\alpha \rightarrow \nu_{\alpha'}) = \delta_{\alpha'\alpha} - 4Re(\Sigma_{i>k} U_{m,\alpha' i} U^*_{m,\alpha i} U^*_{m,\alpha' k} U_{m,\alpha k}) \sin^2\Delta_{ki}$

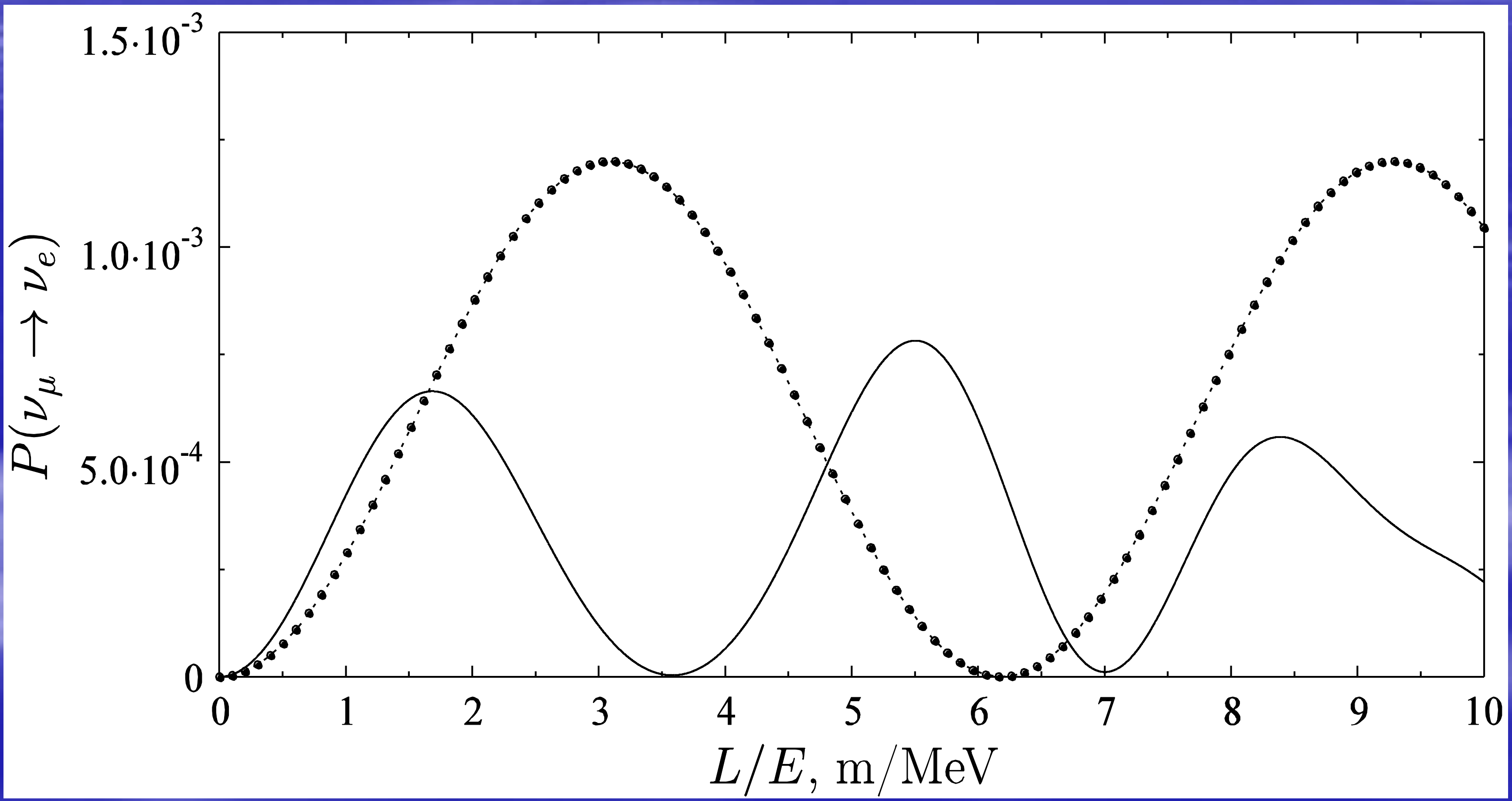
$+2Im(\Sigma_{i>k} U_{m,\alpha' i} U^*_{m,\alpha i} U^*_{m,\alpha' k} U_{m,\alpha k}) \sin 2\Delta_{ki}$

U_m – generalized 6·6 mixing matrix

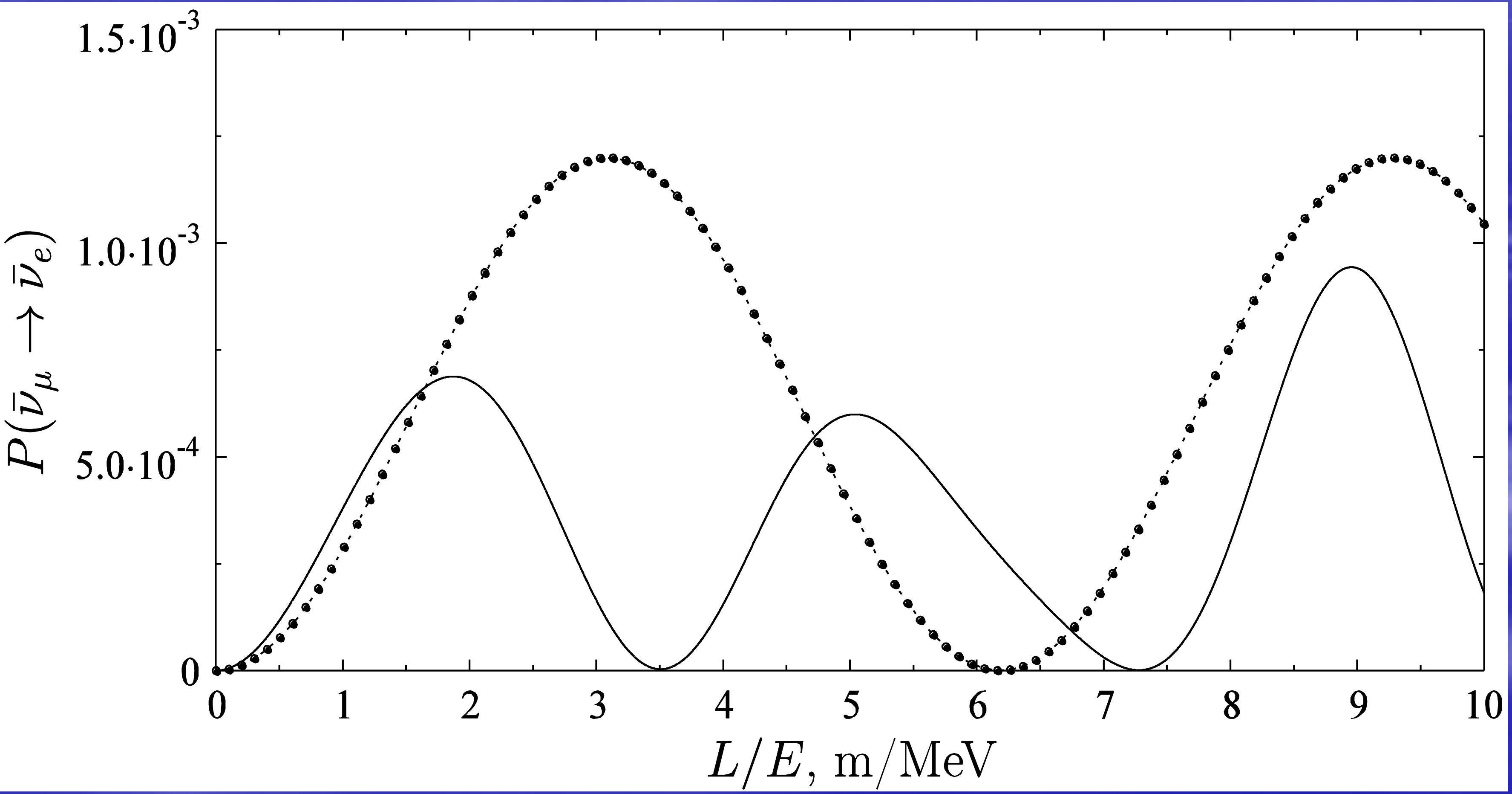
$\Delta_{ki} \equiv \Delta m^2_{ik} L/(4E)$

Δm^2_{ik}, L, 4E are given in *eV²*, *m* and *MeV* respectively

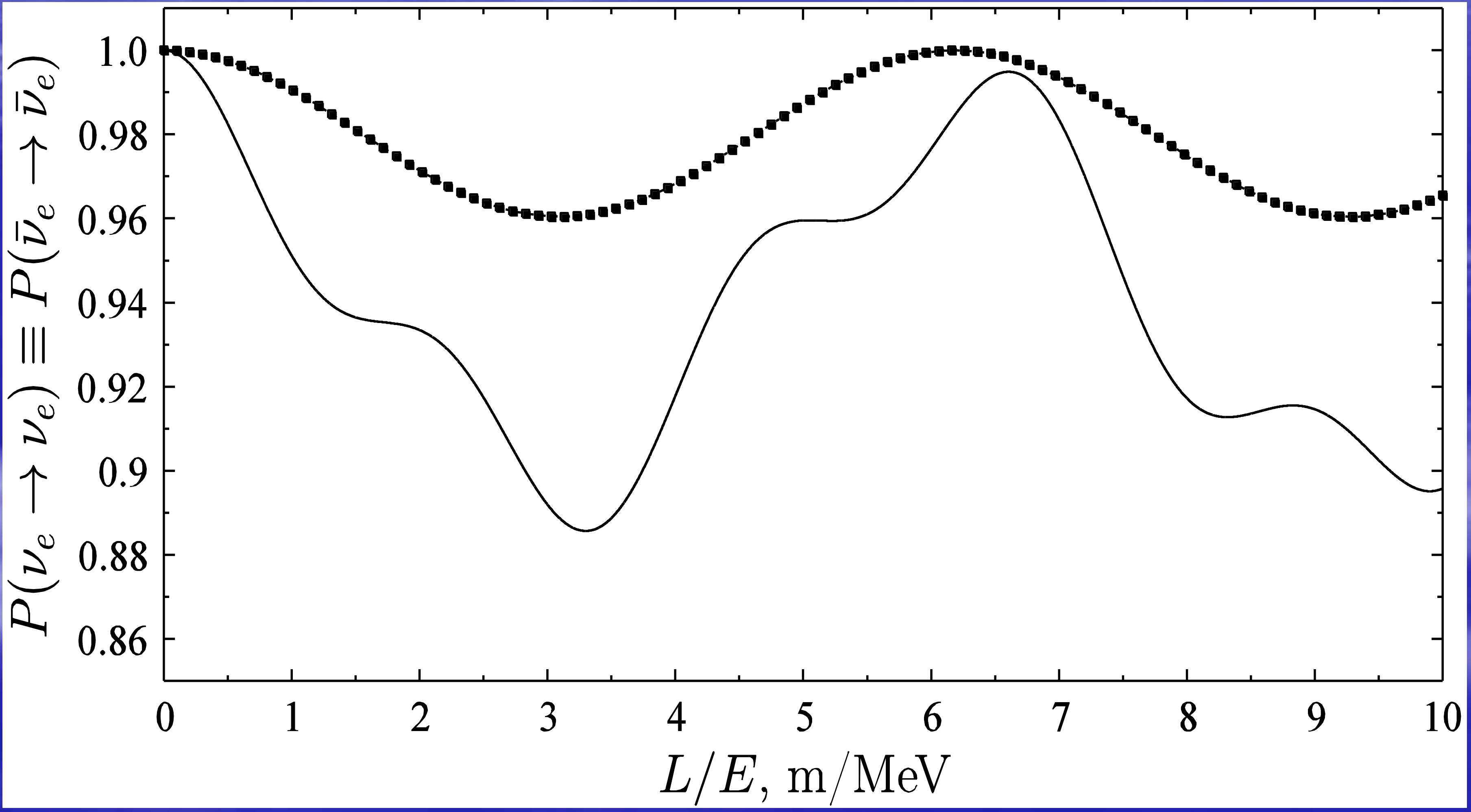
Probability of appearance of ν_e in ν_μ beam as a function of L/E ratio. The dashed curve is a result of (3+1) model



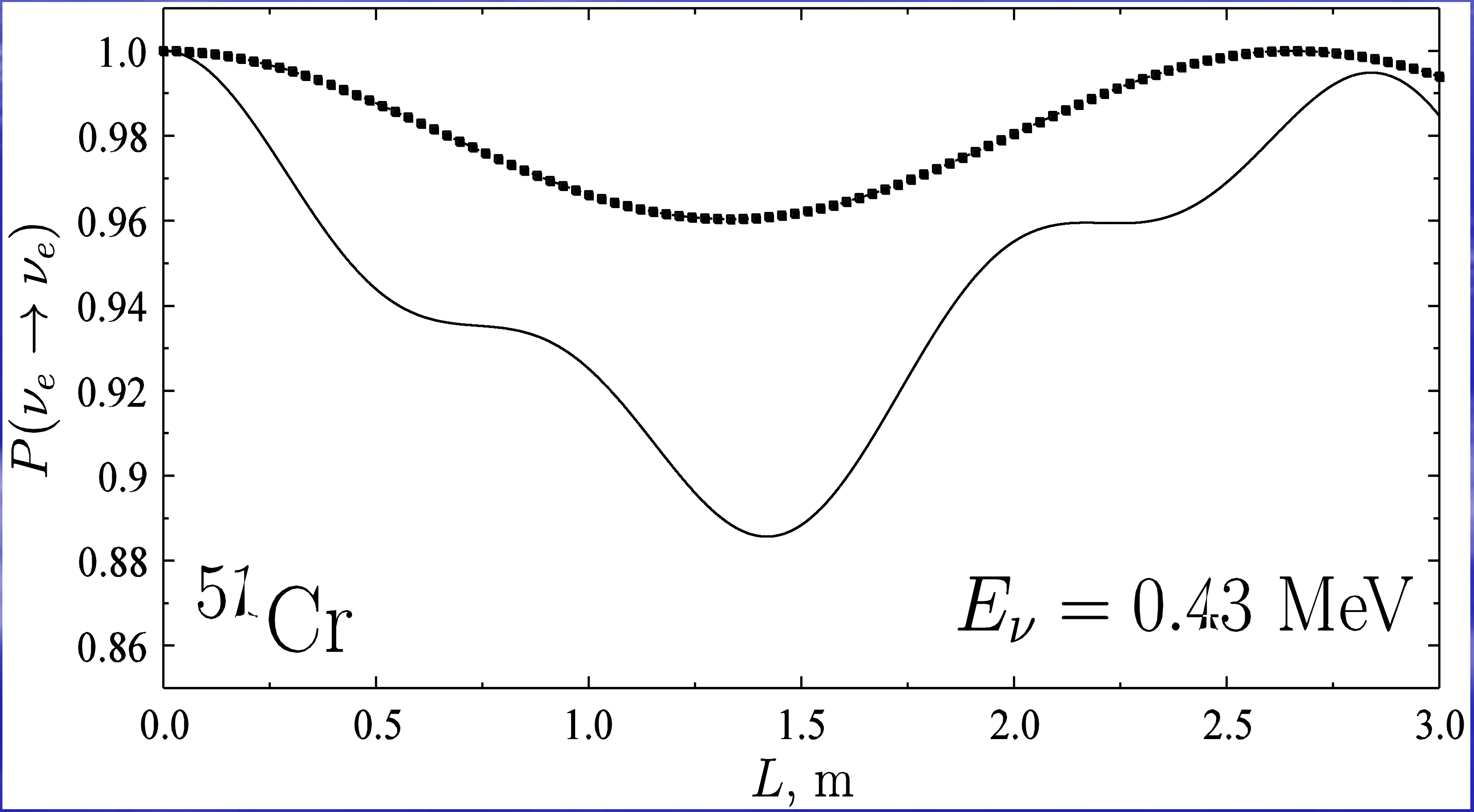
Probability of appearance of anti-ν_e in anti-ν_μ beam as a function of L/E ratio. The dashed curve is a result of (3+1) model



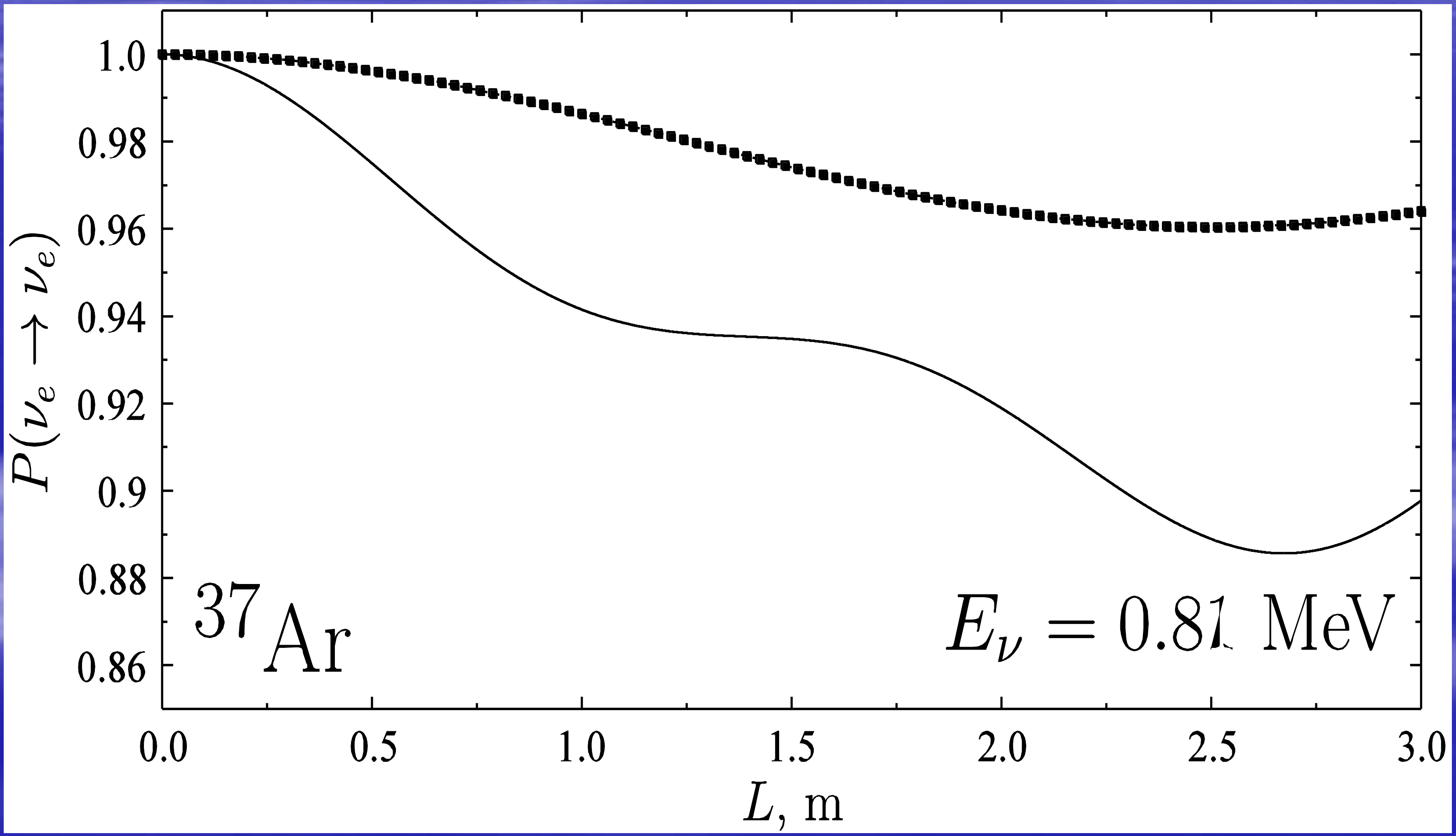
Probability of survival of ν_e (anti-ν_e) as a function of L/E ratio. The dashed curve is a result of (3+1) model



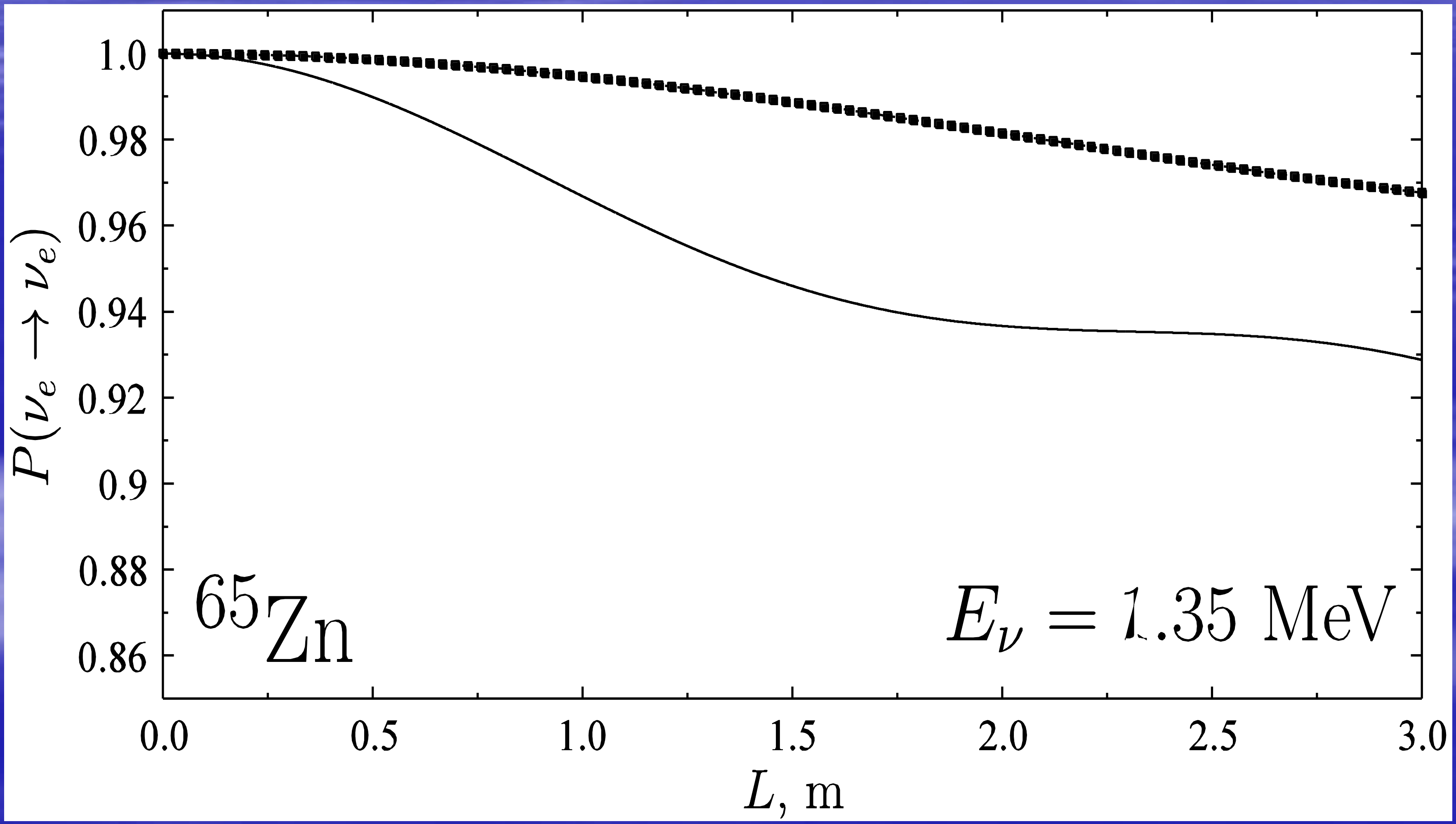
Survival probability for ν_e as a function of distance L for ^{51}Cr neutrino source



Survival probability for ν_e as a function of distance L for ^{37}Ar neutrino source



Survival probability for ν_e as a function of distance L for ^{65}Zn neutrino source



Contribution of sterile neutrino to β- and double-β decay probability

$m^2_\beta = \Sigma_i |U_{ei}|^2 m^2_i$

$m_\beta = 0.131$ eV   AN+SN

KATRIN experiment $m_\beta < 0.2$ eV

Three AN, without SN, NO $m_\beta = 0.001$ eV

Neutrinoless double beta-decay

$m_{\beta\beta}=|\Sigma_i U^2_{ei}\, m_i|$

$m_{\beta\beta}=0.027$ eV   AN+SN

KamLAND-Zen, ^{136}Ar, $m_{\beta\beta}<0.061$ eV

$$T_{1/2}^{0\beta} = \frac{m_e^2}{G^{0\nu} g_A^4 \left| M^{0\nu} m_{\beta\beta} \right|^2}$$

^{82}Se is perspective isotope for $0\nu2\beta$ search

NEMO-3 0.93 kg, $T^{0\nu}_{1/2} > 2.5 \cdot 10^{23}$ yrs

CUPID-0 5.53 kg, $T^{0\nu}_{1/2} > 2.4 \cdot 10^{24}$ yrs

$m_{\beta\beta} = 0.027$ eV

$\{T^{0\nu}_{1/2}\}_{min} = 6.2 \cdot 10^{26}$ yrs

$\{T^{0\nu}_{1/2}\}_{max} = 2 \cdot 10^{27}$ yrs, depending on NME

New large-scale setups are to be built

SuperNEMO, 100 kg ^{82}Se

For calculation of sensitivity for $T^{0\nu}_{1/2}$ exact calculation of unremovable background due to two-neutrino channel are necessary

Calculation of (2ν2β)-decay amplitude for Se-82

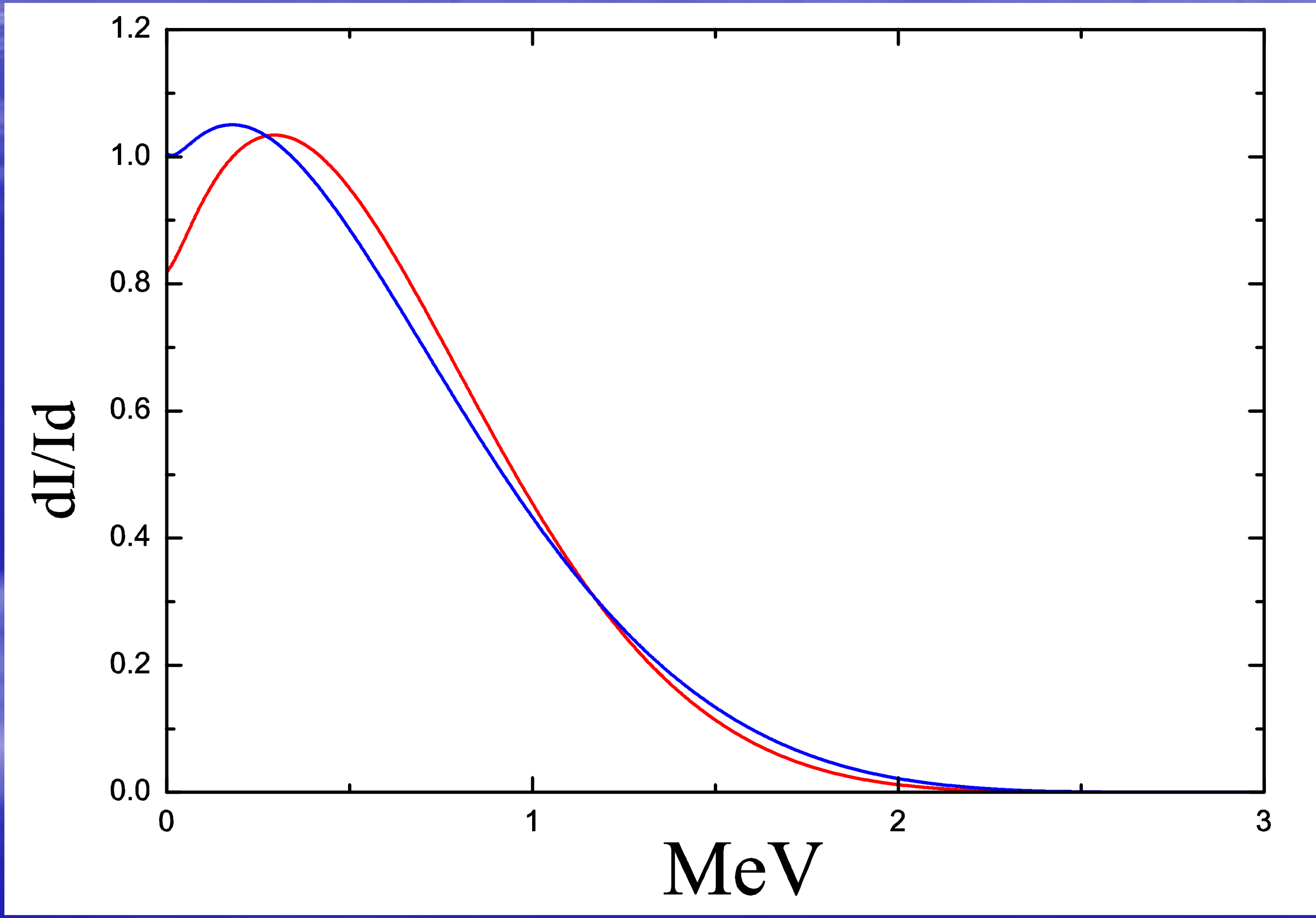
Проведем ниже теоретический расчет полной и дифференциальной интенсивности $2\nu2\beta$-распада ^{82}Se. Для вычисления интенсивности двухнейтринных переходов нужно суммировать по всем возможным 1^+-состояниям промежуточного ядра [60, 61]. Для этого необходимы значения модулей и фаз соответствующего набора матричных элементов:

$$\left[T_{1/2}^{2\nu2\beta}\left(0_i^+ \to 0_f^+\right)\right]^{-1} = \frac{G_\beta^4 g_A^4}{32\pi^7 \ln 2} \int\limits_{m_e}^{T+m_e} d\varepsilon_1 \int\limits_{m_e}^{T+2m_e-\varepsilon_1} d\varepsilon_2 \int\limits_{0}^{T+2m_e-\varepsilon_1-\varepsilon_2} d\omega_1 \times$$
$$\times F(Z_f,\varepsilon_1)F(Z_f,\varepsilon_2)p_1\varepsilon_1 p_2\varepsilon_2\omega_1^2\omega_2^2 A_{0_f^+}. \quad (6.1)$$

Выражение для $A_{0_f^+}$ имеет следующий вид:

$$4A_{0_f^+} = \left|\sum_N \left\langle 0_f^+ \left\|\hat{\beta}^-\right\| 1_N^+\right\rangle \left\langle 1_N^+ \left\|\hat{\beta}^-\right\| 0_i^+\right\rangle (K_N + L_N)\right|^2 +$$
$$+\frac{1}{3}\left|\sum_N \left\langle 0_f^+ \left\|\hat{\beta}^-\right\| 1_N^+\right\rangle \left\langle 1_N^+ \left\|\hat{\beta}^-\right\| 0_i^+\right\rangle (K_N - L_N)\right|^2. \quad (6.2)$$

Здесь p_1, p_2 и ε_1, ε_2 – соответственно импульсы и энергии электронов, ω_1, ω_2 – энергии антинейтрино, $\omega_2 = T + 2m_e - \varepsilon_1 - \varepsilon_2 - \omega_1$, $T = E_i - E_f - 2m_e = Q_{\beta\beta}$ – полная кинетическая энергия лептонов в конечном состоянии, и $E_i(E_f)$ – масса родительского



1.2
1.0
0.8
0.6
0.4
0.2
0.0
dI/Id
0
1
2
3
MeV

Conclusiomn

- Probabilties of appearance and survival of electron neutrino and antineutrino are obtained in (3+3) model for different SBL experiments are obtained. This gives the possibility to explain the set of experimental facts on neutrino anomalies
- Differential intensities for two-neutrino channel are calculated
- The model estimations of effective masses
- m_{β} and $m_{\beta\beta}$ are performed and half-decay time for neutrinoless double beta decay of ^{82}Se is obtained

Thank you