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New approach to the detection of neutrinoless double-beta decay

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A distinctive feature of the double-beta-decay signature that has been neglected in direct counting experiments is the appearance of the daughter atom. The newly created nucleus, usually being stable, is not easily detected. The atomic physics of the daughter, however, may be considerably more accommodating, especially in the case of ionized ^{136}Ba arising from the double-beta decay of ^{136}Xe. The barium ion isolated in the xenon matrix may be detectable by its laser fluorescence. Coincident detection of the ion and the beta particles could well render background nonexistent.

Neutrinoless double-beta decay ($\beta\beta_{0\nu}$) is possible if the distinction between the neutrino and antineutrino is simply a manifestation of two different helicity states of the same particle (the Majorana neutrino), and if a very small mixing of the two states is driven by a nonzero neutrino mass [1]. Massive Majorana neutrinos and a number of other possible consequences of $\beta\beta_{0\nu}$ are at variance with the standard model, and the question of their existence has motivated numerous experimental searches [2] for the $\beta\beta_{0\nu}$ phenomenon.

Several different isotopes have been studied, the best published $\beta\beta_{0\nu}$ result being for ^{76}Ge by the University of California, Santa Barbara–Lawrence Berkeley Laboratory (UCSB-LBL) group [3] who report a lower half-life limit of 2.4×10^{24} yr, and a corresponding upper limit on the effective Majorana mass for the electron neutrino of $\sim$1 eV. Yet one would like to probe still smaller mass regions. Grand unified theories favoring a finite neutrino mass give a very wide range for its predicted magnitude. Indeed, in view of proposed nonadiabatic Mikheyev-Smirnov-Wolfenstein (MSW) solutions to the solar neutrino problem [4,5], and various cosmological arguments, it may be that neutrino masses are far too small to ever result in observable neutrinoless double-beta decay. At present the question remains open, and the $\beta\beta_{0\nu}$ searches continue. A reduction of 2 orders of magnitude in detectable mass is not beyond imagination.

The dependence of the minimum detectable effective neutrino mass $\langle m_\nu\rangle_{\rm min}$ on the source mass and run time for ^{76}Ge $\beta\beta_{0\nu}$ experiments [2(b)] is shown for various combinations of background and isotopic enrichment in Fig. 1. The advantage of *enriched* germanium is clear. Two new experiments [6,7], the larger being $\sim$10 kg, are being assembled with germanium enriched to 85% isotope 76, compared to the 7.8% natural abundance used by UCSB-LBL. These experiments should be able to reach a few tenths of an electron volt. With enrichment, energy resolution, and run time then approaching their practical limits, the only remaining parameters available for improved sensitivity in ^{76}Ge are background b $({\rm keV\,kg\,yr})^{-1}$, and source mass M (kg). The dependence of $\langle m_\nu\rangle_{\rm min}$ on these parameters is weak, being proportional to $(b/M)^{1/4}$. An order-of-magnitude improvement in sensitivity to neutrino mass would require a 10000-fold decrease in b/M. To accomplish this decrease entirely with larger sources is economically out of the question, so very substantial improvements in background are necessary to make meaningful strides toward smaller neutrino masses.

There are other $\beta\beta$ isotopes with more favorable matrix elements and phase space [8–10], and corresponding lines as much as an order of magnitude lower in the figure. As a practical matter, affordable, low-background, high-efficiency, large-scale experiments have not been easy to design for these favored isotopes [11].

Among the candidates for double-beta decay, ^{136}Xe may have the greatest potential for very-large-mass exper-

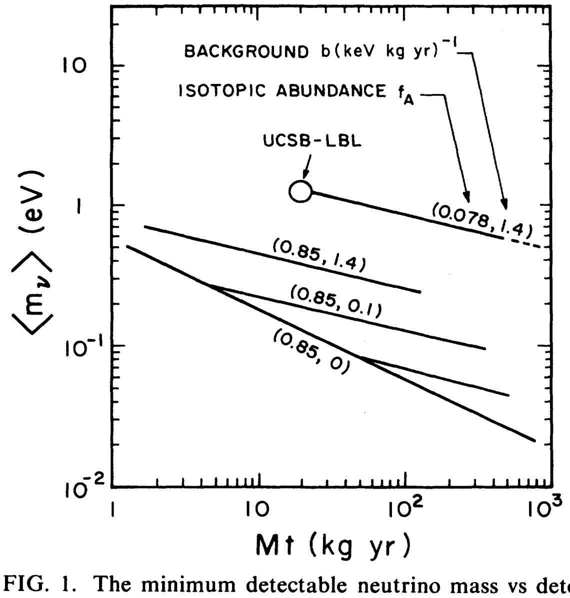

FIG. 1. The minimum detectable neutrino mass vs detector mass and run time for ^{76}Ge experiments with various levels of background and isotopic enrichment. The latest UCSB-LBL result (circle) is shown for comparison. Probing the smallest neutrino masses requires a very large detector mass and very low (preferably zero) background.

iments [12]. The isotope is relatively inexpensive to enrich from its natural abundance of 8.9% to the order of 60% by gas centrifugation; it is a noble gas that can serve simultaneously as source and detector; its $\beta\beta_{0\nu}$ matrix-element, phase-space product is similar to that of ^{76}Ge; and it has a higher transition energy (2479 keV versus 2041 keV for ^{76}Ge). Several experiments have been performed with ^{136}Xe in time projection chambers (TPC's), proportional counters, ionization chambers, and scintillation detectors [13-16]. Some of these experiments have made good progress against background, but all have had to contend with it at some unwanted level.

A feature of double-beta decay previously unexploited in direct counting experiments [17] is the sudden production of two additional protons in the nucleus, which leaves the daughter atom shy two electrons. Decay of ^{136}Xe makes $^{136}Ba^{2+}$. As in single-beta decay, often one or more atomic electrons will also be ejected [18]. The daughter atom, therefore, will be born in a double or higher state of ionization. If the xenon detector is normally kept free of ions by a drift field, the appearance of a barium ion together with a 2.5 MeV energy pulse could be sufficiently unique that demanding their coincident detection would eliminate background completely.

The detector proposed is a liquid xenon TPC to be operated in a deep-underground laboratory. The range of ~2 MeV beta particles in the liquid is a few millimeters, so the position of the barium ion would be localized to that order by detection of the beta-particle ionization and a scintillation trigger. The mobility of positive ions in liquid xenon is relatively low, so the barium ion would not move far from its origin in the time required to target it for laser excitation.

Single-isolated Ba^+ ions have been successfully detected by their laser fluorescence in the classic experiment of Neuhauser and co-workers [19]. Irradiation of this favorite ion in the blue-green at 493 nm results in red fluorescence at 650 nm. Following xenon decay, the third- and higher-ionization states of barium have sufficient potential to pull electrons from neighboring xenon atoms. Once the ion becomes Ba^{2+} its subsequent behavior is less obvious. The ionization potentials listed in Table I suggest that xenon will not surrender further electrons, and Ba^{2+} will remain stable. In this case the ion's emission and absorption wavelengths would be in the vacuum ultraviolet which, together with the lack of a metastable state, would make detection by laser fluorescence difficult. However, in liquid xenon the gap to the conduction band is slightly below the second-ionization potential for barium [20], and the Ba^{2+} ion is likely to take on an electron to become Ba^+. Xenon, being highly polarizable, would also be expected to attach to the ion to ultimately form $(BaXe)^+$.

The spectroscopy of matrix-isolated $(BaXe)^+$ does not appear in the literature. The behavior of this ion is crucial to the proposed detection scheme, and a small experiment is being set up to investigate its spectroscopy in liquid xenon [21].

If a strong fluorescence can be identified, there remain questions of background to be considered. For example, one might ask whether in a large xenon experiment a feeble $\beta\beta_{0\nu}$ spike at the 2479 keV Q value might blend into the high-energy tail of the much stronger $\beta\beta_{2\nu}$ spectrum. The high end of the theoretical $\beta\beta_{2\nu}$ electron sum spectrum for ^{136}Xe is shown in Fig. 2(a) [22]. The spillage of a resolution-smeared version of this spectrum into a $\beta\beta_{0\nu}$ window is shown as a function of full width at half maximum (FWHM) resolution in Fig. 2(b). (The Majoron [1] is assumed to be nonexistent.)

A large liquid xenon TPC should be able to achieve 4% FWHM at 2479 keV without difficulty. Such resolution has already been seen routinely near 1000 keV, and is expected to improve with the square root of the energy [23]. A 4% window centered at Q allows only 2.3×10^{-7} of the $\beta\beta_{2\nu}$ events to spill in. The $\beta\beta_{2\nu}$ spectrum thus limits the $\beta\beta_{0\nu}$ half-life to the $\beta\beta_{2\nu}$ half-life divided by 2.3×10^{-7} (and then multiplied by 0.76 to account for the fraction of the $\beta\beta_{0\nu}$ signal that falls within the FWHM). To take full advantage of this limit one would need enough xenon and run time to produce at least one $\beta\beta_{2\nu}$ count in the $\beta\beta_{0\nu}$ window. At the theoretical ^{136}Xe $\beta\beta_{2\nu}$ half-life of 4.64×10^{21} yr [9], the required source-mass run-time product Mt is ~5000 kg yr. For example, one might run for 5 yr with 1000 kg of ^{136}Xe (a 78 cm fiducial cube of liquid, isotopically enriched to 60%). At ~\$16000/kg [24] for enriched ^{136}Xe it is clear that cost is a more seri-

TABLE I. First and second ionization potentials[a] of Ba and Xe (volts).

	I	II
Ba	5.21	10.00
Xe	12.77	21.2

[a]Reference [30].

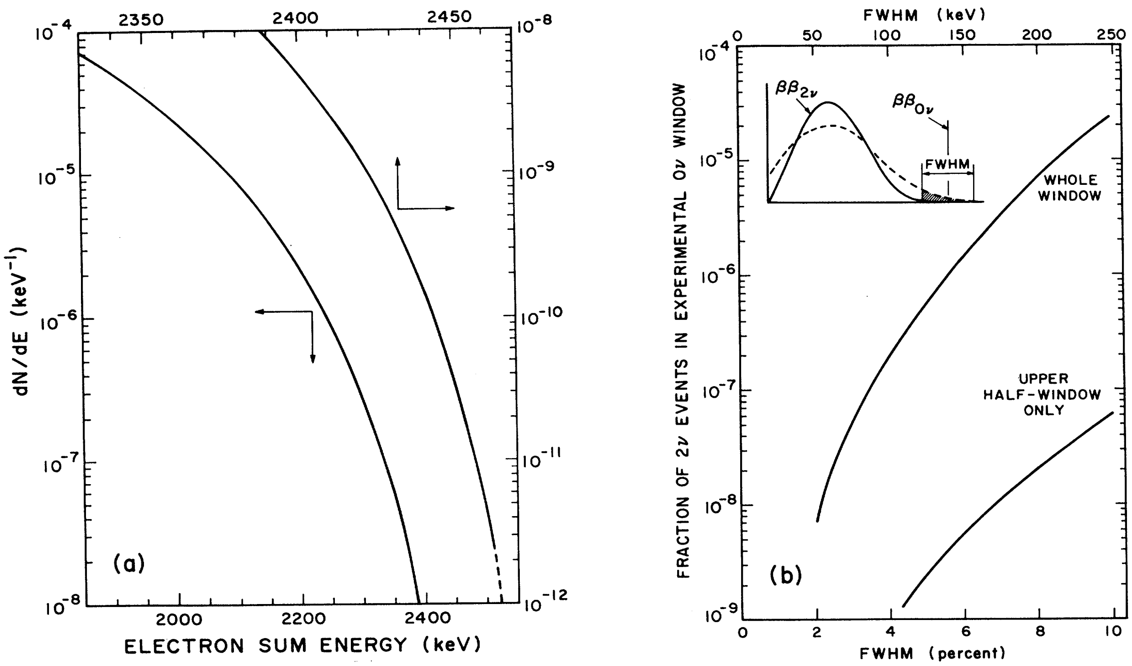

FIG. 2. (a) The high-energy tail of the theoretical $\beta\beta_{2\nu}$ electron sum spectrum for ^{136}Xe, normalized to unity for the whole spectrum from energy = 0 to the Q value at 2479 keV. Calculation courtesy T. Kotani. (b) The fraction of a resolution-broadened $\beta\beta_{2\nu}$ spectrum falling in an experimental FWHM window centered on the expected position of the $\beta\beta_{0\nu}$ spike. For large xenon $\beta\beta_{0\nu}$ experiments, "background" from $\beta\beta_{2\nu}$ must be considered.

ous limitation than interference from $\beta\beta_{2\nu}$.

There are, to be sure, ways other than double-beta decay to create a blob of ionization accompanied by a barium ion. One is Xe(α,n)Ba reactions. For the stable isotopes of xenon the thresholds are between 5.3 and 10.6 MeV—often below the energies of naturally occurring alpha particles of up to 10.5 MeV in the uranium and thorium series. However, the cross sections are strongly suppressed by a Coulomb barrier of 17.5 MeV. There are not enough energetic alpha particles in detector grade xenon to be a problem. Higher-energy alpha particles from spallation by cosmic-ray muons would be vetoed by the muon pulse.

Another source of barium ions accompanied by ionization electrons is the single-beta decay of radioisotopes of cesium. The common fission product, 30 yr ^{137}Cs [which can also arise from ^{136}Xe(n,γ)^{137}Xe followed by beta decay of ^{137}Xe], has a Q value of 1.2 MeV—too low to be of concern. Cs isotopes with Q values greater than 2.1 MeV are all fission products with mass numbers 136 and above [25]. Of these, three have half-lives greater than 65 sec: ^{136}Cs, ^{138}Cs, and ^{139}Cs. Isotopes with shorter half-lives will not have time to migrate into the fiducial volume unless they are born from fission within the xenon itself, in which case the fission event would veto the beta decay.

Scaling from existing experiments [26] indicates that uranium in the xenon could easily be held to $< 10^{-10}$ g/g. In a laboratory such as the Gran Sasso where the thermal-neutron flux [27] is $\sim 10^{-6}$/cm^2 sec, fission by thermal neutrons on uranium in the xenon is completely negligible. The < 25 spontaneous fissions per year from 10^{-10} g/g of ^{238}U in 1000 kg of xenon would yield < 2 atoms each of ^{138}Cs and ^{139}Cs, and a negligible amount of ^{136}Cs [28]. The resulting number of beta particles in a 4% window at 2479 keV is well below one per year.

The heaviest stable xenon isotope being 136 means there is no path to ^{138}Cs, or ^{139}Cs, via ^{A}Xe(n,γ)$^{A+1}$Xe followed by beta decay. Similarly, ^{136}Cs is inaccessible through (n,γ) because there is no stable ^{135}Xe. Although cesium from (α,p), (α,pn), etc., on xenon is strongly suppressed by the Coulomb barrier, spallation alpha particles often do have enough energy to drive these reactions, and the half-lives of the cesium isotopes are too long for a veto by the initiating muon. However, with spallation cross sections for deep-underground muons on the order of 10^{-29} cm^2 per nucleon [29], and a muon flux of ~ 1 (m^2 h)$^{-1}$ at 3600 m water equivalent (e.g., Gran Sasso), high-energy alpha particles are too rare to make significant cesium. Similarly, spallation protons are too few to make troublesome amounts of cesium from (p,n), (p,γ), etc., on xenon, and stopping muons are insufficient to cause significant (μ^+,γ).

Although cesium does not appear to be a background threat, the isotope ^{137}Cs could be purposely introduced to study the efficiency for barium-ion detection. The 2.6 min metastable state in ^{137}Ba would give one a chance to detect the ion and see its presence confirmed by the 0.66 MeV gamma ray or corresponding conversion electron.

Detection of the barium ion in coincidence with the 2.5 MeV energy pulse from the double-beta decay of ^{136}Xe may be a potentially powerful method of eliminating background in the search for the $\beta\beta_{0\nu}$ mode. The utility of the technique depends on the presently unknown spectroscopy of the barium ion in liquid xenon. A test experiment is being assembled. If successful, the method will allow one to relax the requirement for ultrahigh-energy resolution, and concentrate on building a detector of very large mass. A background-free 1000 kg of ^{136}Xe could probe to an effective Majorana mass for the electron neutrino of ~0.01 eV in five years of running.

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