Colloquium: The future of double β decay research

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The current results and future perspectives of 2β decay research are reviewed. The present status of neutrino physics makes it necessary to enhance the sensitivity of 2β decay experiments (in terms of the half-life limit for the neutrinoless mode) to the level of 10^{26}–10^{28} yr. Requirements for future supersensitivity projects are formulated and it is concluded that such a goal will certainly be reached in the most realistic next generation experiments (e.g., CAMEO, CUORE, GEM, GENIUS, and MAJORANA), where restrictions on the neutrino mass may be pushed down to $m_\nu \leqslant 0.01-0.05$ eV. In addition, the GEM and GENIUS projects may advance the best current limits on the existence of neutralinos—as dark matter candidates—by three orders of magnitude, and at the same time may be able to identify unambiguously the dark matter signal by detection of its seasonal modulation. All of these results will provide crucial tests of the key theoretical models of modern astroparticle physics and cosmology.

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I. INTRODUCTION

Double beta (2β) decay was predicted by Goeppert-Mayer in 1935 as a very rare nuclear process in which "... a metastable isobar can change into a more stable one by simultaneous emission of two electrons" (Goeppert-Mayer, 1935). The analysis of nuclear stability shows that observation of such nuclear transitions is possible, in principle, for 35 naturally occurring even-even nuclei (Moe and Vogel, 1994; Tretyak and Zdesenko, 1995, 2002), whose ordinary beta decay is forbidden energetically[1] (see Fig. 1, where the level scheme of the isobaric triplet ^{116}Cd-^{116}In-^{116}Sn is depicted as an example).

Double β decay is considered as a second-order process of the weak interaction, which is responsible in the first order for the usual β decay (with the Fermi coupling constant, $G_F = 1.66\times10^{-5}$ GeV^{-2}). Due to this, the 2β decay half-life is proportional to G_F^{-4}, and, consequently, is very long (Moe and Vogel, 1994; Faessler and Simkovic, 1998). The different possible modes of 2β decay can be distinguished from each other by the feature of the violation (or nonviolation) of the lepton number (L) conservation.

The two-neutrino 2β decay mode ($2\nu2\beta$) does not violate lepton number and is fully consistent with the standard model (SM) of electroweak theory. This process can be regarded as a simultaneous transformation of two neutrons (bound in the initial nucleus) into two protons,

$$n_1 \to p_1 + e_1^- + \overline{\nu}_{e1}, \quad (1)$$
$$n_2 \to p_2 + e_2^- + \overline{\nu}_{e2},$$

which leads to the final state with emission of two electrons and two antineutrinos,

$$(A,Z) \to (A,Z+2) + e_1^- + e_2^- + \overline{\nu}_{e1} + \overline{\nu}_{e2}. \quad (2)$$

Here, A and Z are the mass number and charge of the candidate nucleus. Under some usual assumptions the inverse half-life for $2\nu2\beta$ decay can be expressed as follows (Moe and Vogel, 1994; Faessler and Simkovic, 1998; Suhonen and Civitarese, 1998):

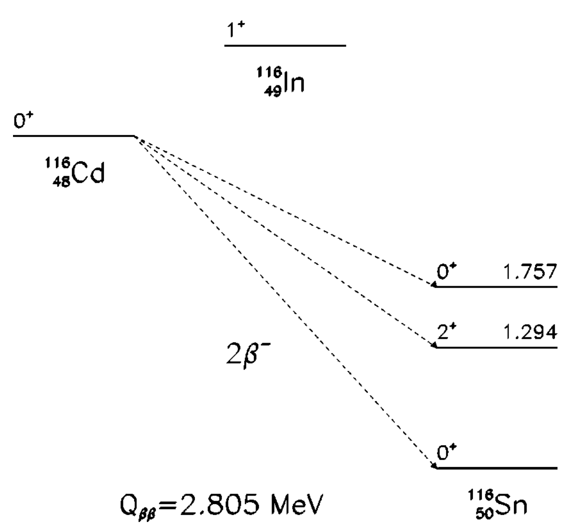

FIG. 1. The level scheme of the isobaric triplet ^{116}Cd-^{116}In-^{116}Sn.

[1]In only two cases, ^{48}Ca and ^{96}Zr, is ordinary β decay allowed energetically; however, it is strongly suppressed as a result of a large difference in angular momentum ($0^+ \to 6^+$). We note that 2β decay is always allowed if the reaction energy $Q_{\beta\beta}$ is positive; however, in the case of a β unstable parent nucleus, it would be extremely difficult to distinguish 2β decays from the intensive β background.

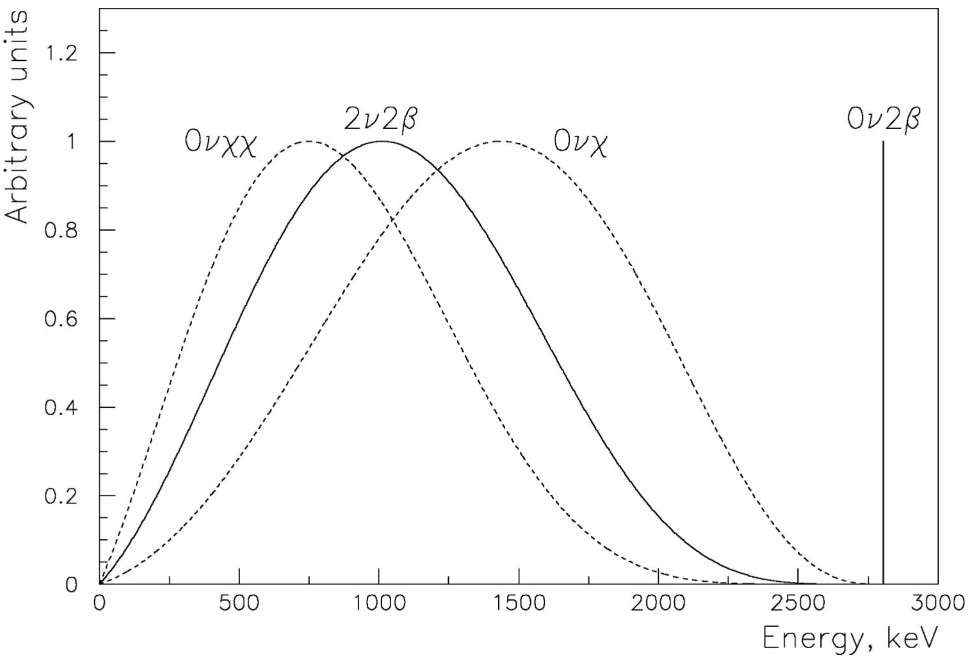

FIG. 2. The electron sum energy spectra calculated for the different 2β decay modes of ^{116}Cd.

$$(T_{1/2}^{2\nu})^{-1}=G^{2\nu}\cdot|\mathrm{NME}|^2, \tag{3}$$

where NME is the nuclear matrix element of the $2\nu2\beta$ decay, and $G^{2\nu}$ is the exactly calculated phase space factor (Doi *et al.*, 1985; Suhonen and Civitarese, 1998). Due to this, the measurement of the $2\nu2\beta$ decay rate can directly give the NME value. Thus, it allows one to precisely test the details of nuclear structure by comparing the measured and the calculated NME value (Faessler and Simkovic, 1998; Suhonen and Civitarese, 1998).

The neutrinoless 2β decay mode ($0\nu2\beta$)—which is far more interesting since it violates lepton number conservation—was considered first by Racah (1937) and Furry (1939) as a tool to distinguish whether the neutrino is of Majorana (particle≡antiparticle) (Majorana, 1937) or Dirac (particle≠antiparticle) type. Namely, if the neutrino emitted in the first neutron decay (1) is a Majorana particle, then it can be absorbed by another neutron in the reaction

$$n_2+\nu_{e1}\rightarrow p_2+e_2^-, \tag{4}$$

which therefore leads to the $0\nu2\beta$ decay mode,

$$(A,Z)\rightarrow(A,Z+2)+e_1^-+e_2^-. \tag{5}$$

While the electron sum energy spectrum of the $2\nu2\beta$ mode is continuous because the available energy release ($Q_{\beta\beta}$) is shared between four particles, in the case of the 0ν decay the two electrons carry the full available energy, and hence the electron sum energy spectrum has a sharp peak at the $Q_{\beta\beta}$ value, as shown in Fig. 2. This feature allows one to distinguish the $0\nu2\beta$ decay signal from the background and to recognize the effect easily.

After discovery of parity violation in weak interactions (Lee and Yang, 1956; Wu *et al.*, 1957) an additional requirement arose that the Majorana neutrino emitted in the first neutron decay (1) should reverse its helicity from right to left handed, since otherwise it cannot be absorbed in process (4) owing to its wrong helicity. Thus it cannot lead to $0\nu2\beta$ decay. Such a reversal might be caused by the neutrino mass (m_ν) and/or might occur explicitly through an admixture of right-handed current in weak interactions. On this basis the $0\nu2\beta$ decay probability can be written in the following form (Doi *et al.*, 1985; Moe and Vogel, 1994; Suhonen and Civitarese, 1998):

$$\begin{aligned}(T_{1/2}^{0\nu})^{-1}=&C_{mm}^{0\nu}\left(\frac{\langle m_\nu\rangle}{m_e}\right)^2+C_{m\lambda}^{0\nu}\langle\lambda\rangle\left(\frac{\langle m_\nu\rangle}{m_e}\right)\\&+C_{m\eta}^{0\nu}\langle\eta\rangle\left(\frac{\langle m_\nu\rangle}{m_e}\right)+C_{\lambda\lambda}^{0\nu}\langle\lambda\rangle^2+C_{\eta\eta}^{0\nu}\langle\eta\rangle^2\\&+C_{\lambda\eta}^{0\nu}\langle\lambda\rangle\langle\eta\rangle,\end{aligned} \tag{6}$$

where m_e is the electron mass, $\langle m_\nu\rangle$, $\langle\lambda\rangle$, and $\langle\eta\rangle$ are the effective electron neutrino mass and effective weak-coupling constants for coupling of right-handed and left-handed nucleonic current, respectively. The definitions of the coefficients $C_{ij}^{0\nu}$ through the specific nuclear matrix elements and phase space integrals of the $0\nu2\beta$ decay are given in reviews (Doi *et al.*, 1985; Suhonen and Civitarese, 1998). Assuming that all NME values may be calculated, i.e., all the coefficients $C_{ij}^{0\nu}$ are known, formula (6) represents an ellipsoid which restricts the allowed range of unknown parameters $\langle m_\nu\rangle$, $\langle\lambda\rangle$, and $\langle\eta\rangle$ for a given value or limit of the $0\nu2\beta$ decay half-life (Moe and Vogel, 1994). In the case of ignoring right-handed contributions ($\langle\lambda\rangle=0$; $\langle\eta\rangle=0$), Eq. (6) may be rewritten as

$$(T_{1/2}^{0\nu})^{-1}=G_{mm}^{0\nu}\cdot|\mathrm{NME}|^2\cdot\langle m_\nu\rangle^2, \tag{7}$$

where NME denotes a combination of Gamow-Teller and Fermi nuclear matrix elements and $G_{mm}^{0\nu}$ denotes the phase space integral of the $0\nu2\beta$ decay.

Obviously, the $0\nu2\beta$ decay is forbidden in the framework of the standard model because it violates lepton charge conservation ($\Delta L=2$) and because it requires the neutrino to be a massive Majorana particle. However, many extensions of the SM, in particular, grand unified theories (GUT's), incorporate L-violating interactions (more exactly, B-L, where B is the baryon number), since in modern gauge theories conservation of lepton (baryon) charge is considered an approximate law, due to the absence of any underlying symmetry principle behind it, such as, for instance, the gauge invariance which guarantees the masslessness of the photon and the absolute conservation of electric charge. Therefore it is quite natural to suppose that the symmetry associated with B-L conservation is approximate and may be broken at a certain energy scale. The B-L violation by two units gives rise to the massive Majorana neutrinos and consequently leads to the neutrino exchange mechanism of $0\nu2\beta$ decay. There are three possibilities: explicit B-L breaking (i), and spontaneous breaking of the local (ii) or global (iii) B-L symmetry. For the last case gauge models imply the existence of a physical Nambu-Goldstone boson (Chikashige *et al.*, 1980, 1981), called a Majoron (χ), which is a hypothetical neutral pseudoscalar particle with zero mass, which couples to Majorana neutrinos and may be emitted in the neutrinoless 2β decay (Doi *et al.*, 1985; Faessler and Simkovic, 1998; Suhonen and Civitarese, 1998):

$$(A,Z)\rightarrow(A,Z+2)+e_1^-+e_2^-+\chi, \tag{8}$$

$$(A,Z)\rightarrow(A,Z+2)+e_1^-+e_2^-+\chi+\chi. \tag{9}$$

Since Majorons do not interact with ordinary matter, they escape detection; thus the electron sum energy spectra for channels (8) and (9) are continuous. However, they can be distinguished from the $2\nu2\beta$ mode because their maxima are at different energies (Fig. 2). The decay rate formula for the Majoron emitting mode of the $0\nu2\beta$ decay can be obtained from Eq. (7) by substituting $\langle m_\nu\rangle$ with $\langle g_\chi\rangle$, where $\langle g_\chi\rangle$ is the effective Majoron neutrino coupling constant, and replacing the $G_{mm}^{0\nu}$ factor by the phase space integral which describes two electrons plus the massless Majoron in the final state (Moe and Vogel, 1994):

$$(T_{1/2}^{0\nu})^{-1}=G_\chi^{0\nu}\cdot|\mathrm{NME}|^2\cdot\langle g_\chi\rangle^2. \tag{10}$$

The phase space integrals $G^{2\nu}(Q_{\beta\beta},Z)$, $G_{mm}^{0\nu}(Q_{\beta\beta},Z)$, and $G_\chi^{0\nu}(Q_{\beta\beta},Z)$ from Eqs. (3), (7), and (10) contain the Fermi function $F(Q_{\beta\beta},Z)$, which represents the Coulomb distortion of the wave functions of the outgoing electrons. The tabulated values of $G^{2\nu}$, $G_{mm}^{0\nu}$, and $G_\chi^{0\nu}$ are given in reviews (Doi *et al.*, 1985; Tomoda, 1991; Suhonen and Civitarese, 1998).

Besides the above-described left-handed neutrino exchange mechanism of $0\nu2\beta$ decay, modern gauge theories offer many other possibilities for triggering this process (Faessler and Simkovic, 1998; Klapdor-Kleingrothaus, 1998). In that sense the $0\nu2\beta$ decay has a great conceptual importance due to the strong statement obtained in a gauge theory of the weak interaction that a nonvanishing $0\nu2\beta$ decay rate requires the neutrino to be a massive Majorana particle (and vice versa), independently of which mechanism induces it (Schechter and Valle, 1982). For instance, in left-right symmetric GUT models neutrinoless 2β decay can be mediated by heavy right-handed neutrinos (Doi *et al.*, 1983; Doi and Kotani, 1993). Leptoquarks, a new type of gauge bosons predicted by some GUT's, can transform quarks to leptons and induce $0\nu2\beta$ decay via leptoquark-Higgs couplings (Hirsch, Klapdor-Kleingrothaus, and Kovalenko, 1996c, 1996d). A hypothetical substructure of quarks and leptons (i.e., compositeness) can also give rise to a new $0\nu2\beta$ decay mechanism by exchange of composite heavy Majorana neutrinos (Cabibbo *et al.*, 1984; Panella *et al.*, 1997). Moreover, there are also possible $0\nu2\beta$ decay mechanisms based on the supersymmetric (SUSY) interactions: exchange of squarks, etc., in R-parity[2] violating SUSY models (Mohapatra, 1986; Vergados, 1987; Hirsch, Klapdor-Kleingrothaus, and Kovalenko, 1995, 1996a, 1996b, 1999; Faessler *et al.*, 1997; Wodecki *et al.*, 1999) and exchange of sneutrinos, etc., in R-parity conserving SUSY models (Hirsch *et al.*, 1997a, 1997b).

The $0\nu2\beta$ decay is very important also for the solar neutrino problem (Kirsten, 1999), especially, in light of the latest data obtained by the Sudbury Neutrino Observatory (SNO), providing evidence that there is a nonelectron flavor-active neutrino component in the solar flux (Ahmad *et al.*, 2001). The solar neutrino data, the measured deficit of the atmospheric muon neutrino flux (Fukuda *et al.*, 1998a, 1998b, 1999a, 1999b), and the result of the LSND accelerator experiment (Church, 2000), all may be explained by means of neutrino oscillations, requiring in turn nonzero neutrino masses. Despite many scenarios offered by theoretical models for the neutrino mass spectrum (see Klapdor-Kleingrothaus, Pas, and Smirnov, 2001, and references therein), the present data on oscillations lead to neutrino masses in the range $0.01\leqslant m_\nu\leqslant 1$ eV (Bilenky *et al.*, 1999). However, while oscillation experiments are sensitive to the neutrino mass difference, only the measured neutrinoless 2β decay rate can give the absolute scale of the effective Majorana neutrino mass,[3] and hence provide a crucial test of neutrino mass models (Bilenky *et al.*, 1999; Klapdor-Kleingrothaus, Pas, and Smirnov, 2001). Therefore $0\nu2\beta$ decay is considered a powerful test of new physical effects beyond the SM. The absence of this process yields strong restrictions on m_ν, lepton violation constants (η, λ), and other parameters of the manifold SM extensions, which allow one to reduce the number of acceptable theoretical models and to address the multi-TeV energy range that is the focus of accelerator experiments (Faessler and Simkovic, 1998; Klapdor-Kleingrothaus, 1998; Vogel, 2000).

Despite the numerous efforts to detect $0\nu2\beta$ decay since 1948 (Fireman, 1948), this process still remains

[2]R-parity is defined as $R_p=(-1)^{3B+L+2S}$, where B, L, and S are the baryon and lepton numbers, and the spin, respectively.

[3]Obviously, its accuracy depends on the uncertainties of the calculated nuclear matrix elements.

TABLE I. The $2\nu2\beta$ decay half-lives measured in direct experiments.

Nuclide	Experimental $T_{1/2}^{2\nu}$ (yr)	Signal to background ratio[a]	Refs.	Range of calculated $T_{1/2}^{2\nu}$ values (yr)
^{48}Ca	$4.3^{+2.8}_{-1.8}\times10^{19}$	0.2–2.0	Balysh *et al.*, 1996	3×10^{19}–5×10^{20}
	$4.2^{+3.3}_{-1.3}\times10^{19}$		Brudanin *et al.*, 2000	
^{76}Ge	$(9.0\pm1.0)\times10^{20}$	0.1	Vasenko *et al.*, 1990	7×10^{19}–6×10^{22}
	$1.1^{+0.6}_{-0.3}\times10^{21}$	0.1	Miley *et al.*, 1990	
	$8.4^{+1.0}_{-0.8}\times10^{20}$		Brodzinski *et al.*, 1993	
	$(1.1\pm0.2)\times10^{21}$		Aalseth *et al.*, 1996	
	$(1.8\pm0.1)\times10^{21}$	1.4–4.0	Gunther *et al.*, 1997	
^{82}Se	$1.1^{+0.3}_{-0.1}\times10^{20}$	7.9	Elliott *et al.*, 1992	3×10^{18}–6×10^{21}
	$(8.3\pm1.2)\times10^{19}$	1.8	Arnold *et al.*, 1998	
^{96}Zr	$2.1^{+0.8}_{-0.4}\times10^{19}$	1.9	Arnold *et al.*, 1999	3×10^{17}–4×10^{20}
^{100}Mo	$1.2^{+0.5}_{-0.3}\times10^{19}$	0.3	Ejiri *et al.*, 1991	1×10^{17}–2×10^{22}
	$(9.5\pm1.0)\times10^{18}$	2.8	Dassie *et al.*, 1995	
	$7.6^{+2.2}_{-1.4}\times10^{18}$	0.6	Alston-Garnjost *et al.*, 1997	
	$6.8^{+0.8}_{-0.9}\times10^{18}$	10.9	De Silva *et al.*, 1997	
^{116}Cd	$2.6^{+0.9}_{-0.5}\times10^{19}$	0.3	Ejiri *et al.*, 1995	3×10^{18}–2×10^{21}
	$2.7^{+1.0}_{-0.7}\times10^{19}$	1.0	Danevich *et al.*, 1995	
	$(3.8\pm0.4)\times10^{19}$	3.9	Arnold *et al.*, 1996	
	$2.6^{+0.7}_{-0.4}\times10^{19}$	4–15	Danevich *et al.*, 2000	
^{150}Nd	$1.9^{+0.7}_{-0.4}\times10^{19}$	4.0	Artemiev *et al.*, 1995	6×10^{16}–4×10^{20}
	$(6.8\pm0.8)\times10^{18}$	6.3	De Silva *et al.*, 1997	

[a]Signal to background ratios in the corresponding energy interval are taken from the original works as given by the authors.

unobserved.[4] The highest half-life limits were set in direct experiments with several nuclides: $T_{1/2}^{0\nu}\geqslant10^{22}$ yr for ^{82}Se (Elliott *et al.*, 1992), ^{100}Mo (Ejiri *et al.*, 2001); $T_{1/2}^{0\nu}\geqslant10^{23}$ yr for ^{116}Cd (Danevich *et al.*, 2000), ^{128}Te, ^{130}Te (Alessandrello *et al.*, 2000), ^{136}Xe (Luescher *et al.*, 1998); and $T_{1/2}^{0\nu}\geqslant10^{25}$ yr for ^{76}Ge (Aalseth *et al.*, 1999; Baudis *et al.*, 1999a). These results have already brought the most stringent restrictions on the values of the Majorana neutrino mass ($m_\nu\leqslant0.5$–5.0 eV), the right-handed admixture in the weak interaction ($\eta\approx10^{-7}$, $\lambda\approx10^{-5}$), the neutrino-Majoron coupling constant ($g_M\approx10^{-4}$), and the R-parity violating parameter of the minimal SUSY standard model ($\zeta\approx10^{-4}$). However, the current status of astroparticle physics makes it very desirable to improve the present level of sensitivity by one or two orders of magnitude (Klapdor-Kleingrothaus, 1998; Zuber, 1998; Vogel, 2000). This means that restrictions, for example, on the neutrino mass, should be pushed down to the level of 0.01 eV, or at least to 0.05 eV! How is it possible (if it is possible at all) and what is the best strategy to reach this goal? Shall we perform 2β decay experiments with different candidates other than ^{76}Ge or must we concentrate on a single nuclide?

In our opinion, undoubtedly there are strong reasons to investigate the process for several nuclei. First of all, one must remember that neutrinoless 2β decay is still an elusive phenomenon and that reliable restrictions on the neutrino mass and on other important parameters can be obtained from experimental data on the basis of theoretical half-life values of the $0\nu2\beta$ decay, which in turn depend on the calculation of nuclear matrix elements for this process. However, it should be stressed that despite the impressive progress in theoretical treatment of 2β decay and its implications, the present situation with calculations of the 2β decay NME does not look completely defined. For instance, there are discrepancies (in some cases up to two orders of magnitude) between calculated and already measured half-lives of the $2\nu2\beta$ decay of ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, and ^{150}Nd (see Table I). Interested readers are referred to the the latest theoretical reviews (Faessler and Simkovic, 1998; Suhonen and Civitarese, 1998), but just for illustration we present here the following citation from Faessler and Simkovic (1998), which speaks for itself: "The calculation of the nuclear many-body Green function governing the $\beta\beta$ decay transitions continues to be challenging and attracts the specialists of different nuclear models. … Within the shell model, which describes well the low-lying states in the initial and final nuclei, it is clearly

[4]There are many early reviews (Zel'dovich *et al.*, 1954; Primakoff and Rosen, 1959; Dell'Antonio and Fiorini, 1960; Fiorini, 1972; Bryman and Picciotto, 1978; Zdesenko, 1980; Doi *et al.*, 1981; Primakoff and Rosen, 1981; Haxton and Stephenson, 1984; Schepkin, 1984; Doi *et al.*, 1985; Vergados, 1986; Avignone and Brodzinski, 1988; Faessler, 1988; Tomoda, 1991; Boehm and Vogel, 1992) as well as some very recent ones (Moe and Vogel, 1994; Tretyak and Zdesenko, 1995, 2002; Faessler and Simkovic, 1998; Klapdor-Kleingrothaus, 1998; Suhonen and Civitarese, 1998; Vogel, 2000).

impossible to construct all the needed states of the intermediate nucleus. Therefore, the proton-neutron quasiparticle random phase approximation (pn-QRPA) … has developed into one of the most popular methods for calculating nuclear wavefunctions involved in the $\beta\beta$ decay. … However, the predictive power of the QRPA is questionable because of the extreme sensitivity of the calculated $2\nu\beta\beta$ decay matrix elements in the physically accepted region on the particle-particle strength of the nuclear Hamiltonian. … A large amount of theoretical work has been done to calculate nuclear matrix elements and decay rates. However, the mechanism which leads to the suppression of these matrix elements is still not completely understood. The practical calculation always involves some approximations, which make it difficult to obtain an unambiguous decay rate."

Moreover, it should be noted that even for the usual β decay, which is well measured and whose theory is well established and understood, there are serious difficulties with half-life calculations. For example, β decay half-lives of nuclei up to $A=150$ were systematically calculated in the framework of pn quasirandom-phase approximation (QRPA) with a schematic Gamow-Teller residual interaction (Homma *et al.*, 1996). This calculation reproduces 97% of experimentally known half-lives shorter than 1 s within a factor of 10. For the longer half-lives, discrepancies with experimental data are much larger: up to four orders of magnitude (Homma *et al.*, 1996). It is rather unlikely that the predictive ability of theory for the unobserved neutrinoless 2β decay could be much better than those for the $2\nu2\beta$ and ordinary β decays; therefore a variety of 2β candidate nuclides has to be studied. Let us reinforce this statement by a citation from Vogel (2000): "The nuclear structure uncertainty can be reduced by further development of the corresponding nuclear models. At the same time, by reaching comparable experimental limits in several nuclei, the chances of a severe error in the NME will be substantially reduced."

Second, success in 2β decay research may be achieved on the leading edge of modern technology as an alloy of science, experimental art, patience, and even luck. Nobody can know *a priori* where and when the highest sensitivity will be reached. New and sometimes unexpected advancements of experimental technique may bring an advantage to particular 2β decay candidates; thus several of them should be used in different experiments.

Third, investigating several decay candidates becomes even more important if $0\nu2\beta$ decay is finally observed in one experiment. Such a discovery certainly has to be confirmed with other nuclides and by using other experimental techniques, which should be well developed by then. However, due to the superlow background nature of the 2β decay experiments, the appropriate procedure is a multistage process and consequently a rather long one. For instance, the first valuable result for the $0\nu2\beta$ decay of ^{76}Ge was obtained in 1970 as $T_{1/2}^{0\nu}\geqslant 10^{21}$ yr (Fiorini *et al.*, 1970). After 30 years of strong efforts, this limit was advanced up to $T_{1/2}^{0\nu}\geqslant 10^{25}$ yr in the two current experiments performed by the IGEX (Aalseth *et al.*, 1999) and Heidelberg-Moscow (Baudis *et al.*, 1999a) Collaborations, which provides an improvement by two orders of magnitude for the neutrino mass limit.

Therefore the present theoretical and experimental status of neutrino physics (more widely, astroparticle physics) makes it necessary that the required highest sensitivity has to be reached for several 2β decay candidate nuclei.

This Colloquium is devoted to experimental aspects of 2β decay research and their implications. In the next section the current status of experiments is reviewed briefly, and careful attention is paid to the sensitivity limitations and requirements of the challenging upcoming projects, which are aiming to reach the level of $T_{1/2}^{0\nu}\geqslant 10^{26}$–$10^{28}$ yr. In Sec. III we consider the projects (i) for the near future, i.e., projects under construction; (ii) for the far future, i.e., proposals requiring long-term intensive efforts; and (iii) the most realistic next generation experiments. The physical implications of the results which might be obtained by the future high sensitivity 2β decay experiments are discussed in the final section.

II. PRESENT STATUS OF 2β DECAY EXPERIMENTS

There are two different classes of 2β decay experiments: (a) those involving a "passive" source, which can be simply placed in the form of a foil between two detectors, or otherwise introduced into the complex detector system; or (b) those involving an "active" source, in which a detector containing a 2β decay candidate nuclei serves as both source and detector simultaneously (Moe and Vogel, 1994; Tretyak and Zdesenko, 1995, 2002). If the neutrinoless 2β decay occurs in the "active" or "passive" source, the sharp peak at the $Q_{\beta\beta}$ value would be observed in the electron sum energy spectrum of the detector(s) (Fig. 2). Since the width of the $0\nu2\beta$ decay peak is determined by the energy resolution of the detector, the latter is very important because the better the energy resolution, the less difficulty in recognizing the effect.

An experiment of type (a) was performed for the first time in 1948 (Fireman, 1948), while one involving an "active" detector was first performed in 1966 (Der Mateosian and Goldhaber, 1966). It is obvious that the sensitivity of a 2β decay study is determined first, by the available source strengths (i.e., the mass of the source), and second, by the detector background. The task of reducing the background is crucial for 2β decay experiments because the effect that is searched for is the most rare nuclear process in nature, with half-lives anticipated in the range of 10^{18}–10^{22} yr for the 2ν mode, and 10^{24}–10^{28} yr for the 0ν mode. Together with the rather low $Q_{\beta\beta}$ value (typically 2–3 MeV), one naturally requires superlow background conditions for the 2β decay experiments, which in turn leads (as was pointed out in the Introduction) to a quite long and multistage development of the appropriate techniques for the research.

Nevertheless, despite all these difficulties, outstanding experimental results have been obtained during the last decade. First of all, from the total number of 35 potential $2\beta^-$ decay candidates, 28 nuclei have been studied in direct experiments, and the highest half-life limits were set for several of them: $T_{1/2}^{0\nu} \geq 10^{22}$ yr for ^{82}Se (Elliott *et al.*, 1992), ^{100}Mo (Ejiri *et al.*, 2001); $T_{1/2}^{0\nu} \geq 10^{23}$ yr for ^{116}Cd (Danevich *et al.*, 2000), ^{128}Te, ^{130}Te (Alessandrello *et al.*, 2000), ^{136}Xe (Luescher *et al.*, 1998); and $T_{1/2}^{0\nu} \geq 10^{25}$ yr for ^{76}Ge (Aalseth *et al.*, 1999; Baudis *et al.*, 1999a).

In contrast with a neutrinoless process, the allowed two neutrino 2β decay was observed in direct experiments with seven nuclides: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, and ^{150}Nd. The measured half-lives are presented in Table I, where the ranges of the theoretical $T_{1/2}^{2\nu}$ values determined for each nuclide on the basis of all available nuclear matrix element calculations[5] are shown for comparison.

In addition, the 2β decay branching ratio of ^{238}U was determined (using a radiochemical technique) to be $T_{1/2}^{2\beta} = (2.0 \pm 0.6) \times 10^{21}$ yr (Turkevich *et al.*, 1991), while the half-lives of ^{82}Se ($\approx 10^{20}$ yr), ^{128}Te ($\approx 10^{24}$ yr), and ^{130}Te ($\approx 10^{21}$ yr) have been measured in geochemical experiments [see reviews (Moe and Vogel, 1994; Tretyak and Zdesenko, 1995, 2002) for references]. However, neither method can distinguish 0ν and 2ν modes, and thus only the total 2β decay rates are stated.

We briefly consider the most sensitive direct experiments for $0\nu 2\beta$ decay below:

^{100}Mo. This nuclide was investigated by several groups [see Moe and Vogel (1994) and Tretyak and Zdesenko (1995, 2002)], but the most stringent half-life limit was reached by means of the spectrometer ELEGANT V (Osaka University), which consists of three drift chambers for measuring two β trajectories, plastic scintillators to measure β ray energies and arrival times, and a NaI(Tl) crystal scintillator array to detect γ rays (Ejiri *et al.*, 2001). Two passive ^{100}Mo sources (enrichment $\approx 95\%$) with 20 mg/cm^2 in thickness and total mass 171 g were set in a central drift chamber. From the 7582 h data collected at Oto Cosmo Observatory (Japan), combined with the previous results (7333 h run at the Kamioka underground laboratory), the limit $T_{1/2}^{0\nu} \geq 5.5 \times 10^{22}$ yr has been obtained at 90% C.L. (Ejiri *et al.*, 2001).

^{116}Cd. The experiment with ^{116}Cd has been performed by the INR (Kiev)[6] at the Solotvina Underground Laboratory (Ukraine) with the help of the ^{116}CdWO$_4$ crystal scintillators enriched in ^{116}Cd to 83%. In the latest run, four crystals (of total mass 339 g) with the energy resolution [full width at half maximum (FWHM)] of 11.5% at 1064 keV and 8.0% at 2615 keV were used (Danevich *et al.*, 2000). Due to efficient passive and active shielding, and as a result of the time-amplitude and pulse-shape analysis of the data, the background rate in the energy region 2.5–3.2 MeV was reduced to the value 0.03 counts/yr kg keV. On the basis of 4629 h statistics the limits for $0\nu 2\beta$ decay mode were set as $T_{1/2}^{0\nu} \geq 0.7 \times 10^{23}$ yr at 90% C.L. (Danevich *et al.*, 2000).

^{130}Te (^{128}Te). The Milano group (University and INFN) has used low temperature thermal detectors (crystal TeO$_2$ bolometers) aiming to study 2β decay of ^{130}Te (Alessandrello *et al.*, 2000). The detector consists of an array (total mass of 6.8 kg) of 20 TeO$_2$ crystals ($3 \times 3 \times 6$ cm^3 each); it is cooled down to a temperature of ≈ 10 mK by a dilution refrigerator installed in the Gran Sasso Underground Laboratory (Italy). High-purity (HP) electrolytic copper (2.2 cm) and low radioactivity Roman lead (10 cm) were utilized as thermal and background shielding of the crystals. The refrigerator was surrounded by a 10-cm layer of common lead. The energy resolution of the array was around 9 keV at 2615 keV, and the background rate in the region of the $0\nu 2\beta$ decay of ^{130}Te ($Q_{\beta\beta} = 2529$ keV) was about 0.5 counts/yr kg keV. The data were accumulated for 66 995 h$\times$crystals, resulting in 0.66 kg$\times$yr of ^{130}Te. The lower limit $T_{1/2}^{0\nu} \geq 1.44 \times 10^{23}$ yr at 90% C.L. was established for the $0\nu 2\beta$ decay of ^{130}Te, while $T_{1/2}^{0\nu} \geq 8.6 \times 10^{22}$ yr at 90% C.L. for ^{128}Te (Alessandrello *et al.*, 2000).

^{136}Xe. The Caltech-Neuchatel-PSI collaboration has built a time projection chamber (TPC) with an active volume of 180 l containing 24.2 moles (3.3 kg) of Xe gas (enriched in ^{136}Xe to 62.5%) at a pressure of 5 atm (Luescher *et al.*, 1998). The FWHM energy resolution of the detector was 6.6% at the transition energy ($Q_{\beta\beta} = 2481$ keV). The track reconstruction capability of the time projection chamber provided an efficient rejection of the background, which rate was reduced to the value of ≈ 0.02 counts/yr kg keV around 2.48 MeV (within a FWHM energy interval). From 6830+6013 h (or 4.9 kg $\times$yr) of data taking in the Gotthard Underground Laboratory (Switzerland), a limit of $T_{1/2}^{0\nu} \geq 4.4 \times 10^{23}$ yr at 90% C.L. has been set (Luescher *et al.*, 1998).

^{76}Ge. Currently there are two large experiments devoted to the quest for 2β decay of ^{76}Ge performed by

[5]The theoretical reviews (Haxton and Stephenson, 1984; Doi *et al.*, 1985; Tomoda, 1991; Faessler and Simkovic, 1998; Suhonen and Civitarese, 1998) and the following references were used as sources for the calculated NME and $T_{1/2}$ values: Vergados (1983); Vogel and Zirnbauer (1986); Engel *et al.*, (1988, 1989); Staudt *et al.* (1990); Suhonen *et al.* (1991a, 1991b); Pantis *et al.* (1992, 1996); Castanos *et al.* (1994); Caurier *et al.* (1994, 1996); Civitarese and Suhonen (1994, 1998); Dhiman and Raina (1994); Hirsch *et al.* (1994); Piepke *et al.* (1994); Hirsch, Castanos, *et al.* (1995); Poves *et al.* (1995); Rumyantsev *et al.* (1995); Stoica (1995); Aunola and Suhonen (1996); Barabash *et al.* (1996); Bhattacharya *et al.* (1998); Hirsch and Klapdor-Kleingrothaus (1998).

[6]From 1998 this experiment has been carried out by the Kiev-Firenze collaboration (Danevich *et al.*, 2000).

TABLE II. The best reported $T_{1/2}^{0\nu}$ and m_ν limits from direct 2β decay experiments.

Nuclide	Experim. Limit $T_{1/2}^{0\nu}$ (yr) 68% C.L.	90% C.L.	Refs.	Limit on m_ν (eV) after calcul. Staudt *et al.*, 1990 68% C.L.	90% C.L.	Range of m_ν limit (eV) 90% C.L.
^{76}Ge	2.8×10^{25}	1.6×10^{25}	Baudis *et al.*, 1999a	0.29	0.38	0.3–2.5
		1.6×10^{25}	Aalseth *et al.*, 1999		0.38	0.3–2.5
^{100}Mo	1.0×10^{23}	5.5×10^{22}	Ejiri *et al.*, 2001	3.6	4.9	1.4–256
^{116}Cd	2.5×10^{23}	7.0×10^{22}	Danevich *et al.*, 2000	1.4	2.6	2.4–8.4
^{130}Te		1.4×10^{23}	Alessandrello *et al.*, 2000		1.9	1.1–6.4
^{136}Xe		4.4×10^{23}	Luescher *et al.*, 1998		2.2	0.8–5.2

the IGEX (Aalseth *et al.*, 1999) and Heidelberg-Moscow (Baudis *et al.*, 1999a) Collaborations.

The IGEX is operating three 2-kg enriched in ^{76}Ge ($\approx 88\%$) high-purity Ge detectors in the Canfranc Underground Laboratory (Spain). The shield consists of 2.5 tons of archeological and 10 tons of 70-yr-old low-activity lead, and a plastic scintillator to shield against the cosmic muons. Pulse shape discrimination techniques are applied to the data. The background rate is equal to ≈ 0.06 counts/yr kg keV (within the energy interval 2.0–2.5 MeV). The combined energy resolution for the $0\nu2\beta$ peak ($Q_{\beta\beta}=2038.5$ keV) is 4 keV. Analysis of 116.75 mole years (or 8.87 kg$\times$yr in ^{76}Ge) of data yields a lower bound of $T_{1/2}^{0\nu}\geqslant 1.57\times10^{25}$ yr at 90% C.L. (Aalseth *et al.*, 1999).

The Heidelberg-Moscow experiment in the Gran Sasso Underground Laboratory uses five high purity Ge detectors (enriched in ^{76}Ge to 86%) with a total active mass of 10.96 kg (125.5 moles of ^{76}Ge). The passive and active shielding, as well as a pulse-shape analysis (PSA) of the data allows a reduction in the background rate in the energy region of interest to the value of ≈ 0.06 counts/yr kg keV. The energy resolution at the energy of 2038.5 keV is 3.9 keV. After 24 kg$\times$yr of data with pulse-shape analysis, a lower half-life limit of $T_{1/2}^{0\nu}\geqslant 1.6\times10^{25}$ yr with 90% C.L. has been set for ^{76}Ge (Baudis *et al.*, 1999a).

The best $T_{1/2}$ limits on $0\nu2\beta$ decay obtained in the most sensitive direct experiments and the corresponding restrictions on the Majorana neutrino mass are given in Table II. The m_ν constraints are presented in two ways: (i) in column 4 the values of m_ν limits are determined on the basis of the NME calculations of Staudt *et al.* (1990);[7] (ii) in column 5 the ranges of m_ν limits are estimated by using all available NME calculations[8] [see Tretyak and Zdesenko (1995, 2002) and footnote 5 for references].

It is obvious from Table II that ^{76}Ge studies, in which the limits $T_{1/2}^{0\nu}\geqslant 10^{25}$ yr have been reached, have brought the most stringent restrictions on the neutrino mass, at the level of ≈ 0.5 eV. It is interesting to note that experiments with ^{116}Cd, ^{130}Te, and ^{136}Xe—just overcoming $T_{1/2}^{0\nu}\geqslant 10^{23}$ yr—offer m_ν bounds in the range of 2–3 eV (Staudt *et al.*, 1990), which are not so drastically different from the ^{76}Ge results. In order to understand the reason for such a sensitivity, we consider next the choice of the 2β decay candidate nuclei for study.

With this aim let us use Eq. (7) for the $0\nu2\beta$ decay probability (neglecting right-handed contributions):

$$(T_{1/2}^{0\nu})^{-1}=G_{mm}^{0\nu}\cdot|\mathrm{NME}|^2\cdot\langle m_\nu\rangle^2,$$

where NME denotes a combination of the Gamow-Teller and Fermi nuclear matrix elements of the $0\nu2\beta$ decay, and $G_{mm}^{0\nu}(Z,Q_{\beta\beta})$ is the phase space factor. If we skip (for the moment) the complicated problem of the NME calculation, it is evident from Eq. (7) that the available energy release ($Q_{\beta\beta}$) is the most important parameter for the sensitivity of a 2β decay study with particular candidates.

First, it is because the phase space integral $G_{mm}^{0\nu}$ strongly depends on the $Q_{\beta\beta}$ value (roughly as $Q_{\beta\beta}^5$) (Moe and Vogel, 1994; Suhonen and Civitarese, 1998). Second, the larger the 2β decay energy, the simpler it is—from an experimental point of view—to overcome background problems.[9] Among 35 candidates, there are only 13 nuclei with $Q_{\beta\beta}$ larger than ≈ 1.7 MeV (Audi and Wapstra, 1995). They are listed in Table III, where $Q_{\beta\beta}$, the natural abundance δ (Rosman and Taylor, 1998), and the calculated values of the phase space integral $G_{mm}^{0\nu}$ (Doi *et al.*, 1985; Tomoda, 1991; Suhonen and Civitarese, 1998) and $T_{1/2}^{0\nu}\times\langle m_\nu\rangle^2$ (Staudt *et al.*, 1990) are given. Note, that due to the low $Q_{\beta\beta}$ value of ^{76}Ge (2039 keV), its phase space integral $G_{mm}^{0\nu}$ is about 7–10 times smaller as compared with, e.g., those of ^{48}Ca, ^{96}Zr, ^{100}Mo, ^{116}Cd, ^{130}Te, and ^{136}Xe.

The next stage is the consideration of the experimental sensitivity, which can be expressed in terms of a lower half-life limit, as follows (Moe and Vogel, 1994; Tretyak and Zdesenko, 1995, 2002):

[7] The NME results of Staudt *et al.* (1990) were chosen because of the extensive list of 2β decay candidate nuclei calculated in this work, which allows one to compare the sensitivity of different experiments to the m_ν bound within the same scale.

[8] We are using the second form of presentation proposed by Vogel (2000): "Since there is no objective way to judge which calculation is correct, one often uses the spread between the calculated values as a measure of the theoretical uncertainty."

[9] We note that the background from natural radioactivity drops sharply above 2615 keV, which is the energy of the γ's from ^{208}Tl decay (^{232}Th family).

TABLE III. Double-β-decay candidates with $Q_{\beta\beta} \geqslant 1.7$ MeV.

Nuclide	$Q_{\beta\beta}$, keV	Abundance δ, %	Parameter $G^{0\nu}_{mm}$, 10^{-14} yr	$T^{0\nu}_{1/2} \times \langle m_\nu \rangle^2$, yr·eV^2 (after NME Staudt *et al.*, 1990)
^{48}Ca	**4272**	0.187	6.4	
^{76}Ge	2039	7.61	0.6	2.3×10^{24}
^{82}Se	**2995**	8.73	2.7	6.0×10^{23}
^{96}Zr	**3350**	2.80	5.7	5.3×10^{23}
^{100}Mo	**3034**	9.63	4.6	1.3×10^{24}
^{110}Pd	2000	11.72		2.0×10^{24}
^{116}Cd	**2805**	7.49	4.9	4.9×10^{23}
^{124}Sn	2287	5.79	2.6	1.4×10^{24}
^{130}Te	**2529**	**34.08**	4.1	4.9×10^{23}
^{136}Xe	**2468**	8.87	4.4	2.2×10^{24}
^{148}Nd	1929	5.7		1.4×10^{24}
^{150}Nd	**3367**	5.6	19	3.4×10^{22}
^{160}Gd	1730	**21.86**		8.6×10^{23}

$$T_{1/2} \sim \varepsilon \cdot \delta \sqrt{\frac{m \cdot t}{R \cdot Bg}}. \tag{11}$$

Here ε is the detection efficiency; δ is the abundance or enrichment of candidate nuclei contained in the detector; t is the measurement time; m and R are the total mass and the energy resolution (FWHM) of the detector, respectively; and Bg is the background rate in the energy region of the $0\nu2\beta$ decay peak (expressed, for example, in counts/yr keV kg).

As regards the challenging goal of increasing the current sensitivity of 2β decay research by two orders of magnitude, let us study Eq. (11) step by step.

First of all, it is clear that efficiency and enrichment are the most important characteristics of the setups, because any other parameters are under the square root. Obviously, $\approx$100% enrichment is very desirable.[10] In order to reach the required sensitivity we have to use enriched sources, whose masses should be in the range of a hundred kg. The latter requirement immediately restricts the list of candidate nuclei given in Table III because a large mass production of enriched materials is possible only for several of them.[11] These are ^{76}Ge, ^{82}Se, ^{116}Cd, ^{130}Te, and ^{136}Xe, which could be produced by means of centrifugal separation[12] and therefore for a reasonable price (Artukhov *et al.*, 1998).

Second, one could require that the detection efficiency should be close to 100%, which is possible, in fact, only for the active source-detector technique. Indeed, for experiments involving a passive source, the sensitivity is restricted by the contradiction between source strengths and detection efficiency. The number of 2β decay candidate nuclei used can be enlarged by increasing the source thickness, which at the same time leads to a lower detection efficiency caused by the absorption of electrons in the source and transformation of the measured 2β decay spectra (broadening of the peak and shifting it to low energies, etc.).

Besides, a very important characteristic of the setup is the energy resolution of the detector. It is because for the case of poor resolution, the events from the high-energy tail of the $2\nu2\beta$ decay distribution could run into the energy window of the $0\nu2\beta$ decay peak and generate the background which cannot be discriminated from the $0\nu2\beta$ decay signal, even in principle.[13] However, with better energy resolution only a smaller part of the 2ν tail can fall within the 0ν interval, and thus the irremovable background would be lower.

All these requirements are illustrated in Fig. 3, where the results of a model experiment to study 2β decay of ^{100}Mo are presented. The simulations were performed with the help of the GEANT3.21 package (Brun *et al.*, 1994) and the event generator DECAY4 (Ponkratenko *et al.*, 2000). The following assumptions were made: the mass of the ^{100}Mo source is 1 kg ($\approx 6\times10^{24}$ nuclei of ^{100}Mo); the measuring time is 5 yr; the 2β decay half-lives of ^{100}Mo are $T^{2\nu}_{1/2} = 10^{19}$ yr and $T^{0\nu}_{1/2} = 10^{24}$ yr. The initial 2β decay spectra [shown in Figs. 3(a) and 3(b) on different vertical scales] were obtained with ^{100}Mo nuclei contained in the ideal ("active" source) detector with 100% efficiency, zero background, and the FWHM energy resolution of 10 keV. In the next row the ^{100}Mo source was introduced in the same detector but in the

[10]Let us consider two detectors with different masses (m_1, m_2) and enrichments (δ_1, δ_2). Supposing that their other characteristics (ε, t, R, Bg) are the same and requiring equal sensitivities $(T^1_{1/2} = T^2_{1/2})$, we can obtain the relation between the masses and enrichment ratios of the detectors: $m_1/m_2 = (\delta_2/\delta_1)^2$, which speaks for itself.

[11]Note that only two nuclides from Table III (^{130}Te and ^{160}Gd) can be used without enrichment owing to their relatively high natural abundances ($\approx$34% and $\approx$22%, respectively).

[12]Centrifugal isotope separation requires the substances to be in gaseous form. Thus xenon gas can be used directly. There also exist volatile germanium, selenium, molybdenum and tellurium hexafluorides, as well as the metal to organic cadmium-dimethyl compound (Artukhov *et al.*, 1998).

[13]All their features are similar: the same two particles are emitted simultaneously from one point of the source, in the same energy region and with an identical angular distribution.

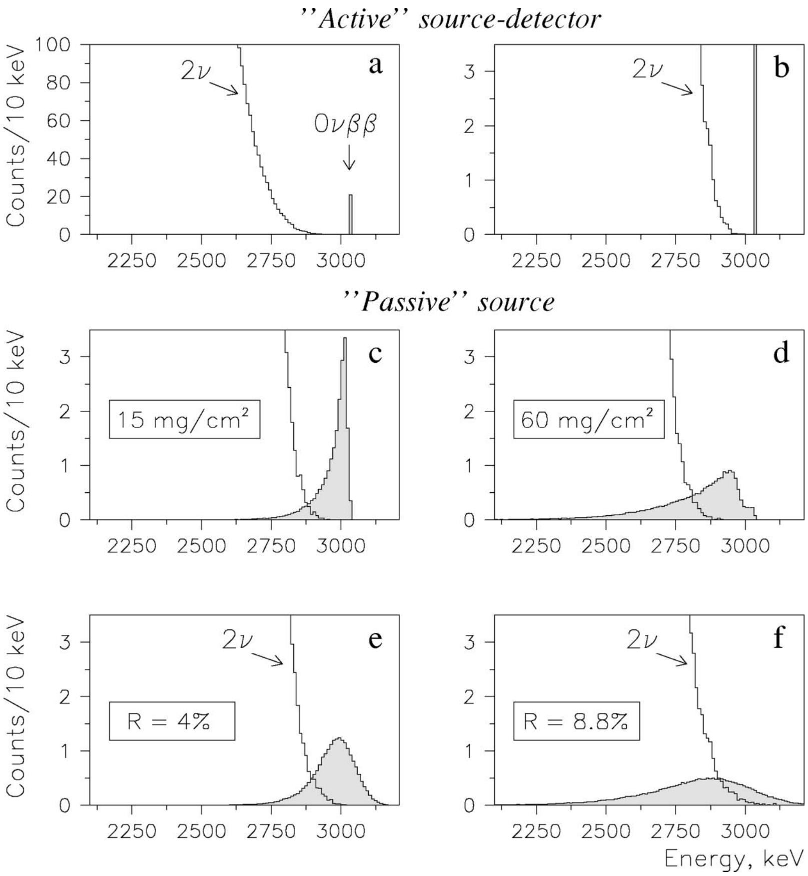

FIG. 3. Simulated spectra of the model 2β decay experiment with 1 kg of ^{100}Mo. (a) "Active" source technique: ^{100}Mo nuclei in the detector with 100% efficiency, zero background, and with 10 keV energy resolution. (b) Same as (a), but for a different vertical scale. "Passive" source technique: ^{100}Mo source in the same detector with foil thicknesses as of (c) 15 mg/cm^2 and (d) 60 mg/cm^2. (e) The same as (c) but with the energy resolution of the detector at 3 MeV FWHM $=4\%$. (f) The same as (d) but with FWHM $=8.8\%$.

form of a foil ("passive" source technique). The simulated spectra are depicted in Fig. 3(c) (the thickness of the ^{100}Mo foil is 15 mg/cm^2) and Fig. 3(d) (60 mg/cm^2). Then, the energy resolution of the detector was taken into account and the results are shown in Fig. 3(e) (FWHM$=4\%$ at 3 MeV) and Fig. 3(f) (FWHM$=8.8\%$ at 3 MeV).

It should be stressed that Fig. 3 represents the results of an ideal experiment reached in principle, while in any real study the available results can only be worse by reason of the actual background, higher energy threshold, and lower detection efficiency, etc. In fact, this is a very strong statement because it allows one to set the sensitivity limit for any real apparatus. For instance, it is evident from Fig. 3 that the "passive" source technique is not appropriate for the observation of the $0\nu2\beta$ decay with half-life ratio $T_{1/2}^{0\nu}/T_{1/2}^{2\nu}$ larger than 10^5. Hence we can conclude that the "active" source approach has the following advantages: (a) 4π geometry for the source, (b) absence of self-absorption in the source, and (c) better energy resolution, which is not dependent on the angular and energy distribution of the electrons emitted in 2β decay.

Therefore, on the basis of this brief analysis of the present status of 2β decay experiments, we can formulate the following requirements for future ultimate sensitivity projects:

(i) The best reported 0ν limits were reached with the help of the "active" source method (^{76}Ge, ^{116}Cd, ^{130}Te, ^{136}Xe), and thus one can suppose that future projects will employ the same kind of technique because only in this case can the detection efficiency be close to 100%.

(ii) The best ^{76}Ge results were obtained by using ≈ 10 kg of enriched detectors. Hence, to reach the required level of sensitivity, one has to employ enriched sources with masses of hundreds of kg (see footnotes 11 and 12).

(iii) Because of the square-root dependence of the sensitivity versus source mass, it is not enough, however, to increase detector mass alone (even by two orders of magnitude). The background should also be reduced substantially (practically to zero).

(iv) As is obvious from Fig. 3, the energy resolution is a crucial characteristic, and for such challenging projects the FWHM value cannot be worse than $\approx 4\%$ at $Q_{\beta\beta}$ energy.

(v) It is anticipated that the measuring time of the future experiments will be of the order of ≈ 10 yr. Hence detectors and setups should be as simple as possible to provide stable and reliable operation during such a long period.

Evidently, it may be very difficult to carry out such a project and build up the experiment in a way that would satisfy these severe requirements completely. However, perhaps some of the recent proposals, considered during the past few years with regard to these goals, are up to the task.

III. FUTURE PROJECTS

An interesting approach to study 2β decay of ^{136}Xe ($Q_{\beta\beta}=2468$ keV) makes use of the coincident detection of $^{136}Ba^{2+}$ ions (the final state of the atomic core resulting from the ^{136}Xe decay) and the $0\nu2\beta$ signal, with the energy of $\approx$2.5 MeV, in a time projection chamber filled with liquid or gaseous Xe (Miyajima *et al.*, 1991; Moe, 1991).[14] Resonance ionization spectroscopy was proposed as a possible method for identification of $^{136}Ba^{2+}$ ions in the liquid Xe drift ionization chamber (Miyajima *et al.*, 1996). Recently, the EXO project has been considered (Danilov *et al.*, 2000), in which this method would be applied in a large (40 m^3) TPC operated at 5–10 atm pressure of enriched xenon (about 1–2 tons of ^{136}Xe). The estimated sensitivity of such an apparatus to neutrino mass could be $\approx$0.02 eV (Danilov *et al.*, 2000). Another proposal (Raghavan, 1994; Caccianiga and Giammarchi, 2000) is to dissolve $\approx$80 kg ($\approx$1.5 tons) of enriched (natural) Xe in the liquid scintillator of the BOREXINO Counting Test Facility (CTF) (Bellini, 1996; Alimonti *et al.*, 1998a) in order to reach the $T_{1/2}^{0\nu}$ limit in the range of 10^{24}–10^{25} yr (Caccianiga and Giammarchi, 2000). The XMASS project intends to use an ultrapure liquid Xe scintillator as a real time, low-energy solar neutrino detector (by means of ν-e^- scattering) (Suzuki, 2001). Such a detector, with $\approx$10 tons fiducial mass, will contain $\approx$1 tons of ^{136}Xe, which could allow a simultaneous search for $0\nu2\beta$ decay of the latter with a neutrino mass limit of $\approx$0.02 eV.

Similarly, the project MOON aims to make both the study of $0\nu2\beta$ decay of ^{100}Mo ($Q_{\beta\beta}$=3034 keV) and the real time studies of low-energy solar ν by inverse β decay (Ejiri *et al.*, 2000). The detector module will be composed of $\approx$60 000 plastic scintillators (6×0.2 m $\times0.25$ cm), the light outputs from which are collected by 866 000 length wave shifter fibers ($\varnothing$1.2 mm$\times$6 m), viewed through clear fibers by 6800 photomultiplier tubes with 16 anodes. The proposal calls for the use of 34 tons of natural Mo (i.e., 3.3 tons of ^{100}Mo) per module in the form of foil ($\approx$50 mg/cm^2). The sensitivity of such a module to the neutrino mass could be of the order of $\approx$0.05 eV (Ejiri *et al.*, 2000).

The DCBA project is under development in KEK (Japan) (Ishihara *et al.*, 1996, 2000). The drift chamber placed in the uniform magnetic field (0.6 kG) can measure the momentum of each β particle emitted in 2β decay and the position of the decay vertex by means of a three-dimensional reconstruction of the tracks. With 18 kg of an enriched ^{150}Nd ($Q_{\beta\beta}$=3367 keV) passive source (50 mg/cm^2), the projected sensitivity to the Majorana neutrino mass is $\approx$0.05 eV (Ishihara *et al.*, 1996, 2000).

^{160}Gd ($Q_{\beta\beta}$=1730 keV) is an attractive candidate due to a large natural abundance (21.9%), allowing the construction of a sensitive apparatus with natural Gd_2SiO_5:Ce crystal scintillators (GSO). A large scale experiment with ^{160}Gd that uses the GSO multicrystal array with a total mass of two tons ($\approx$400 kg of ^{160}Gd) is proposed (Danevich *et al.*, 2001). The careful purification of raw materials from actinides and their daughters (technically available now) could decrease the intrinsic radioactive contaminations of the GSO crystals to the level of several μBq/kg.[15] Besides, the pulse-shape analysis could be applied with GSO crystals to discriminate α events from the residual impurities (Danevich *et al.*, 2001). It is also proposed to place the multicrystal array into a high purity liquid (water or scintillator), which serves as shield and light guide simultaneously.[16] The estimated sensitivity of the experiment with two tons of GSO crystals and for 10 yr of run time would be of the order of $T_{1/2}^{0\nu}\geqslant2\times10^{26}$ yr ($m_\nu\leqslant0.07$ eV). Moreover, such an experiment could be of great interest for solar neutrino spectroscopy with ^{160}Gd because solar neutrino capture by this nuclide has a low-energy threshold and can be easily distinguished from the background due to the highly specific time signature of this reaction (Cribier, 2000). Hence an even larger setup with $\approx$30 tons of the GSO crystals (needed for solar neutrino detection) would become available, enhancing at the same time the sensitivity of the by-product $0\nu2\beta$ decay study of ^{160}Gd.

The future large scale Yb-loaded liquid scintillation detector LENS, which is under development for solar neutrino spectroscopy (Cribier, 2000), would be also used to search for $2\beta^-$ decay of ^{176}Yb ($Q_{\beta\beta}$ =1087 keV) and for electron capture plus β^+ decay of ^{168}Yb ($Q_{\beta\beta}$=1422 keV). It is supposed that with about 20 tons of natural Yb ($\approx$2.5 tons of ^{176}Yb) the limit $T_{1/2}^{0\nu}\geqslant10^{26}$ yr could be set on $0\nu2\beta$ decay of ^{176}Yb (m_ν $\leqslant$0.1 eV) (Zuber, 2000).

Let us also note two new approaches for studying 2β decay: induced 2β decay[17] and 2β decay of α and β unstable nuclei. In the first process the 2ν mode can be induced by neutrinos (antineutrinos) and positrons (electrons) for $2\beta^-$ ($2\beta^+$) decay,[18] while the 0ν mode

[14]The idea to detect $^{136}Ba^{2+}$ ions with the aim of determining the 2β decay rate of ^{136}Xe was presented for the first time by Mitchel and Winograd (1986).

[15]Such a radiopurity has been reached already in the $CdWO_4$ crystal scintillators used for the 2β decay study of ^{116}Cd (Danevich *et al.*, 2000).

[16]The existing and future large underground neutrino detectors [SNO (Boger, 2000), BOREXINO (Bellini, 1996), KamLand (Suzuki, 1999)] could be appropriate for this purpose. The GSO crystals located in the water or liquid scintillator would be homogeneously spread out on a sphere with diameter 3–4 m and viewed by distant PMT's.

[17]To our knowledge, for the first time the $2\nu2\beta$ decay induced by solar neutrinos and by antineutrinos from the decay of ^{40}K, ^{232}Th, ^{238}U, etc., in the Earth's core was discussed in connection with the background in geochemical 2β decay experiments (Bozoki and Lande, 1972). Capture rates of solar neutrinos (Earth's antineutrinos) estimated for the set of $2\beta^-$ ($2\beta^+$) nuclides yield induced $T_{1/2}$ values in the range of 10^{27-29} yr (10^{28-30} yr) (Bozoki and Lande, 1972).

[18]The use of reactor (accelerator) neutrino beam or artificial radioactive ν_e sources (similar to ^{51}Cr) to induce such a reaction was proposed recently (Inzhechik *et al.*, 1998; Semenov *et al.*, 1998).

can be induced by positrons and electrons. Preliminary calculations indicate that for the particular transition $e^- + {}^{124}_{54}\mathrm{Xe} \rightarrow {}^{124}_{52}\mathrm{Te} + e^+ + 2\nu_e$ the capture rate increases rapidly with the incident electron energy (Muto, 1998). The second approach (Tretyak and Zdesenko, 2002) is the search for 2β decay of unstable nuclei, whose $Q_{\beta\beta}$ values are much higher than those for stable 2β candidates.[19] The probability of $0\nu2\beta$ decay is proportional to $Q^5_{\beta\beta}$; thus, e.g., for ^{19}B or ^{22}C [$Q_{\beta\beta} \simeq 43$ MeV (Audi and Wapstra, 1995)] their $0\nu2\beta$ decay rates would be faster by 4×10^6 times as compared with that for ^{76}Ge with $Q_{\beta\beta} \simeq 2$ MeV (for equal NME's). However, because of the enormous difficulties with accumulating large numbers of fast decaying parent nuclides and with detecting 2β decay in the presence of an intense β background, no reliable schemes for such experiments have been considered up to this point.

It should be stressed that not only the last two approaches, but all proposals mentioned above require a significant amount of research and development to demonstrate their feasibility. Thus arduous efforts and a long time will be needed before they are approved. Because of this, we offer the following safer proposals.

First of all, there are two projects, NEMO-3 (Piquemal, 1999) and CUORICINO (Fiorini, 1998), that are under construction now.

NEMO-3. The NEMO-3 apparatus will allow direct detection of the two electrons by a tracking device (with 6180 drift cells) and measurement of their energies by 1940 large blocks of plastic scintillators. Up to 10 kg of a ^{100}Mo passive source with the equivalent thickness of ≈ 60 mg/cm^2 (≈ 50 mg/cm^2 of ^{100}Mo foil itself, plus ≈ 10 mg/cm^2 of scintillator wrapping made of Teflon foil, gas, and wires of the tracking counters) will hang between two concentric cylindrical tracking volumes. The energy resolution of the calorimeter at 3 MeV is 8.8% (or 15% at 1 MeV). For a 5-yr measuring time and with a 7-kg ^{100}Mo source, the sensitivity of the NEMO-3 detector would be at the level of $T^{0\nu}_{1/2} \geqslant 4\times10^{24}$ yr and for the neutrino mass limit, $m_\nu \leqslant 0.3-0.7$ eV (NEMO Collaboration, 2000).

CUORICINO (CUORE). The CUORICINO setup will contain 56 low-temperature bolometers made of TeO_2 crystals (750 g mass each) with a total mass of 42 kg (Fiorini, 1998; Gervasio, 2000). They will be mounted and cooled down to a temperature of ≈ 10 mK by the dilution refrigerator installed in the Gran Sasso Underground Laboratory (Italy). This refrigerator, shielded by high purity copper and lead having a low radioactivity, has already been used for a 2β decay quest with ^{130}Te involving 20 TeO_2 crystals (Alessandrello *et al.*, 2000). The projected CUORICINO sensitivity is $T^{0\nu}_{1/2} \geqslant 10^{24}-10^{25}$ yr or $m_\nu \leqslant 0.1-0.5$ eV, depending on the background rate reached at the energy 2.5 MeV (0.5–0.05 counts/yr kg keV) (Fiorini, 1998; Gervasio, 2000).

The main goal of the CUORICINO setup is to be a pilot step for a future CUORE project, which would consist of 1000 TeO_2 bolometers with a total mass of 750 kg. The excellent energy resolution of TeO_2 bolometers (5–10 keV at 2.5 MeV) is a powerful tool for discriminating the 0ν signal from the background. However, the complexity of cryogenic technique requires the use of many different construction materials in the setup, which makes it quite difficult to reach the same superlow level of background as those obtained in the best experiments with semiconductor and scintillation detectors (Aalseth *et al.*, 1999; Baudis *et al.*, 1999a; Danevich *et al.*, 2000). Because of this, the CUORE sensitivity is quoted by the authors for a different background (0.5–0.05 counts/yr kg keV) and would be as high as $T^{0\nu}_{1/2} \geqslant (1-5)\times10^{25}$ yr or $m_\nu \leqslant 0.05-0.2$ eV (Fiorini, 1998; Gervasio, 2000).

In addition, there are four large scale projects for the 2β decay quest of ^{116}Cd [CAMEO (Bellini *et al.*, 2000, 2001)] and ^{76}Ge [MAJORANA (Aalseth *et al.*, 2002), GENIUS (Klapdor-Kleingrothaus *et al.*, 1998) and GEM (Zdesenko *et al.*, 2001)], which we now discuss in more detail.

CAMEO. It is proposed (Bellini *et al.*, 2000, 2001) to use the already existing BOREXINO Counting Test Facility (CTF) installed in the Gran Sasso Underground Laboratory (Bellini, 1996; Alimonti *et al.*, 1998a, 1998b) for the 2β decay study of ^{116}Cd. With this aim ≈ 100 kg of enriched $^{116}CdWO_4$ crystal scintillators will be placed in the liquid scintillator of the CTF, serving as both light guide and veto shield. The CTF consists of an external ≈ 1000-ton water tank (11 m in diameter and 10 m in height), which serves as a passive shield for a 4.8-m^3 liquid scintillator contained in an inner vessel, having a 2.1 m diameter. The radiopurity of water is $\approx 10^{-14}$ g/g for U/Th, $\approx 10^{-10}$ g/g for K, and <5 μBq/l for ^{222}Rn (Bellini *et al.*, 1996; Alimonti *et al.*, 1998b). The high purity ($\approx 5\times10^{-16}$ g/g for U/Th) liquid scintillator has an attenuation length $\geqslant 5$ m above 380 nm, and a principal scintillator decay time of ≈ 5 ns (Alimonti *et al.*, 2000). The inner transparent vessel made of nylon film, which is 500 μm thick, allows one to collect the scintillation light with the help of 100 photomultiplier tubes (PMT's), each having a diameter of 8 in., that are fixed on the 7-m-diameter support structure inside the water tank. The PMT's with light concentrators provide a 20% efficient optical coverage, which yields (300±30) photoelectrons per 1 MeV of energy deposit, on average.

Because ^{116}Cd studies performed by the INR (Kiev) in the Solotvina Underground Laboratory with the help of the $^{116}CdWO_4$ crystals (Danevich *et al.*, 1989, 1995, 1998, 1999, 2000) is considered as the pilot step of the CAMEO project, we briefly recall their main results. The cadmium tungstate crystal scintillators (enriched in ^{116}Cd to 83%) were grown for research (Danevich *et al.*, 1989). Their light output is $\approx 40\%$ of that of NaI(Tl),

[19] As mentioned in footnote 1, double β decay is always allowed if the reaction energy, $Q_{\beta\beta}$, is positive. In the case of an α or β unstable parent nucleus, the 2β process will be only one of a few branches of the decay.

and their maximal peak emission is at 480 nm with a principal decay time of $\approx 14\ \mu s$ (Fazzini *et al.*, 1998). The refractive index of the $CdWO_4$ crystal is 2.3, the density is 7.9 g/cm^3, and the material is nonhygroscopic and chemically inert. In the latest phase of the experiment, four $^{116}CdWO_4$ crystals (with a total mass of 339 g) have been used. The detectors are viewed by the low background 5-in. EMI tube (with RbCs photocathode) through one light guide that is 10 cm in diameter and 55 cm long. Enriched detectors are surrounded by an active shield made of 15 natural $CdWO_4$ crystals (Georgadze *et al.*, 1996) with a total mass 20.6 kg. The latter are viewed by a PMT through an active plastic light guide that is 17 cm in diameter and 49 cm long. The whole $CdWO_4$ array is situated in an additional active shield made of plastic scintillator measuring $40\times40\times95\ cm^3$, and thus a complete 4π active shield is provided. The outer passive shield consists of high-purity copper (3–6 cm), lead (22.5–30 cm), and polyethylene (16 cm). The data acquisition records the amplitude, arrival time, and pulse shape (PS) of each $^{116}CdWO_4$ event. The PS technique is based on an optimal digital filter and ensures clear discrimination between γ rays and α particles, and hence selection of "illegal" events: double pulses, α events, etc. (Fazzini *et al.*, 1998).

The energy resolution of the main detector is 11.5% at 1064 keV and 8.0% at 2615 keV. The background spectrum measured during 4629 h with four $^{116}CdWO_4$ crystals (Danevich *et al.*, 2000) is given in Fig. 4, where previous data obtained with only one $^{116}CdWO_4$ crystal (Danevich *et al.*, 1999) are also shown for comparison. The background is decreased in the whole energy range, except for the β spectrum of ^{113}Cd ($Q_\beta=316$ eV).[20] In the energy region 2.5–3.2 MeV the background rate is 0.03 counts/yr kg keV, which is achieved due to improved shielding, and as a result of the pulse-shape and time-amplitude analysis of the data. For example, the following sequence of α decays from the ^{232}Th family was searched for ^{220}Rn ($Q_\alpha=6.40$ MeV, $T_{1/2}=55.6$ s) $\rightarrow ^{216}Po$ ($Q_\alpha=6.91$ MeV, $T_{1/2}=0.145$ s)$\rightarrow ^{212}Pb$. The equivalent energy of a ^{220}Rn α particle, as measured by the $^{116}CdWO_4$ scintillator, is ≈ 1.2 MeV; thus events in the energy region 0.7–1.8 MeV were used as triggers. Then any signals following the triggers in the time interval 10–1000 ms (94.5% of ^{216}Po decays) were selected. The spectra obtained for the first and second events, as well as the distribution of the time intervals between them are in excellent agreement with those expected from α particles of ^{220}Rn and ^{216}Po. The activity of ^{228}Th in $^{116}CdWO_4$ crystals is determined as 38(3) μBq/kg. The same technique applied to the sequence of α decays from the ^{235}U family yields 5.5(14) μBq/kg for ^{227}Ac impurity in the crystals (Danevich *et al.*, 2000).

The $T_{1/2}$ limits for $0\nu2\beta$ decay are set as $T_{1/2}^{0\nu} \geqslant 0.7(2.5)\times10^{23}$ yr at 90%(68%) C.L., while for 0ν decay with Majoron emission as $T_{1/2}^{0\nu}(M1)\geqslant 3.7$ (5.8) $\times10^{21}$ yr at 90% (68%) C.L. (Danevich *et al.*, 2000). These translate into constraints on the neutrino mass $m_\nu \leqslant 2.6$ (1.4) eV [using the calculation in Staudt *et al.* (1990)] and on the neutrino-Majoron coupling constant $g_M \leqslant 12$ $(9.5)\times10^{-5}$ [using the calculation in Hirsch *et al.* (1996)], both at 90% (68%) C.L. (Danevich *et al.*, 2000). It is expected that after ≈ 5 yr of measurements, a limit on the neutrino mass of less than 1 eV would be reached. However, further advance of this limit into the sub-eV neutrino mass domain would only be possible if there is a substantial enhancement of sensitivity, which is the main goal of the CAMEO project.

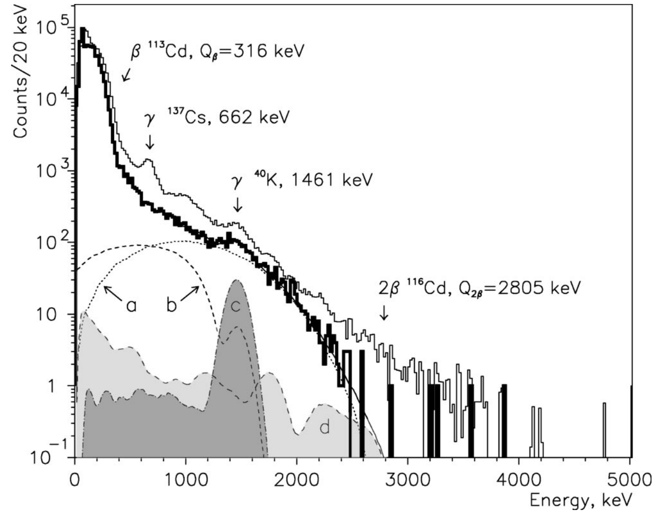

FIG. 4. Solid histogram: Background spectrum of four enriched $^{116}CdWO_4$ crystals (339 g) measured over 4629 h (Danevich *et al.*, 2000). Thin-line histogram: The previous data with only one $^{116}CdWO_4$ crystal (121 g; 19 986 h) normalized to 339 g and 4629 h. The model components: (a) $2\nu2\beta$ decay of ^{116}Cd with $T_{1/2}^{2\nu}=2.6(1)\times10^{19}$ yr; (b) ^{40}K in the $^{116}CdWO_4$ detectors (0.8 ± 0.2 mBq/kg); (c) ^{40}K in the shielding $CdWO_4$ crystals (2.1 ± 0.3 mBq/kg); (d) ^{226}Ra and ^{232}Th in the PMT's.

In the preliminary design concept of the CAMEO experiment 40 enriched $^{116}CdWO_4$ crystals of large volume ($\approx 320\ cm^3$) are located in the liquid scintillator of the CTF and homogeneously distributed on a sphere having a diameter of 0.8 m. With the 2.5 kg mass of each crystal (7 cm in diameter and 8 cm in height), the total number of ^{116}Cd nuclei is $\approx 1.5\times10^{26}$. It is supposed that 200 PMT's with light concentrators are fixed at a diameter of 5 m, thus providing an optical coverage of 80%. The $CdWO_4$ scintillator yields $\approx 1.5\times10^4$ emitted photons per 1 MeV of energy deposited. The GEANT Monte Carlo simulation of the light propagation in the considered geometry gives ≈ 4000 photoelectrons for a 2.8-MeV energy deposit; thus a $0\nu2\beta$ decay peak of ^{116}Cd would be measured with an energy resolution of FWHM=4%. The feasibility of obtaining such an energy resolution with a $CdWO_4$ crystal has been successfully demonstrated by the measurements with a cylindrical $CdWO_4$ crystal (40 mm in diameter and 30 mm in height) placed in transparent paraffin oil (refractive index ≈ 1.5) (Bellini *et al.*, 2000, 2001). An increase of the

[20]The abundance of ^{113}Cd in enriched $^{116}CdWO_4$ crystals is $\approx 2\%$ (Danevich *et al.*, 1995).

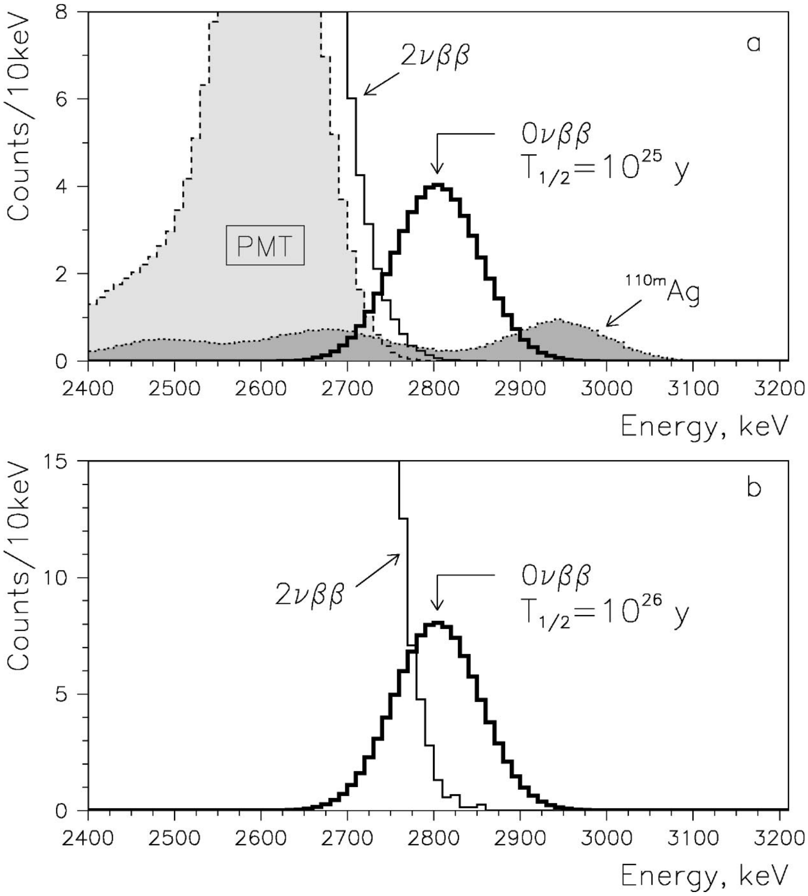

FIG. 5. (a) Solid histogram: The response functions of the CAMEO (Bellini *et al.*, 2000, 2001) with 100 kg of $^{116}CdWO_4$ crystals in the CTF (5-yr measuring period) for 2β decay of ^{116}Cd with $T_{1/2}^{2\nu}=2.7\times10^{19}$ yr, and $T_{1/2}^{0\nu}=10^{25}$ yr. Dashed line: The simulated contribution from ^{208}Tl in the PMT's. Dotted histogram: The simulated contribution from cosmogenic ^{110m}Ag. (b) The response functions of the 1000 kg of $^{116}CdWO_4$ crystals placed into a large liquid neutrino detector (BOREXINO, SNO, etc.) for 2β decay of ^{116}Cd with $T_{1/2}^{2\nu}=2.7\times10^{19}$ yr (thin line histogram), and $T_{1/2}^{0\nu}=10^{26}$ yr (thick line histogram) and for a 10-yr measuring time.

light collection efficiency to $\approx$42% has been obtained, which leads to improvement of the $CdWO_4$ energy resolution in the whole energy region. The FWHM values (7.4% at 662 keV; 5.8% at 1064 keV; 5.4% at 1173 keV; and 4.3% at 2615 keV) are similar to those for NaI(Tl) crystals and have never been reached before with $CdWO_4$ scintillators (Bellini *et al.*, 2000, 2001).

Moreover, for the CAMEO geometry a strong dependence of the amount of light collected by each PMT versus the coordinate of the emitting source in the crystal has been found. Such a dependence can be explained by the difference between the refraction indexes of the $CdWO_4$ crystal ($n=2.3$) and the liquid scintillator ($n'=1.5$), which leads to a redistribution between reflected and refracted light for different source positions. The Monte Carlo simulation shows that with a $CdWO_4$ crystal (7 cm in diameter and 8 cm in height) viewed by 200 PMT's, a spatial resolution of 1–5 mm can be reached depending on the event's location and the energy deposited. These interesting features of light collection from $^{116}CdWO_4$ permit one to reduce the background in the energy region of interest.

The background simulation for CAMEO was performed with the help of the GEANT3.21 and DECAY4 codes. The simulated contributions from different background sources and the response functions for 2β decay of ^{116}Cd with $T_{1/2}^{2\nu}=2.7\times10^{19}$ yr, and $T_{1/2}^{0\nu}=10^{25}$ yr are depicted in Fig. 5(a). The sensitivity of the experiment can be expressed with the help of the formula

$$\lim T_{1/2}^{0\nu}=\ln 2\cdot\varepsilon\cdot N\cdot t/\lim S, \tag{12}$$

where N is the number of ^{116}Cd nuclei ($N=1.5\times10^{26}$) and $\lim S$ is the maximum number of $0\nu2\beta$ events which can be excluded with a given confidence level. To estimate the value of $\lim S$ we can use the so-called "one (two, ...) σ approach," in which the excluded number of effect events is determined simply as the square root of the number of background counts in the energy region of interest, multiplied by a parameter (1, 1.6, or 2) in accordance with the confidence level chosen (68%, 90%, or 95%). The sensitivity of the CAMEO experiment calculated in this way is $T_{1/2}^{0\nu}\geq10^{26}$ yr, which translates to a neutrino mass bound of $m_\nu\leq0.06$ eV. On the other hand, it is evident from Fig. 5(a) that $0\nu2\beta$ decay of ^{116}Cd with a half-life of $\approx10^{25}$ yr would be clearly registered (Bellini *et al.*, 2000, 2001).

Moreover, these results can be advanced further by exploiting one ton of $^{116}CdWO_4$ detectors ($\approx1.5\times10^{27}$ nuclei of ^{116}Cd) placed in one of the existing or future large underground neutrino detectors such as BOREXINO (Bellini, 1996), SNO (Boger *et al.*, 2000), or KamLand (Suzuki, 1999). The simulated response functions of such a detector system for 2β decay of ^{116}Cd with $T_{1/2}^{2\nu}=2.7\times10^{19}$ yr and $T_{1/2}^{0\nu}\geq10^{26}$ yr assuming a 10-yr measuring period are depicted in Fig. 5(b). The sensitivity is estimated as $T_{1/2}^{0\nu}\geq10^{27}$ yr, which corresponds to a restriction on the neutrino mass of $\approx$0.02 eV (Bellini *et al.*, 2000, 2001). It should be noted also that the CAMEO technique with $^{116}CdWO_4$ crystals is extremely simple and reliable. Therefore the experiment can run stably for decades with a low maintenance cost.

MAJORANA. The idea of this proposal is to use 210 high-purity Ge (enriched in ^{76}Ge to $\approx$86%) semiconductor detectors ($\approx$2.4-kg mass, single crystal), which are contained in a "conventional" superlow background cryostat (21 crystals in one cryostat) (Aalseth *et al.*, 2002). The detectors are shielded by high-purity lead or copper. Each crystal will be supplied with six azimuthal and two axial contacts, and hence spatial information will be available for the detected events. It is anticipated that a segmentation of the crystals and a pulse-shape analysis of the data would reduce the background rate of the detectors to the level of $\approx$0.01 counts/yr kg keV at the energy 2 MeV, i.e., six times lower than that already reached in the most sensitive ^{76}Ge experiments (Aalseth *et al.*, 1999; Baudis *et al.*, 1999). Thus, after 10 yr of measurements, $\approx$200 background counts will be recorded in the vicinity of the $0\nu2\beta$ decay peak ($\approx$4-keV energy interval), and thereby one can get $\lim S \approx 20$ counts at 90% C.L. On this basis the projected half-life limit can be determined with the help of the formula (12) as $T_{1/2}^{0\nu} \geqslant 10^{27}$ yr. Depending on the nuclear matrix element calculations used [see Faessler and Simkovic (1998), Suhonen and Civitarese (1998), Baudis *et al.* (1999a), Bobyk *et al.* (2001), Stoica and Klapdor-Kleingrothaus (2001)], one expects the following interval for the neutrino mass limit: $m_\nu \leqslant 0.05-0.15$ eV.

GENIUS. This project intends to operate one ton of "naked" high-purity Ge (enriched in ^{76}Ge to $\approx$86%) semiconductor detectors placed in extremely high-purity liquid nitrogen (LN_2), which simultaneously serves as a cooling medium and as a shielding for the detectors (Klapdor-Kleingrothaus *et al.*, 1998). Owing to this shielding and due to the absence of any other materials (except high-purity Ge and liquid nitrogen), the background of the GENIUS setup would be reduced $\approx$300 times as compared with that of present experiments (Aalseth *et al.*, 1999; Baudis *et al.*, 1999a). The feasibility of operating "naked" Ge detectors in LN_2 was demonstrated by the measurements with three high-purity Ge crystals (mass of $\approx$0.3 kg each) placed on a common plastic holder inside liquid nitrogen (Baudis *et al.*, 1999b). With the 6-m cables between the detectors and the outer preamplifiers, an energy threshold of $\approx$2 keV and an energy resolution of $\approx$1 keV (at 300 keV) were obtained (Baudis *et al.*, 1999b). The second question (i.e., "Is it indeed achievable to obtain the scheduled background level?") has been answered by means of the Monte Carlo simulations. The latest were independently performed by the MPI, Heidelberg (Klapdor-Kleingrothaus *et al.*, 1998) and the INR, Kiev (Ponkratenko *et al.*, 1998) groups. In accordance with these simulations the necessary dimensions of the liquid-nitrogen shield, which could fully suppress the radioactivity from the surroundings (at the level measured, for instance, in the Gran Sasso Underground Laboratory) should be about 12 m in diameter and 12 m in height. The required radioactive purity of the liquid nitrogen should be at the level of $\approx 10^{-15}$ g/g for ^{40}K and ^{238}U, $\approx 5\times10^{-15}$ g/g for ^{232}Th, and 0.05 mBq/m^3 for ^{222}Rn (Klapdor-Kleingrothaus *et al.*, 1998; Ponkratenko *et al.*, 1998). All these requirements (except for radon) are less stringent than those already achieved in the BOREXINO CTF: $(2-5)\times10^{-16}$ g/g for ^{232}Th and ^{238}U contamination in the liquid scintillators (Bellini, 1996). Therefore purification of the liquid nitrogen to satisfy the GENIUS demands seems to be quite realistic. One concludes, finally, that the total GENIUS background rate in the energy region of the $\beta\beta$ decay of ^{76}Ge may be reduced down to $\approx$0.2 counts/yr keV t (Klapdor-Kleingrothaus *et al.*, 1998; Ponkratenko *et al.*, 1998). On this basis the projected $T_{1/2}$ limit can be estimated similarly as for the CAMEO and MAJORANA proposals. For a 10-yr measuring time, the value of $\lim S$ is equal $\approx$5 counts (90% C.L.), so that, with 7×10^{27} nuclei of ^{76}Ge, the bound $T_{1/2}^{0\nu} \geqslant 10^{28}$ yr may be achieved, which translates to a neutrino mass constraint of $m_\nu \leqslant 0.015-0.05$ eV.

However, to reach such a sensitivity the GENIUS apparatus must satisfy very stringent, and, in some cases, contradictory demands. For example, a superlow background rate of the detectors requires an ultrahigh purity of liquid nitrogen and large dimensions of the vessel (12 m in diameter and 12 m in height) with $\approx$1000 tons of LN_2. The power and maintenance costs of the LN_2 purification system strongly depend on the liquid-nitrogen consumption, which in turn depends on the dimensions of the LN_2 tank (heat losses through the walls are directly proportional to their square) and the quality of the thermal insulation. For GENIUS the method of passive thermal insulation with the help of 1.2-m-thick polyethylene foam isolation was adopted (Klapdor-Kleingrothaus *et al.*, 1998). Despite its simplicity, this solution cannot provide efficient thermal insulation for such a large vessel, and thus will lead to large LN_2 consumption. The latter would make it very difficult to maintain the required ultrahigh purity of LN_2 during the whole running period. Because evaporation of LN_2 is the method of purification, pure vapor will leave the vessel, while all impurities will remain in the remaining LN_2. For large liquid-nitrogen consumption, this process leads to a monotonic increase of the LN_2 contamination level with time.

These problems and difficulties for the project can be examined and perhaps solved with the help of the test facility (GENIUS-TF), which is under development now (Baudis *et al.*, 2000). Anyhow, it is clear that production, purification, operation, and maintenance (together with safety requirements) of more than one kiloton of ultrahigh purity liquid nitrogen in an underground laboratory requires additional efforts and will be both costly and time consuming.

GEM. Aiming to make realization of the high sensitivity ^{76}Ge experiment simpler, the GEM design is based on the following main ideas (Zdesenko *et al.*, 2001):

(a) "Naked" HP Ge detectors (enriched in ^{76}Ge to 86–90 %) will operate in ultrahigh-purity liquid nitrogen, which will serve simultaneously as both a cooling medium and a first layer of shielding.

(b) Liquid nitrogen is contained in the vacuum cryostat, which is made of high-purity copper. The dimensions of the cryostat, and consequently the volume of liquid nitrogen, are as small as possible consistent with the necessity of eliminating contributions of radioactive contaminants in the Cu cryostat to the background of the high-purity Ge detectors.

(c) The shield is composed of two parts: (i) an inner shielding—ultrahigh-purity liquid nitrogen, whose contaminations are less than $\approx 10^{-15}$ g/g for ^{40}K and ^{238}U, $\approx 5\times 10^{-15}$ g/g for ^{232}Th, and 0.05 mBq/m^3 for ^{222}Rn; (ii) an outer part—high-purity water, whose volume is large enough to suppress any external background to a negligible level.

The optimization of the setup design was performed with the help of the GEANT3.21 package and event generator DECAY4. A schematic of the GEM device created on the basis of the simulation is shown in Fig. 6. About 400 enriched high-purity Ge detectors (8.5 cm in diameter and 8.5 cm in height, with a weight of $\approx$2.5 kg each) are located in the center of a copper sphere (the inner enclosure of the cryostat) having a diameter of 4.5 m and a thickness of 0.6 cm, which is filled with liquid nitrogen. The detectors, arranged in nine layers, occupied a space of $\approx$90 cm in diameter. It is supposed that the crystals are fixed with the help of a holder system made of nylon strings. The thin copper wire 0.2 mm in diameter is attached to each detector to provide the signal connection.

The outer encapsulation of the cryostat, with a diameter of 5 m, is also made of high-purity Cu with a thickness of 0.6 cm. Both enclosures of the cryostat are connected by two concentric copper pipes to an outer vacuum pump, which maintains $\approx 10^{-6}$-torr pressure in the space between the two walls of the cryostat. This space (in combination with several layers of $\approx$5-μm-thick aluminized Mylar film enveloping the inner Cu vessel and serving as a thermal radiation reflector) reduces the heat current through the walls of the cryostat to the value of $\approx$2.5 W/m^2 (Kropschot, 1961). Thus the total heat losses (including heat conduction through the pipes, the support structure, and the cables) are near 200 W. This corresponds to a reasonable LN_2 consumption of less than 100 kg per day.

Moreover, to provide the most stable and quiet operation of the high-purity Ge detectors, the volume with liquid nitrogen is divided in turn into two zones with the help of an additional Cu sphere with a diameter of 3.8 m and a thickness of 1 mm. The high-purity Ge detectors are contained in this latter sphere, where only a tiny fraction of heat current through the thin signal cables and holder strings can reach this volume. The outer LN_2 zone between the inner wall of the cryostat and the sphere with Ge crystals serves as an additional and very efficient thermal shield (Kropschot, 1961). Hence LN_2 consumption in the inner volume with the detectors should be extremely low, which allows one to maintain

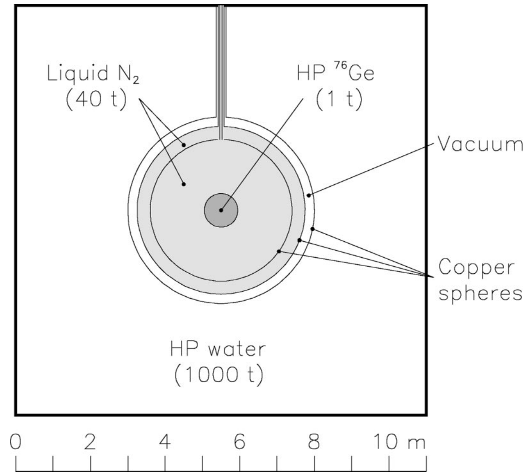

FIG. 6. Schematic of the GEM setup (Zdesenko *et al.*, 2001).

the necessary ultrahigh purity of LN_2 and stable operation conditions for the entire running period.

The cryostat is placed into the high-purity water shield ($\approx 10^{-14}$ g/g for ^{40}K, ^{232}Th, ^{238}U, and $\approx$10 mBq/m^3 for ^{222}Rn) having a mass of $\approx$1000 tons contained in a steel tank 11 m in diameter and 11 m in height. Note that even better radio-purity levels have been achieved for the water shield of the BOREXINO CTF. The dimensions of the CTF water tank are practically the same (11 m in diameter and 10 m in height), hence this shield could be used for the GEM experiment. The design developed for the GEM setup reduces the dimensions of the LN_2 volume substantially and allows a solution to the problems of thermal insulation, ultrahigh-purity conditions, LN_2 consumption, safety requirements, etc.

For the background simulations with the help of GEANT3.21 and DECAY4 programs the schematic of the setup (see Fig. 6) was used. The total mass of the detectors is equal to $\approx 1\,t$; liquid nitrogen, $\approx 40\,t$; copper cryostat, $\approx 7\,t$; water shield, $\approx 1000\,t$; holder system, $\approx$2 kg; and copper wires, $\approx$1 kg. The internal and external origins of the background were investigated carefully. The internal background arises from residual impurities in the Ge crystals themselves and in their surroundings (i.e., the crystal holder system, liquid nitrogen, copper cryostat, water, and steel vessel), and from activation of all these mentioned materials at the Earth's surface during production and construction. The external background is generated by events originating outside the shield, such as photons and neutrons from the Gran Sasso rock, muon interactions, and muon-induced activities.

In the calculation of the GEM background caused by radioactive contamination of the Ge detectors and materials used by ^{40}K and nuclides from the natural radioactive chains of ^{232}Th and ^{238}U, the values of their impurities were taken from real measurements (Jagam and Simpson, 1993; Bellini, 1996; Gunther *et al.*, 1997; Baudis *et al.*, 1999b, 2000). The radiopurity criteria supposed for liquid nitrogen ($\approx 10^{-15}$ g/g for ^{40}K and ^{238}U, $\approx 5\times 10^{-15}$ g/g for ^{232}Th) seem to be realistic in light of the results already achieved by the BOREXINO Collaboration for the purity of the liquid scintillators: $(2-5)\times10^{-16}$ g/g for ^{232}Th and ^{238}U (Bellini, 1996). Moreover, due to recent development of the liquid-nitrogen purification system for the BOREXINO experiment (Heusser *et al.*, 2000), the ^{222}Rn contamination of the liquid nitrogen was also reduced down to the level of ≈ 1 μBq/m^3. It was shown by the simulation that the requirements for the purity of the GEM water shield can be lowered to the level of about 10^{-13} g/g for U/Th contaminations (Zdesenko *et al.*, 2001).

Cosmogenic activities in high-purity ^{76}Ge detectors were estimated with the help of the program COSMO (Martoff and Lewin, 1992). An activation time of 30 days at sea level,[21] and a deactivation time of 3 yr underground were assumed. It was found that the background at 2038 keV is caused mainly by ^{22}Na, ^{60}Co, and ^{68}Ga (a daughter of cosmogenic ^{68}Ge), whose contributions could be lowered to a value less than 3×10^{-2} counts/yr keV t near 2038 keV (Zdesenko *et al.*, 2001).

Combining all background contributions from both internal and external sources, the total background rate of the GEM experiment is less than 0.2 counts/yr keV t at 2038 keV. The simulated response functions of the GEM setup after a 10-yr measuring time for 2β decay of ^{76}Ge with $T_{1/2}^{2\nu}=1.8\times10^{21}$ yr (Gunther *et al.*, 1997) and $T_{1/2}^{0\nu}=10^{27}$ yr, as well as background contributions from contaminations in the holder system and in the copper cryostat walls, are depicted in Fig. 7. It is obvious from this figure that the measured background at the energies below 1950 keV is dominated by the two neutrino 2β decay distribution of ^{76}Ge (a total of $\approx 2.6\times10^7$ counts are recorded), while at 2040 keV the main sources of the background are contaminations of the holder system and the copper cryostat walls by nuclides from U and Th chains. On the other hand, it is also evident from Fig. 7 that $0\nu2\beta$ decay of ^{76}Ge with a half-life of 10^{27} yr would be clearly registered (there are 42 counts in the $0\nu2\beta$ decay peak). The sensitivity of the GEM experiment can be expressed in the same manner as for the MAJORANA and GENIUS proposals [see Eq. (12)]. For a 10-yr measuring period, the value of $\lim S$ is equal to ≈ 5 counts (90% C.L.). Thus, taking into account the number of ^{76}Ge nuclei (7×10^{27}) and the detection efficiency $(\varepsilon\approx 0.95)$, a half-life bound of $T_{1/2}^{0\nu}\geqslant 10^{28}$ yr may be achieved. Depending on the nuclear matrix element calculations (Faessler and Simkovic, 1998; Suhonen and Civitarese, 1998; Baudis *et al.*, 1999a; Bobyk *et al.*, 2001; Stoica and Klapdor-Kleingrothaus, 2001), this limit corresponds to the following neutrino mass constraints: $m_\nu \leqslant 0.015-0.05$ eV.

[21]It was supposed that Ge materials and crystals were additionally shielded against activation during production and transportation. For example, 20 cm of Pb would lower the cosmic nucleon flux by one order of magnitude, which implies the same reduction factor for most cosmogenic activities.

The realization of the GEM experiment seems to be reasonably simple due to the fact that the design of the setup has practically no technical risk. Indeed, a very attractive feature of the project is the possibility of using the already existing BOREXINO CTF as an outer shield, because it fits all the GEM requirements concerning radiopurity and dimensions of the water shield. In addition, one of the forthcoming large underground neutrino detectors, such as KamLand (Suzuki, 1999) or BOREXINO (Bellini, 1996), could also be appropriate for this purpose.

The cost of the GEM experiment is estimated at $\approx$\$150 M, with a major part budgeted for the production of enriched materials. However, in the first phase of the project, the measurements will be performed with one ton of natural high-purity Ge detectors, whose cost (together with the cost of the cryostat) does not exceed \$10 M. Besides the important technical tasks which must be solved during this first phase to prove the feasibility of the project, the GEM-I phase with its relatively modest cost would bring outstanding physical results. Indeed, in accordance with the formula (12) for sensitivity of any $0\nu2\beta$ decay experiment, the reachable half-life limit is strictly proportional to the enrichment (abundance) of candidate nuclei contained in the detector. For the GEM-I phase, the natural abundance of ^{76}Ge (7.6%) is about 11 times smaller than the enrichment supposed for the second stage (86%). Because all other characteristics of the setup (ε,m,t,R,Bg) could be the same for both phases, the $T_{1/2}$ bound, which would be obtained with natural high-purity Ge detectors is about one order of magnitude lower: $T_{1/2}^{0\nu}\geqslant 10^{27}$ yr. This translates to a neutrino mass constraint of $m_\nu \leqslant 0.05$ eV, which is also of great interest for many theoretical models.

Hence we can conclude that a challenging scientific goal to reach the 0.01–0.05-eV neutrino mass domain would indeed be feasible for the next generation of superhigh sensitivity 2β experiments, like CAMEO, CUORE, GEM, GENIUS, and MAJORANA projects, whose realization seems to have practically no technical risk.

IV. IMPLICATIONS OF 2β DECAY RESEARCH AND CONCLUSIONS

In this section we discuss briefly the physical implications of future 2β decay experiments, whose sensitivity to the neutrino mass limit would be of the order of 0.05 eV (CAMEO, CUORE, DCBA, EXO, GEM-I, MAJORANA, MOON, XMASS, etc.) and ≈ 0.01 eV (GEM-II, GENIUS).

As mentioned in the Introduction, many extensions of the standard model incorporate lepton number violating interactions, and thus could lead to $0\nu2\beta$ decay. Besides the conventional left-handed neutrino exchange mechanism of $0\nu2\beta$ decay, such theories offer many other possibilities for triggering this process (Faessler and Simkovic, 1998; Klapdor-Kleingrothaus, 1998).

In left-right symmetric GUT models, neutrinoless 2β decay can be mediated by heavy right-handed neutrinos

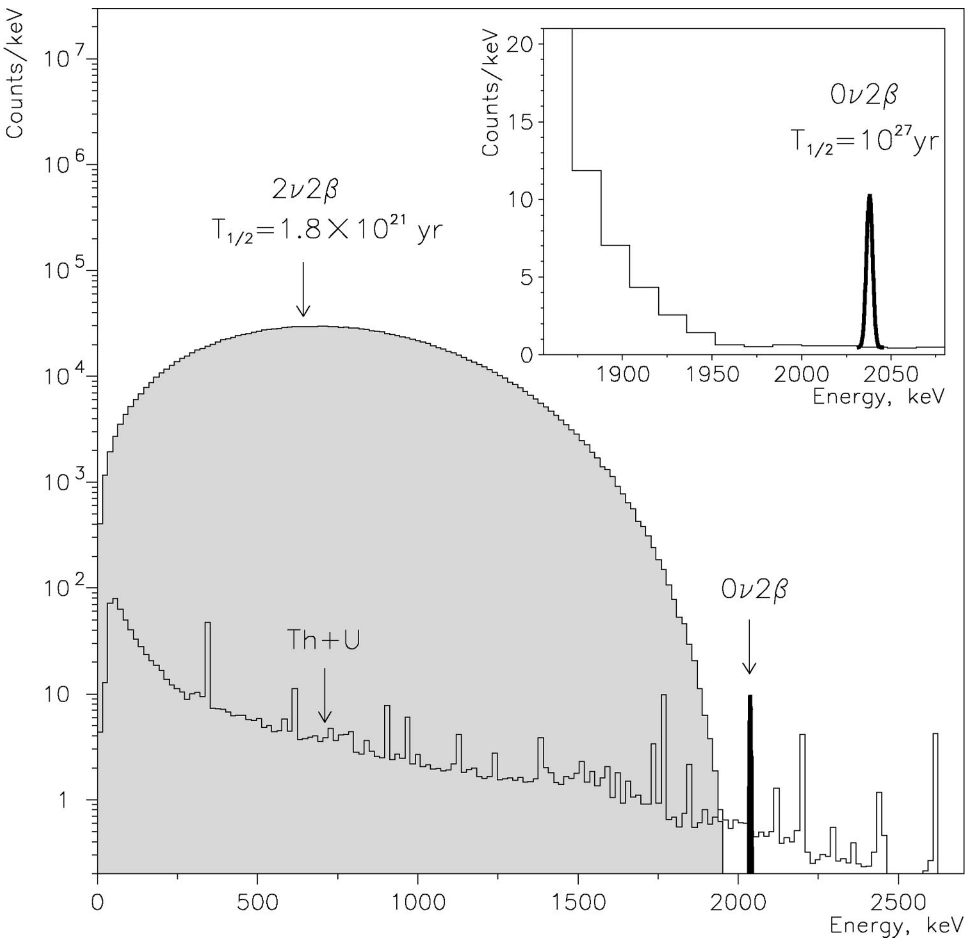

FIG. 7. Thick-line and shadowed histograms: The response functions of the GEM-II setup (Zdesenko *et al.*, 2001) with 1000 kg of high-purity ^{76}Ge crystals and after 10 yr of measurements for 2β decay of ^{76}Ge with $T_{1/2}^{2\nu}=1.8\times10^{21}$ yr (Gunther *et al.*, 1997) and $T_{1/2}^{0\nu}=10^{27}$ yr. Thin-line histogram: Background contributions from contaminations of the holder system and the copper cryostat walls by nuclides from the ^{232}Th and ^{238}U families. Inset: The summed spectrum in the vicinity of the $0\nu2\beta$ decay peak of ^{76}Ge is shown on a linear scale.

(Doi *et al.*, 1983; Doi and Kotani, 1993), and consequently, 2β experiments could probe right-handed W_R boson masses. It was shown (Klapdor-Kleingrothaus and Hirsch, 1997) that 2β decay experiments with a sensitivity of $m_\nu\leqslant0.01$ eV would be at the same time sensitive to right-handed W_R boson masses up to $m_{W_R}\geqslant8$ TeV (for a heavy right-handed neutrino mass $\langle m_N\rangle=1$ TeV) or $m_{W_R}\geqslant5.3$ TeV (for $\langle m_N\rangle=m_{W_R}$). These limits, which therefore could be established by the GEM-II and GENIUS experiments, are nearly the same as expected for the LHC (Rizzo, 1996).

Another new type of gauge bosons predicted by some GUT's are leptoquarks, which can transform quarks to leptons. Direct searches for leptoquarks in deep inelastic *ep* scattering at HERA give lower limits on their masses $M_{LQ}\geqslant225-275$ GeV (depending on the leptoquark type and coupling) (Aida *et al.*, 1996). Leptoquarks can induce $0\nu2\beta$ decay via leptoquark-Higgs couplings, and thus restrictions on leptoquark masses and coupling constants can be derived (Hirsch, Klapdor-Kleingrothaus, and Kovalenko, 1996c, 1996d). A detailed study performed by Klapdor-Kleingrothaus *et al.* (1999) yields the conclusion that a GENIUS-like experiment would be able to reduce the limit on leptoquark-Higgs couplings down to $\approx10^{-7}$ for leptoquarks with masses in the range of 200 GeV. If no effect ($0\nu2\beta$ decay) is found, it means that either the leptoquark-Higgs coupling must be smaller than $\approx10^{-7}$ or that there exist no leptoquarks (coupled with electromagnetic strength) with masses below ≈10 TeV (Klapdor-Kleingrothaus *et al.*, 1999).

A hypothetical substructure of quarks and leptons (compositeness) can also give rise to a new $0\nu2\beta$ decay mechanism by exchange of composite heavy Majorana neutrinos (Cabibbo *et al.*, 1984; Panella *et al.*, 1997), and consequently the compositeness could be checked at low energy. Recent analysis (Cabibbo *et al.*, 1984; Panella *et al.*, 1997, 2000) shows that the most sensitive $0\nu2\beta$ results at present with ^{76}Ge (Aalseth *et al.*, 1999; Baudis *et al.*, 1999a) yield a bound on the excited Majorana neutrino mass of $m_N\geqslant272$ GeV, which already exceeds the ability of the LEP-II to test compositeness. Future ^{76}Ge experiments (GEM-II, GENIUS) would shift this limit to $m_N\geqslant1$ TeV, which is competitive with the sensitivity of the LHC (Cabibbo *et al.*, 1984; Panella *et al.*, 1997, 2000).

There are also possible $0\nu2\beta$ decay mechanisms based on supersymmetric (SUSY) interactions: exchange of squarks, etc., within R-parity violating SUSY models (Mohapatra, 1986; Hirsch, Klapdor-Kleingrothaus, and Kovalenko, 1995, 1996a, 1996b, 1999; Faessler *et al.*, 1997; Wodecki *et al.*, 1999) and exchange of sneutrinos, etc., within R-parity conserving SUSY models (Hirsch *et al.*, 1997a, 1997b). These allow 2β decay experiments to enter the field of supersymmetry, where competitive restrictions on the sneutrino masses, R-parity violating couplings, and other parameters could be obtained (Hirsch *et al.*, 1998; Bhattacharya *et al.*, 1999).

We consider now the relations between $0\nu2\beta$ decay studies and neutrino oscillation searches in order to demonstrate the role which future 2β experiments can play in the reconstruction of the neutrino mass spectrum. At present this topic is widely discussed in the literature, and thus interested readers are referred to the latest publications (Bilenky *et al.*, 1999, 2001a, 2001b; Czakon *et al.*, 1999, 2000a, 2000b; Vissani, 1999; Klapdor-Kleingrothaus, Pas, and Smirnov, 2001; Klapdor-Kleingrothaus, 2001a, 2001b, 2001c; Klapdor-Kleingrothaus and Majorovits, 2001), while we focus here on some of the most important results.

There exist several schemes for the neutrino masses and their mixing that are offered by various theoretical models on the basis of the observed oscillation data for the solar and atmospheric neutrinos (Bilenky *et al.*, 1999, 2001a, 2001b; Klapdor-Kleingrothaus, Pas, and Smirnov, 2001). These schemes include: normal and inverse neutrino mass hierarchy, partial and complete mass degeneracy, as well as a scenario with four neutrinos, etc. For each of these schemes several solutions exist: the small mixing angle (SMA) Mikheyev-Smirnov-Wolfenstein (MSW) solution; the large mixing angle (LMA) MSW solution; the low mass (LOW) MSW solution; and the vacuum oscillation (VO) solution. Careful analyses of these schemes (Bilenky *et al.*, 1999, 2001a, 2001b; Klapdor-Kleingrothaus, Pas, and Smirnov, 2001) lead to the following conclusions: (a) the effective neutrino mass, $\langle m_\nu \rangle$, which is allowed by oscillation data and could be observed in 2β decay, is different for different scenarios, and hence 2β decay data could substantially narrow or restrict this wide choice of possible models; (b) the whole range of allowed $\langle m_\nu \rangle$ values is 0.001–1 eV, where there are three key scales of $\langle m_\nu \rangle$: 0.1, 0.02, and 0.005 eV. If future 2β decay experiments will prove that $\langle m_\nu \rangle \geq 0.1$ eV, then all schemes would be excluded, except those with neutrino mass degeneracy or with four neutrinos and inverse mass hierarchy (Klapdor-Kleingrothaus, Pas, and Smirnov, 2001). With a bound on $\langle m_\nu \rangle$ of about 0.02–0.05 eV, several other solutions will be excluded, while if the neutrino mass limit is $\langle m_\nu \rangle \leq 0.005$ eV, the surviving schemes are those with 3ν mass hierarchy or with partial degeneracy. The following citation (Bilenky *et al.*, 2001a, 2001b) emphasizes importance of future 2β decay searches: "The observation of the $0\nu2\beta$ decay with a rate corresponding to $\langle m_\nu \rangle \approx 0.02$ eV can provide unique information on the neutrino mass spectrum and on the CP-violation in the lepton sector, and if CP-invariance holds, on the relative CP-parities of the massive Majorana neutrinos."

Hence it is obvious that future experiments will bring crucial results for the reconstruction of the neutrino mass spectrum and mixing not only at their best sensitivity of $\langle m_\nu \rangle \approx 0.015$ eV (as for GEM-II with enriched detectors), but also at the sensitivity level of $\langle m_\nu \rangle \approx 0.05$ eV (as for GEM-I with natural high-purity Ge crystals). This statement is also true for any of the other topics discussed above.

Furthermore, another very important issue for future projects like CUORE, GEM, GENIUS, and MAJORANA is the quest for dark matter particles (Ramachers, 1999; Baudis and Klapdor-Kleingrothaus, 2000). It has been shown by Monte Carlo simulations (Klapdor-Kleingrothaus *et al.*, 1998; Ponkratenko *et al.*, 1998) that, for the GENIUS project exploiting ≈ 100 kg of natural high-purity Ge detectors, the background rate of ≈ 40 counts/yr keV t could be obtained in the low-energy region (10–100 keV) that is relevant for the WIMP dark matter study. The main contributions to this rate are from (a) $2\nu2\beta$ decay of ^{76}Ge with $T_{1/2}^{2\nu} = 1.8 \times 10^{21}$ yr (≈ 20 counts/yr keV t); (b) cosmogenic activities in high-purity Ge crystals (≈ 10 counts/yr keV t); (c) internal radioactive contamination of the liquid nitrogen, copper wires, and holder system (≈ 10 counts/yr keV t). It is estimated that an even lower background rate could be reached in the GEM-I setup, where only an inner volume with ≈ 200 kg of high-purity Ge detectors will be used for the dark matter search, while the outer layers with the remaining ≈ 800 kg of high-purity Ge crystals would serve as a superhigh-purity passive and active shield for the inner detectors. A simulation shows that in such a configuration additional suppression of the background component from internal radioactive contamination of the liquid nitrogen, copper wires, and holder system could be obtained. Thus the GEM-I (or GENIUS) setup with a realistic energy threshold of 10 keV and with a background rate[22] of ≈ 40 counts/yr keV t below 100 keV would provide the highest sensitivity for the WIMP dark matter search as compared with other projects [see, for example, Klapdor-Kleingrothaus (2001a), Klapdor-Kleingrothaus *et al.* (2001)]. This fact is demonstrated by the exclusion plots for the WIMP-nucleon elastic scattering cross section, which have been calculated for the GEM-I and GENIUS experiments and depicted in Fig. 8 together with the best current and other projected limits. The theoretical prediction for the allowed spin-independent elastic WIMP-proton scattering cross section obtained in the framework of the constrained minimal supersymmetric standard model (MSSM) (Ellis *et al.*, 2000) is also shown.[23] It is obvious from Fig. 8 that GEM-I and GENIUS would test the MSSM prediction by covering the larger part of the predicted SUSY parameter space. In that sense the GEM and GENIUS experiments could be competitive even with the LHC in the SUSY quest (Rizzo, 1996). At the same time, with a

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[22]The most serious background problem for the dark matter quest with Ge detectors is cosmogenic activity of ^{3}H produced in Ge (Ponkratenko *et al.*, 1998; Klapdor-Kleingrothaus and Majorovits, 2001). For the GEM-I the total ^{3}H activity is estimated as ≈ 5000 decays/yr t, which is in good agreement with the result of Klapdor-Kleingrothaus and Majorovits (2001) and contributes ≈ 10 counts/yr keV t to the total background rate in the energy interval 10–100 keV (Zdesenko *et al.*, 2001).

[23]Very similar predictions from theoretical considerations for the MSSM with a relaxed unification condition were derived by Bednyakov and Klapdor-Kleingrothaus (2001).

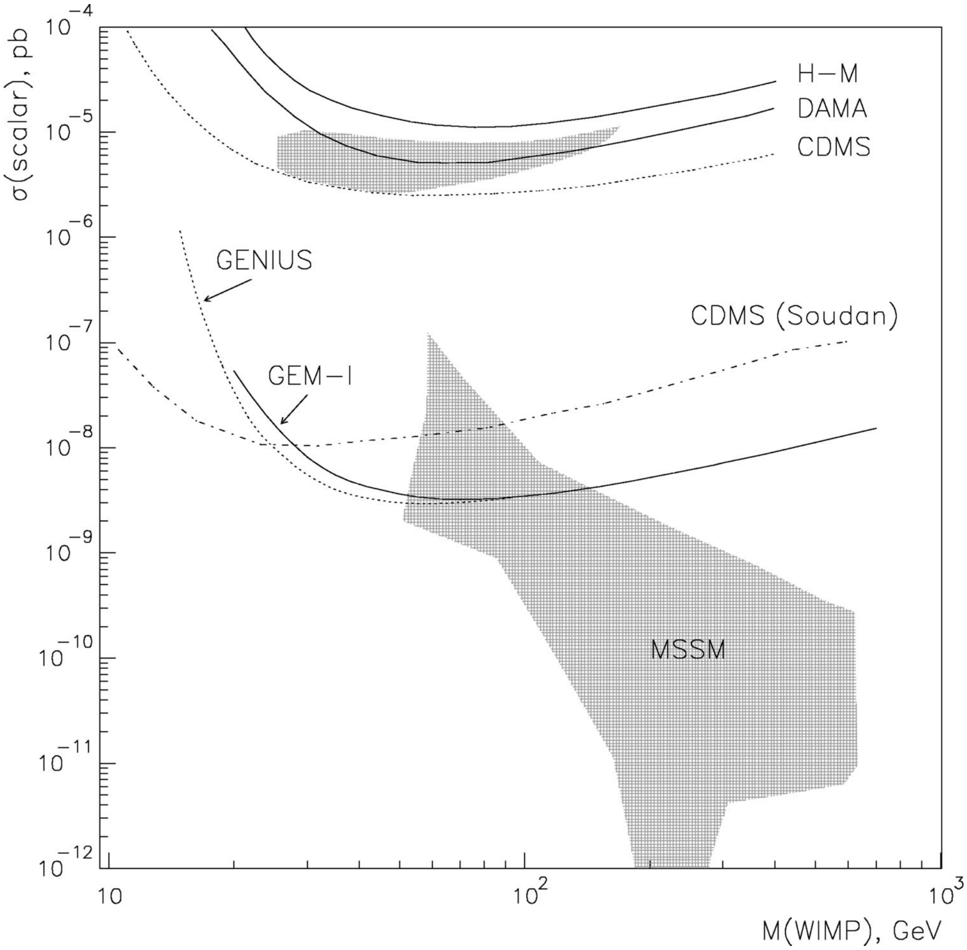

FIG. 8. Exclusion plots of the spin-independent WIMP-nucleon elastic cross section versus WIMP mass. The regions above the curves are excluded at 90% C.L. Current limits from the Heidelberg-Moscow (H-M) (Baudis *et al.*, 1999c), DAMA (Bernabei *et al.*, 1996, 1998), and CDMS (Abusaidi *et al.*, 2000a) experiments are shown in the upper part of the figure. The small shaded area gives the 2σ evidence region from the DAMA experiment (Bernabei *et al.*, 2000). Projected exclusion plots for the CDMS (Soudan) (Abusaidi *et al.*, 2000b), GENIUS (Klapdor-Kleingrothaus and Majorovits, 2001), and GEM-I (Zdesenko *et al.*, 2001) experiments are depicted also. The large shaded area represents the theoretical prediction for the allowed spin-independent elastic WIMP-proton scattering cross section calculated in the framework of the constrained MSSM (Ellis *et al.*, 2000).

fiducial mass of high-purity Ge detectors of $\approx$100 kg (GENIUS) or $\approx$200 kg (GEM-I) it would be possible to test and identify unambiguously [within one year of data taking (Cebrian *et al.*, 2001)] the seasonal modulation signature of the dark matter signal from the DAMA experiment (Bernabei *et al.*, 2000) by using an alternative detector technology.

In conclusion, 2β decay research is entering a new era of large scale and ultimate sensitivity experimentation. Competition among the projects with different 2β decay candidates can promote them to the high level of sensitivity required by the present status of the neutrino physics, and hence would make this field a viable science thriving on a diversity of complementary instruments, techniques, and approaches. In sum, they will bring outstanding results not only for the 2β decay studies but also for the dark matter searches as well, thereby providing crucial tests of certain key problems and theoretical models of modern astroparticle physics and cosmology.

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