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ON PROSPECTS FOR EXPLORATION OF SUPERSYMMETRY IN DOUBLE BETA DECAY EXPERIMENTS

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О перспективах исследования суперсимметрии в экспериментах по поиску двойного бета-распада

В рамках суперсимметричной модели с нарушенной R_p четностью ($\not R_p$SUSY) проведен анализ ограничений на ее параметры, которые могут быть получены из условия ненаблюдения безнейтринного ядерного двойного бета-распада (0νββ). Анализ охватывает широкий класс феноменологически приемлемых $\not R_p$SUSY-моделей. Вводятся специальные характеристики: «чувствительность к SUSY'» изотопа, распадающегося по ββ-каналу, и «способность достичь SUSY'» в том или ином 0νββ-эксперименте. Первая дает физический критерий выбора наиболее выгодного для поиска SUSY изотопа, вторая позволяет оценить возможности конкретного 0νββ-эксперимента с точки зрения значимости информации, которую он может дать для изучения $\not R_p$SUSY-параметрического пространства. На этой основе обсуждаются перспективы исследования суперсимметрии различными экспериментами по поиску 0νββ-распада.

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On Prospects for Exploration of Supersymmetry in Double Beta Decay Experiments

We analyze constraints on the parameters of the R_p violating supersymmetry ($\not R_p$SUSY) which can be extracted from non-observation of the neutrinoless nuclear double-beta decay (0νββ) at a given half-life lower bound. Our analysis covers a large class of phenomenologically viable $\not R_p$SUSY models. We introduce special characteristics: the SUSY sensitivity of a ββ-decaying isotope and the SUSY reach of a 0νββ-experiment. The former provides a physical criterion for a selection of the most promising isotopes for SUSY searches and the latter gives a measure of success for a 0νββ-experiment in exploring the $\not R_p$SUSY parameter space. On this basis, we discuss prospects for exploration of supersymmetry in various 0νββ-experiments.

The investigation has been performed at the Laboratory of Nuclear Problems, JINR.

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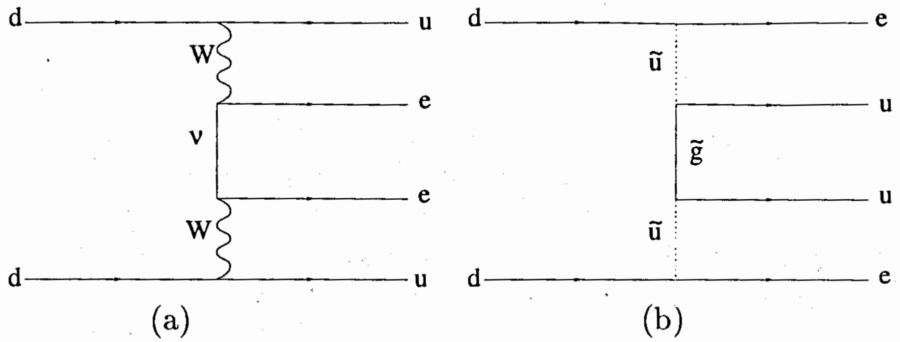
Observation of the neutrinoless double beta ($0\nu\beta\beta$) decay ${}^Z_AY \rightarrow {}^{Z+2}_{\ \ A}Y + 2e^-$ of some nucleus ${}^Z_AY$ would be an unambiguous signal of the physics beyond the standard model (SM) of electroweak interactions [1], [2]. This process is forbidden within the SM since it violates lepton number (L) conservation.

During a long time the $0\nu\beta\beta$-decay has been attracting great theoretical and experimental efforts. A number of experimental collaborations are involved in searching for this exotic phenomenon (see for instance [3]). Unfortunately, there is not yet any evidence for the $0\nu\beta\beta$-decay. Nevertheless, impressive progress has been achieved in establishing a lower bound on the half-life of various isotopes and further advance in this direction is expected in the near future.

The question is: what sort of new information on the physics beyond the SM we are provided with this experimental progress.

It was a common practice to answer this question in terms of the Majorana neutrino mass. This implies that the $0\nu\beta\beta$-decay proceeds via the conventional mechanism based on Majorana neutrino exchange between the decaying neutrons, as presented in Fig. 1a. The measure of experimental success in this case is a reduction of the upper bound on the effective neutrino mass $\langle m_\nu \rangle$. The best result to date is $\langle m_\nu \rangle \leq 0.65$ eV (90% C.L.) [4]. Other experiments are also nearly penetrating the sub-eV neutrino mass range.

Quite recently it has been realized that the conventional neutrino exchange mechanism is not the only possible one. Modern particle physics offers a mechanism based on the supersymmetric (SUSY) interactions [5]-[9]. In a certain sense this mechanism is more interesting than the conventional one since it allows the



(a) (b)

FIG. 1. (a) The conventional massive Majorana neutrino exchange mechanism and (b) the supersymmetric mechanism (the dominant contribution) of the neutrinoless double beta decay.

$\beta\beta$-decay experiments in the exciting field of supersymmetry. SUSY interactions, inducing the $0\nu\beta\beta$-decay, can contribute to many other processes. Therefore, one can compare information about these interactions obtained from different experiments including $0\nu\beta\beta$-decay experiments. It has been shown in [8] that $0\nu\beta\beta$-decay experiments are more sensitive to certain SUSY manifestations than the other running and forthcoming accelerator and non-accelerator experiments.

In this note we give a quite general parametrization of the SUSY effect in the $0\nu\beta\beta$-decay and formulate criterion for the success of a $0\nu\beta\beta$-experiment in terms of an upper bound on the effective SUSY parameter. The latter is a certain combination of the fundamental SUSY parameters. We introduce the sensitivity of an isotope to the SUSY manifestation and the SUSY reach of a given $0\nu\beta\beta$-experiment characterizing the depth of its penetrating to the SUSY realm. The latter is represented by the unexplored part of the SUSY model parameter space. This provides us with a convenient basis for estimating prospects of the exploration of the SUSY in various $0\nu\beta\beta$-experiments.

We start with a short theoretical introduction. The $0\nu\beta\beta$-decay is allowed within a special class of the SUSY models admitting B-L violation (B and L are baryon and lepton quantum numbers). These are presently popular SUSY models with R-parity violation ($R_p = (-1)^{3B+L+2S}$, where S is the spin). The $\not{R}_p$ terms can be introduced explicitly into the superpotential as

$$W_{\not{R}_p} = \lambda_{ijk} L_i L_j \bar{E}_k + \lambda'_{ijk} L_i Q_j \bar{D}_k + \lambda''_{ijk} \bar{U}_i \bar{D}_j \bar{D}_k. \qquad (1)$$

The indices i, j, k stand for generations. L, Q denote lepton quark doublet superfields, while $\bar{E}$, $\bar{U}$, $\bar{D}$ correspond to lepton and *up*, *down* quark singlet superfields. The first two terms in (1) lead to lepton number violation, while the last one violates the baryon number. For the $0\nu\beta\beta$-decay only the λ and λ' type couplings are of relevance. The presence of lepton number violating interactions in the $\not{R}_p$SUSY model allows one to construct the SUSY mechanism of the $0\nu\beta\beta$-decay [5]-[9].

A complete analysis of this mechanism within the $\not{R}_p$ minimal supersymmetric standard model ($\not{R}_p$MSSM) was carried out in [8]. On rather general grounds it was also shown [8] that the dominant contribution to this mechanism within a phenomenologically viable $\not{R}_p$SUSY model comes from the gluino $\tilde{g}$ exchange diagram presented in Fig. 1b. This contribution does not depend on specific details of a $\not{R}_p$SUSY model such as the neutralino content, the mixing coefficients, etc. Thus, for any such model we can write down a dominant term of the effective quark-electron Lagrangian in the same form as for the $\not{R}_p$MSSM derived in [7]

$$\mathcal{L}_{eff}(x) = \frac{G_F^2}{2m_p} \cdot \eta_{SUSY} \left[J_P J_P + J_S J_S - \frac{1}{4} J_T^{\mu\nu} J_{T\mu\nu} \right] \bar{e}(1+\gamma_5)e^c + \text{subdominant terms.} \qquad (2)$$

The quark currents are defined as $J_P = \bar{u}^\alpha \gamma_5 d_\alpha$, $J_S = \bar{u}^\alpha d_\alpha$, $J_T^{\mu\nu} = \bar{u}^\alpha \sigma^{\mu\nu}(1+\gamma_5) d_\alpha$. The effective parameter η_{SUSY} accumulates certain fundamental parameters of the $\not{R}_p$SUSY model. In the particular case of the $\not{R}_p$MSSM it has the form

$$\eta_{\tilde{g}} = \frac{2\pi\alpha_s}{9} \frac{\lambda'^2_{111}}{G_F^2 m^4_{\tilde{d}_R}} \frac{m_p}{m_{\tilde{g}}} \left[1 + \left(\frac{m_{\tilde{d}_R}}{m_{\tilde{u}_L}} \right)^4 \right]. \qquad (3)$$

Here $m_{\tilde{g}}$ is the gluino mass and $m_{\tilde{u}_L, \tilde{d}_L}$ are masses of the superpartners of u_L and d_R quarks; α_s is the strong coupling constant. Starting from the Lagrangian (2) describing the basic quark-lepton transition $d + d \to u + u + 2e^-$, which triggers the $0\nu\beta\beta$-decay, one can derive the following half-life formula [7]

$$[T_{1/2}(0\nu\beta\beta)]^{-1} = G_{01} \left(\frac{m_A}{m_p} \right)^4 \eta^2_{SUSY} \left| \mathcal{M}_{\tilde{q}} \right|^2 . \qquad (4)$$

The factor in brackets implies the normalization of $\mathcal{M}_{\tilde{q}}$ as in [8]. $m_A = 0.85$ GeV is the momentum scale of the nucleon dipole form factor $F(q^2) = (1 + q^2/m_A^2)^{-2}$ used in calculation of the nuclear matrix element $\mathcal{M}_{\tilde{q}}$. The leptonic phase space integral G_{01} is defined as

$$G_{01} = \frac{(G_F \cos\Theta_C f_A/f_V)^4 m_e^9}{64\pi^5 \hbar (m_e R_0)^2 \ln 2} \int d\Omega_1 d\Omega_2 b_{01} \qquad (5)$$

and tabulated in [2] for various nuclei. Values of G_{01} for nuclei analyzed in the present letter are given in the Table. Here, R_0

Table: The SUSY sensitivity ζ, phase space factor G_{01} and nuclear matrix element for the SUSY mechanism of the $0\nu\beta\beta$-decay calculated within the pn-QRPA for several experimentally interesting isotopes. ζ defines the constraint on the SUSY parameter $\eta_{SUSY} \leq \frac{1}{\zeta \cdot 10^7} \left(\frac{10^{24}}{T_{1/2}^{0\nu\beta\beta}} \right)^{1/2}$.

Isotope ^{A}Y	Nuclear Matrix Element $\mathcal{M}_{\tilde{q}}$	Phase Space Factor $G_{01} \cdot 10^{14}$	SUSY Sensitivity ζ
^{150}Nd	416	20.808	19
^{100}Mo	328	4.56316	7
^{130}Te	262	4.41596	5.5
^{82}Se	253	2.80583	4.24
^{116}Cd	190	4.92614	4.2
^{136}Xe	143	4.71196	3.11
^{76}Ge	283	0.635941	2.26
^{128}Te	298	0.181888	1.27

is the nuclear radius and $f_A = 1.261$, $f_V = 1$. The kinematical factor b_{01} accounts for the Coulomb distortion of the electron waves [2].

The nuclear matrix element $\mathcal{M}_{\tilde q}$ for the SUSY contribution to the $0\nu\beta\beta$-decay can be written in the form independent of the nuclear wave function [7]

$$\begin{aligned}\mathcal{M}_{\tilde q} &= \frac{m_p}{m_e}\langle 0_f^+ || \sum_{i\neq j} \tau_+^{(i)}\tau_+^{(j)} \left(\frac{R_0}{r_{ij}}\right) \Big[\alpha_V^{(0)} F_N(x_A) + \alpha_V^{(1)} F_4(x_A) + \\ &+ \ \sigma_i\cdot\sigma_j \left(\alpha_A^{(0)} F_N(x_A) + \alpha_A^{(1)} F_4(x_A)\right) + \\ &+ \ \alpha_T\{3(\sigma_i\cdot\hat{r}_{ij})(\sigma_j\cdot\hat{r}_{ij}) - \sigma_i\cdot\sigma_j\}F_5(x_A)\Big] ||0_i^+\rangle. \qquad (6)\end{aligned}$$

The following notations are used

$$r_{ij} = (\vec{r}_i - \vec{r}_j), \quad r_{ij} = |r_{ij}|, \quad \hat{r}_{ij} = r_{ij}/r_{ij}, \quad x_A = m_A r_{ij},$$

where $\vec{r}_i$ is the coordinate of the ith nucleon. The nucleon structure parameters $\alpha_V^{(0)} = 0.15$, $\alpha_V^{(1)} = 7.5$, $\alpha_A^{(0)} = -1.2$, $\alpha_A^{(1)} = 0.28$, $\alpha_T = 1.3$ were calculated in [7].

Three different structure functions F_i are given by the integrals over the momentum $\mathbf{q}$ transferred between two decaying nucleons and have the form

$$\begin{aligned}F_N(x) &= \frac{xe^{-x}}{48}(3 + 3x + x^2), \\ F_4(x) &= \frac{xe^{-x}}{48}(3 + 3x - x^2), \quad F_5(x) = \frac{x^3 e^{-x}}{48}. \qquad (7)\end{aligned}$$

Expression (6) allows numerical calculation of the matrix element $\mathcal{M}_{\tilde q}$ within any nuclear structure model. So far such calculations have been carried out only within the pn-QRPA (proton-neutron Quasiparticle Random Phase Approximation) in [8]. It is well-motivated and reliable approach [10] successfully describing the $2\nu\beta\beta$-decay recently observed in several experiments. Numerical values of $\mathcal{M}_{\tilde q}$ for several experimentally most interesting isotopes are given in the Table. We point out that this matrix element drastically differs in structure from the well known $0\nu\beta\beta$ nuclear matrix elements of the Majorana neutrino exchange mechanism.

Non-observation of the $0\nu\beta\beta$-decay at the half-life level $T_{1/2}^{exp}$ leads to the following constraint on the $R\!\!\!/_p$ SUSY parameter η_{SUSY}

$$T_{1/2}^{th} \geq T_{1/2}^{exp} \longrightarrow \eta_{SUSY} \leq \frac{10^{-7}}{\zeta(Y)}\sqrt{\frac{10^{24}\text{years}}{T_{1/2}^{exp}}} = 10^{-7}\cdot\epsilon(Y, exp)^{-1}. \qquad (8)$$

where $T_{1/2}^{th}$ is the theoretical expression given in (4). We have introduced the following characteristics of a $\beta\beta$-decaying isotope Y and a particular $0\nu\beta\beta$-experiment giving a quantitative basis for assessing its ability to search for a SUSY signal. These are the SUSY sensitivity of an isotope Y

$$\zeta(Y) = 10^5 \mathcal{M}_{\tilde q}\sqrt{G_{01}} \qquad (9)$$

and the SUSY reach of the $0\nu\beta\beta$-experiment with the isotope Y

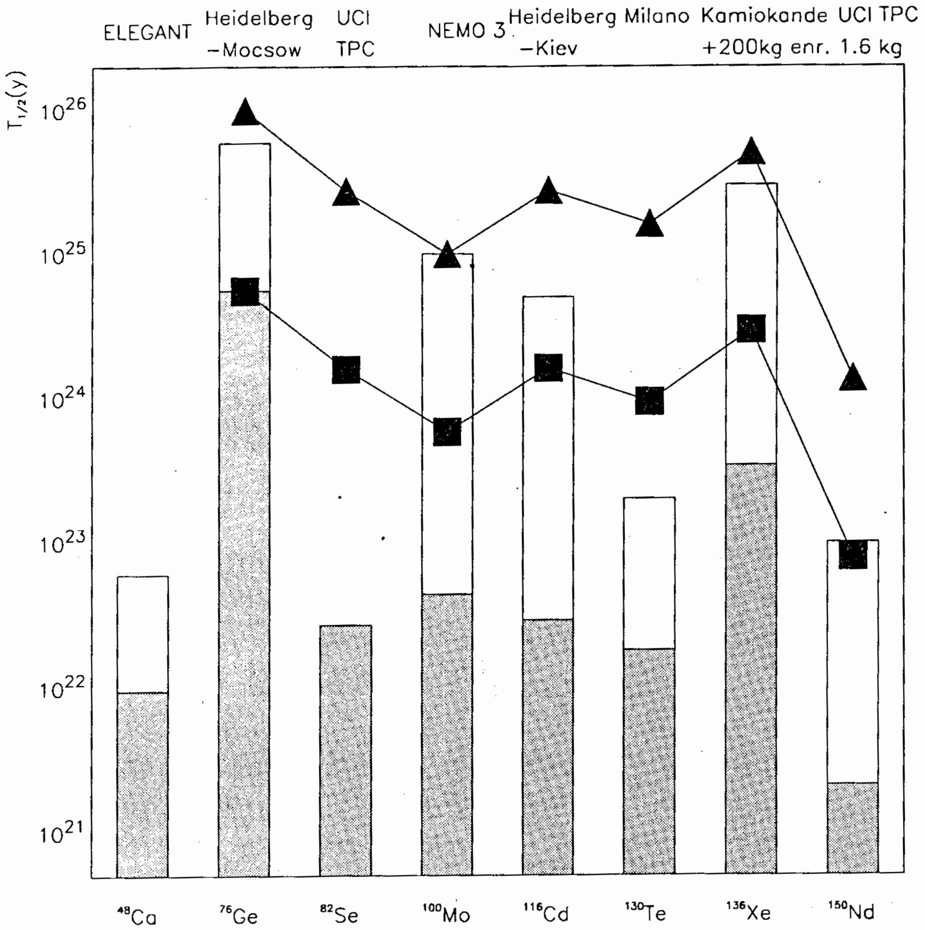
$$\epsilon(Y, exp) = \zeta(Y)\sqrt{\frac{T_{1/2}^{exp}}{10^{24}\text{years}}}. \qquad (10)$$

The former is an intrinsic characteristic of an isotope Y depending only on the matrix element and the phase space factor. The latter characterizes the experimental set-up as a whole. $T_{1/2}^{exp}$ is the lower half-life bound reached with this set-up. This is a time dependent characteristic for improving experiments.

The large numerical values of the SUSY sensitivity ζ in (9) correspond to those isotopes within the group of $\beta\beta$-decaying nuclei which are most promising candidates for searching for SUSY in $0\nu\beta\beta$-decay experiments. Using general formulas in (6)-(7) one can calculate ζ in the framework of any nuclear structure model. Its numerical values calculated in the pn-QRPA are presented in the Table. As is seen, the most sensitive isotope is ^{150}Nd, then follows ^{100}Mo. Unfortunately, we are not able to make any conclusion concerning ^{48}Ca, which is also an experimentally interesting isotope. This is because the pn-QRPA does not provide reliable results for this light nucleus. It would be important to reconstruct a whole picture showing potential abilities of all $\beta\beta$-decaying nuclei from the point of view of their sensitivity to the SUSY signal. Therefore, calculation of the SUSY nuclear matrix element $\mathcal{M}_{\tilde{q}}$ for ^{48}Ca within a certain nuclear model is demanded. It could be done, for instance, on the basis of the nuclear shell. This approach allows exact nuclear structure calculations for ^{48}Ca [11], [12].

Of course, the SUSY sensitivity ζ cannot be the only criterion for selecting an isotope for the $0\nu\beta\beta$-experiment. Other microscopic and macroscopic properties of the isotope are also important for building a $0\nu\beta\beta$-detector.

The SUSY reach parameter $\epsilon(Y, exp)$ of the $0\nu\beta\beta$-experiment takes into account both the SUSY sensitivity of the isotope Y and specific experimental conditions determining the reach in the half-life limit. The current and the near future experimental situation in terms of the accessible half-life and the SUSY reach parameter ϵ is presented in Fig. 2a,b. For completeness, in Fig. 2c we also present a situation with the experimental reach



(a)

FIG. 2. 1995 experimental situation (gray bars) and expectations up to 2000 (open bars). (a) half-life $T_{1/2}$; two broken lines correspond to the two fixed values of the SUSY reach $\epsilon(^{76}\text{Ge, H-M})^{\text{present}} = 5.3$ (lower line) and $\epsilon(^{100}\text{Mo, NEMO})^{\text{future}} = 22.2$ (upper line); experiments reaching these lines provide the same constraints as the Heidelberg-Moscow experiment now (lower line) or as expected from the NEMO experiment in the near future (upper line). (b) the SUSY reach parameter ϵ (see (10)) and (c) the inverse neutrino mass reach $1/m_\nu$ (taken from [4]).

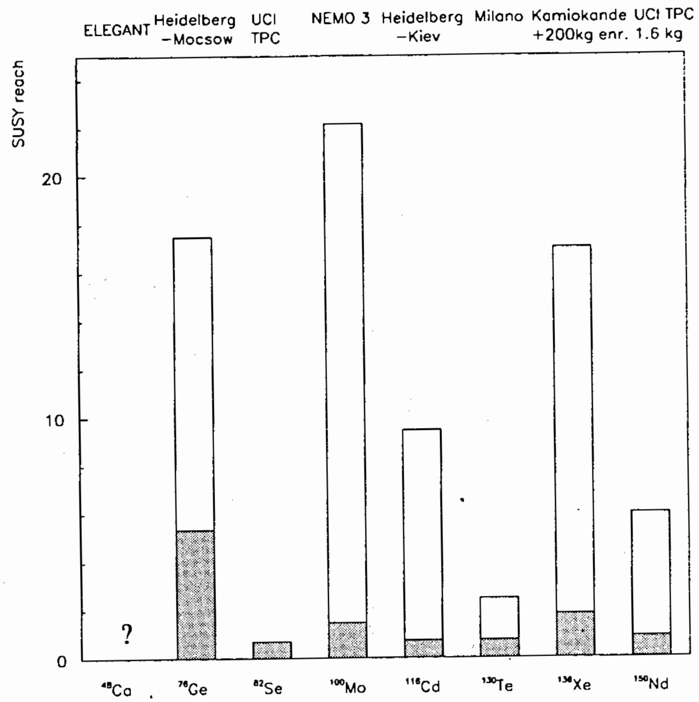


FIG. 2(b)

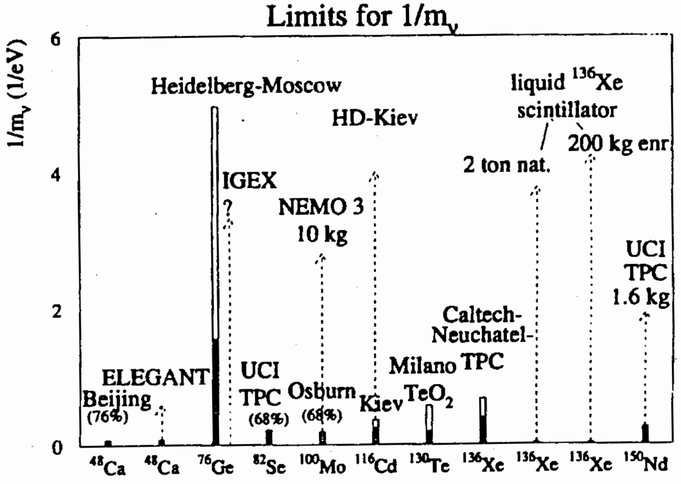


FIG. 2(c)

in the inverse neutrino mass. Fig. 2c is taken from [4]. Figs. 2 show the running $\beta\beta$-experiments: the Heidelberg-Moscow (H-M) ^{76}Ge experiment [4], the NEMO ^{100}Mo experiment [13], and other $0\nu\beta\beta$-experiments that also crossed the half-life barrier of 10^{21} years with the isotopes ^{48}Ca [14]; ^{82}Se [15]; ^{100}Mo [16]; ^{116}Cd [17]; ^{130}Te [18]; ^{136}Xe [19]; ^{150}Nd [20]. We also included in Fig. 2 the forthcoming or partly operating experiments: the Gottard ^{136}Xe TPC experiment [21], the ^{130}Te cryogenic experiment [18], the ELEGANT experiment with 64 g of ^{48}Ca [22], the experiment with 1.6 kg of ^{150}Nd using an improved UCI TPC [20].

In Fig. 2a two broken lines with black squares and triangles correspond to the two fixed values of the SUSY reach $\epsilon(^{76}\mathrm{Ge},\ \text{H-M})^{\text{present}} = 5.3$ (lower line) and $\epsilon(^{100}\mathrm{Mo},\ \text{NEMO})^{\text{future}} = 22.2$ (upper line). Experiments reaching these lines provide the same constraints on η_{SUSY} in (8) as the Heidelberg-Moscow experiment at present (lower line) and as expected from the NEMO experiment in the near future (upper line) respectively.

These lines are interrupted on the left from the ^{76}Ge since we have no value of the SUSY nuclear matrix element $\mathcal{M}_{\tilde{q}}$ for ^{48}Ca.

It is seen from Fig. 2 that the Heidelberg-Moscow ^{76}Ge detector is the best m_ν explorer at present and up to the year 2000. This experiment is also the best SUSY explorer at present. However, in the near future the NEMO experiment is able to take over the leadership in exploration of SUSY as follows from Fig. 2a.

In conclusion, we stress that from the physical point of view the lower half-life bound itself is not a satisfactory characteristic of the $0\nu\beta\beta$-decay experiment. An objective characteristic should be related to the fundamental parameters of the underlying physics. In this note we give the parameterization of the SUSY contribution to the $0\nu\beta\beta$-decay in terms of one effective parameter η_{SUSY}. The parameterization is valid for a wide class of $\not{R}_p$SUSY models and can be used for the quantitative presentation of the SUSY effect in the $0\nu\beta\beta$-decay experimental data. Together with the effective Majorana neutrino mass $\langle m_\nu \rangle$ the parameter η_{SUSY} is an important physical characteristic of the $0\nu\beta\beta$-decay experiment.

Our results for the SUSY sensitivities ζ of various $\beta\beta$-decaying isotopes and for the SUSY reach ϵ of $\beta\beta$-decay detectors based on the η_{SUSY} parameterization can be used for planning the future experiments.

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References

[1] W.C. Haxton and G.J. Stephenson, Progr. Part. Nucl. Phys. 12 (1984) 409 J. D. Vergados, Phys. Report, 133 (1986) 1; K. Grotz and H.V. Klapdor-Kleingrothaus, The Weak Interactions in Nuclear, Particle and Astrophysics, Adam Hilger, Bristol, New York, 1990; J.W.F. Valle, Prog. Part. Nucl. Phys. 26 (1991) 91.

[2] M. Doi, T. Kotani and E. Takasugi, Progr.Theor.Phys. Suppl. 83(1985)1.

[3] M. Moe and P. Vogel, Annual Review of Nucl. and Part. Science 44 (1994) 247; H.V.Klapdor-Kleingrothaus in Proc. Nucl.Phys. (proc. Suppl.) B31 (1993) 72; Progr.Part.Nucl.Phys. 32 (1994) p.261.

[4] HEIDELBERG-MOSCOW Collaboration: A. Balysh et al., Phys. Lett. B356 (1995)450.

[5] R.N. Mohapatra, Phys.Rev. D34 (1986) 3457.

[6] J.D Vergados, Phys.Lett. B184 (1987) 55.

[7] M. Hirsch, H.V. Klapdor-Kleingrothaus and S.G. Kovalenko, Phys.Lett. B352 (1995) 1.

[8] M. Hirsch, H.V. Klapdor-Kleingrothaus and S.G. Kovalenko Phys.Rev. D53 (1996)1329; Phys.Rev.Lett., 75 (1995) 17.

[9] K.S. Babu and R.N. Mohapatra, Phys.Rev.Lett., 75 (1995)2276; M. Hirsch, H.V. Klapdor-Kleingrothaus and S.G. Kovalenko, Phys.Lett. B372 (1996) 181.

[10] K. Muto, E. Bender and H.V. Klapdor, Z. Phys. A334 (1989) 177,187

[11] A. Willaims and W.C. Haxton, in "Intersection between Particle and Nuclear Physics, edited by G.M. Bunce, AIP Conf. Proc. No. 176 (AIP, New York, 1988), p.924.

[12] J.Retamosa, E. Caurier and F.Nowacki, Phys. Rev, C 51 (1995) 371.

[13] NEMO Collaboration, Nucl.Phys. (Proc. Suppl.) B 35 (1994) 369.

[14] Ke You et al., Phys. Lett. B 265 (1995) 53.

[15] S.R. Elliott et al., Phys. Rev. C 46 (1992) 1535.

[16] M. Alston-Garnjost et al., Phys. Rev. Lett. 71 (1993) 831.

[17] F.A. Danevich et al., Phys.Lett. B 344 (1995) 72.

[18] A. Alessandrello et al., Phys. Lett. B 335 (1994) 519.

[19] J.-L. Vuilleumier et al., Phys. Rev. D 48 (1993) 1009.

[20] M.K. Moe et al., Progr. Part. Nucl. Phys 32 (1994) 247; Nucl. Phys. (Proc. Suppl.) B 38 (1995) 36.

[21] V. Jörgens et al., Nucl.Phys. (Proc. Suppl.) B 35 (1994) 378.

[22] K. Kume (ELEGANT Collaboration), Proc. Int. Workshop on Double Beta Decay and Related Topics, (Trento, 24 April - 5 May 1995), eds. H.V. Klapdor-Kleingrothaus and S. Stoica (World Scientific Singapore).

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