Atomic Data and Nuclear Data Tables **80,** 83–116 (2002)
doi:10.1006/adnd.2001.0873, available online at http://www.idealibrary.com on IDEAL®

TABLES OF DOUBLE BETA DECAY DATA—AN UPDATE

VLADIMIR I. TRETYAK and YURI G. ZDESENKO

Institute for Nuclear Research, MSP 03680 Kiev, Ukraine

Email: vit@tretyak.kiev.ua, zdesenko@kinr.kiev.ua

An updated version of a previous compilation of data on double beta decay is presented. The tables contain the most stringent experimental limits or positive results known on half-lives for 2β transitions to ground and excited states of daughter nuclei for different channels ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε) and modes (0ν; 2ν; 0νM; etc.) of decay. Theoretical estimates are given for comparison as well. The literature has been covered to April 2001. © 2001 Elsevier Science (USA)

0092-640X/01 $35.00

CONTENTS

INTRODUCTION

The six years which have passed since the publication of Ref. [1] have brought many new and exciting results in the field of neutrino physics and, in particular, in the field of double beta (2β) decay research. In fact, neutrino physics has recently undergone a revolution which makes it extremely interesting to search for neutrinoless (0ν) 2β decay. Indeed, the solar neutrino data [2] (including the latest results from the Sudbury Neutrino Observatory which provide evidence on a non-electron-flavor active neutrino component in the solar flux [3]), the measured deficit in the flux of atmospheric muon neutrinos [4], and the results of the LSND accelerator experiment [5] can all be explained by means of neutrino oscillations requiring, in turn, nonzero neutrino masses.[1] According to many scenarios offered by theoretical models for the neutrino mass (m_ν) spectrum (see Ref. [8] and references therein) the current data on oscillation allows the range $0.01 \leq m_\nu \leq 1$ eV [9]. However, oscillation experiments are sensitive to neutrino mass differences, while only the measured $0\nu2\beta$ decay rate can give the absolute scale of the effective Majorana neutrino mass[2] and, hence, provide a crucial test of m_ν models [8, 9].

The $0\nu2\beta$ decay is forbidden in the Standard Model (SM) because it violates lepton number (L) conservation. However, many extensions of the SM—in particular, grand unified theories (GUTs) incorporating L-violating interactions—permit $0\nu2\beta$ decay. Double β decay assumes great conceptual importance as a result of the strong statement obtained in the gauge theory of weak interaction that a nonvanishing $0\nu2\beta$ decay rate, independent of the mechanism that induces it, requires neutrinos to be massive Majorana particles [10]. Currently, besides a conventional left-handed neutrino exchange mechanism, modern gauge theories offer many other possibilities to trigger the $0\nu2\beta$ process [11–13]. For instance, in left–right symmetric GUT models, this process can be mediated by heavy right-handed neutrinos [14–16]. Consequently, 2β experiments are sensitive to right-handed W_R boson masses. Another type of gauge bosons predicted by some GUTs is leptoquarks, which can transform quarks to leptons and induce $0\nu2\beta$ decay via

[1] Another hint of nonzero neutrino mass was obtained in Ref. [6] from consideration of the long-range forces induced by neutrino exchange between nucleons in some massive object (neutron star). Contribution from multibody neutrino exchange can exceed the self-energy of a neutron star, and, to suppress this contribution, a nonzero neutrino mass is needed. In this way a *lower* limit on neutrino mass $m_\nu > 0.4$ eV was derived. The obtained results, however, have been criticized (see Ref. [7] and references therein).

[2] Obviously, its accuracy depends on the uncertainties of the nuclear matrix elements calculation.

leptoquark–Higgs couplings. Thus, restrictions on leptoquark masses and coupling constants can be derived [17]. 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 [18, 19] and, for this reason, compositeness can be checked at low energy. Moreover, there are also possible $0\nu2\beta$ decay mechanisms based on the supersymmetric (SUSY) interactions: exchange of squarks, etc., within R-parity[3] violating SUSY models [20–25] and exchange of sneutrinos, etc., in R-parity conserving SUSY models [26–27]. Consequently, the competitive restrictions on the sneutrino masses, R-parity violating couplings, etc., can be obtained from 2β decay studies.

Therefore, at present, the neutrinoless 2β decay is considered as a powerful test of the new physical effects beyond the SM. The absence of this process yields strong constraints on m_ν, lepton violation constants, and other parameters of the manifold SM extensions. These constraints make it possible to narrow the wide choice of theoretical models and to touch the multi-TeV energy range competitive in some cases to the accelerator experiments [11–13, 28].

Despite numerous efforts since 1948 to detect $0\nu2\beta$ decay [29], this process still remains unobserved.[4] Nevertheless, outstanding experimental results have been obtained during the last decade. First of all, from the total number of 35 potential $0\nu2\beta^-$ decay candidates, 28 have been studied in direct experiments, and the highest half-life limits have been set for several of them: $T_{1/2}^{0\nu} \geq 10^{22}$ yr for ^{82}Se [47] and ^{100}Mo [48]; $T_{1/2}^{0\nu} \geq 10^{23}$ yr for ^{116}Cd [49], ^{128}Te [50], ^{130}Te [50], and ^{136}Xe [51]; and $T_{1/2}^{0\nu} \geq 10^{25}$ yr for ^{76}Ge [52, 53].

In contrast with a neutrinoless process, the allowed $2\nu2\beta$ decay has been observed in direct experiments with seven nuclides: ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, and ^{150}Nd.[5] The measured half-lives are presented in Table A, where the ranges of theoretical $T_{1/2}^{2\nu}$ values determined for each nuclide on the basis of available nuclear matrix elements (NME) calculations are shown for comparison.

[3] 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.

[4] There are several early reviews [30–45], as well as more recent ones [1, 11–13, 28, 46].

[5] Besides, 2β decay branching ratio of ^{238}U was determined by using a radiochemical technique as $T_{1/2}^{2\beta} = (2.0 \pm 0.6) \times 10^{21}$ yr [54], while half-lives of ^{82}Se ($\approx 10^{20}$ yr), ^{96}Zr ($\approx 4\times10^{19}$ yr), ^{128}Te ($\approx 10^{24}$ yr), and ^{130}Te ($\approx 10^{21}$ yr) were measured by geochemical experiments (see Table I). However, these methods cannot distinguish between 0ν and 2ν modes, thus only total 2β decay rates were measured.

Most Sensitive $0\nu2\beta$ Decay Experiments

^{100}Mo

This nuclide has been investigated by several groups (see Refs. [1, 46]). 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 as γ-ray detectors [48]. Two passive, 20 mg/cm^2 thick, ^{100}Mo sources (enrichment $\approx$95%) with a total mass of 171 g were set in the 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 $T_{1/2}^{0\nu} \geq 5.5(10.3) \times 10^{22}$ yr has been obtained at 90% (68%) CL [48].

^{116}Cd

The experiment with ^{116}Cd has been performed by the INR (Kiev)[6] at the Solotvina Underground Laboratory (Ukraine) with $^{116}CdWO_4$ crystal scintillators enriched to 83% in ^{116}Cd. In the latest run, four crystals (total mass 339 g) with energy resolutions (FWHM) of 11.5% at 1064 keV and 8.0% at 2615 keV were used [49]. Passive and active shieldings together with the time-amplitude and pulse-shape analysis of the data lowered the background rate in the energy region 2.5–3.2 MeV to 0.03 counts/yr · kg · keV. On the basis of runs lasting 4629 h, the limits for the $0\nu2\beta$ decay mode were set as $T_{1/2}^{0\nu} \geq 0.7(2.5) \times 10^{23}$ yr at 90% (68%) CL [49].

^{130}Te (^{128}Te)

The Milano group (Milan University and INFN) has used low-temperature detectors (crystal TeO_2 bolometers) to study the 2β decay of ^{130}Te [50]. The detector consists of an array (total mass of 6.8 kg) of 20 TeO_2 crystals ($3\times3\times6$ cm^3 each) which is cooled down to a temperature of $\approx$10 mK by the dilution refrigerator installed in the Gran Sasso Underground Laboratory (Italy). High-purity (HP) electrolytic copper (2.2 cm thick) and low-radioactivity Roman lead (10 cm thick) were utilized as inner shields of the crystals,

[6] From 1998 onwards, this experiment has been carried out by the Kiev–Firenze collaboration.

TABLE A
The $2\nu 2\beta$ Decay Half-Lives Measured in Direct Experiments

Nuclide	Experimental $T_{1/2}^{2\nu}$ (yr)	Signal to background ratio[a]	Reference	Range of calculated $T_{1/2}^{2\nu}$ values (yr)[b]
^{48}Ca	$4.3^{+2.8}_{-1.8}\times10^{19}$	0.2–2.0	[55]	$6\times10^{18}-5\times10^{20}$
	$4.2^{+3.3}_{-1.3}\times10^{19}$	—	[56]	
^{76}Ge	$(9.0\pm1.0)\times10^{20}$	0.1	[57]	$7\times10^{19}-6\times10^{22}$
	$1.1^{+0.6}_{-0.3}\times10^{21}$	0.1	[58]	
	$8.4^{+1.0}_{-0.8}\times10^{20}$	—	[59]	
	$(1.1\pm0.2)\times10^{21}$	—	[60]	
	$(1.8\pm0.1)\times10^{21}$	1.4–4.0	[61]	
^{82}Se	$1.1^{+0.3}_{-0.1}\times10^{20}$	7.9	[47]	$3\times10^{18}-6\times10^{21}$
	$(8.3\pm1.2)\times10^{19}$	1.8	[62]	
^{96}Zr	$2.1^{+0.8}_{-0.4}\times10^{19}$	1.9	[63]	$3\times10^{17}-6\times10^{20}$
^{100}Mo	$3.3^{+2.0}_{-1.0}\times10^{18}$	5.6	[64]	$1\times10^{17}-2\times10^{22}$
	$1.2^{+0.5}_{-0.3}\times10^{19}$	$\simeq0.2$	[65]	
	$(9.5\pm1.0)\times10^{18}$	2.8	[66]	
	$7.6^{+2.2}_{-1.4}\times10^{18}$	0.6	[67]	
	$6.8^{+0.8}_{-0.9}\times10^{18}$	10.9	[68]	
^{116}Cd	$2.6^{+0.9}_{-0.5}\times10^{19}$	0.3	[69]	$3\times10^{18}-2\times10^{21}$
	$2.7^{+1.0}_{-0.7}\times10^{19}$	1.0	[70]	
	$(3.8\pm0.4)\times10^{19}$	3.9	[71]	
	$2.6^{+0.7}_{-0.4}\times10^{19}$	4–15	[49]	
^{150}Nd	$1.9^{+0.7}_{-0.4}\times10^{19}$	4.0	[72]	$6\times10^{16}-4\times10^{20}$
	$(6.8\pm0.8)\times10^{18}$	6.3	[68]	

[a] The values of the signal-to-background ratio (or their ranges corresponding to different energy intervals) are given as estimated by the authors of the original works.
[b] See Table I and Ref. [1] for references to calculated results.

while the refrigerator itself 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 $0\nu 2\beta$ decay of ^{130}Te ($Q_{\beta\beta} = 2529$ keV) was about 0.5 counts/yr · kg · keV. The data were accumulated for 62,995 h × crystals, resulting in 0.66 kg × yr statistics for ^{130}Te. The lower limit $T_{1/2}^{0\nu} \geq 1.44 \times 10^{23}$ yr at 90% CL was established for $0\nu 2\beta$ decay of ^{130}Te, while $T_{1/2}^{0\nu} \geq 8.6 \times 10^{22}$ yr at 90% CL was set for ^{128}Te [50].

^{136}Xe

The Caltech–Neuchatel–PSI collaboration has built a time projection chamber (TPC) with an active volume of 180 liters containing 24.2 moles (3.3 kg) of Xe gas (enriched to 62.5% in ^{136}Xe) at a pressure of 5 atm [51]. The FWHM energy resolution of the detector was 6.6% at the transition energy ($Q_{\beta\beta} = 2468$ keV). The track reconstruction capability of the TPC provided an efficient rejection of the background, which was reduced to ≈0.02 counts/yr · kg · keV around 2.48 MeV (within a FWHM energy interval). From 6830 + 6013 h (or 4.9 kg × 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% CL has been set [51].

^{76}Ge

Currently there are two large ^{76}Ge experiments being performed by the IGEX [73] and by the Heidelberg–Moscow [52] collaborations. (i) The IGEX is operating three 2-kg HP Ge detectors (enriched to ≈88% in ^{76}Ge) in the Canfranc Underground Laboratory (Spain). The shield consists of 2.5 tons of archaeological lead and 10 tons of 70-yr-old low-activity lead, with a plastic scintillator as a cosmic muon veto. The pulse-shape discrimination technique is applied to the data. The background rate is ≈0.06 counts/yr · kg · keV (within the energy interval 2.0–2.5 MeV). The combined energy resolution for the $0\nu 2\beta$ peak ($Q_{\beta\beta} = 2039$ keV) is 4 keV. Analysis of 116.75 mol × yr (or 8.87 kg × yr in ^{76}Ge) of data yielded a lower bound $T_{1/2}^{0\nu} \geq 1.57 \times 10^{25}$ yr at 90% CL [53]. (ii) The Heidelberg–Moscow experiment in the Gran Sasso Underground Laboratory uses five HP Ge detectors (enriched to 86% in ^{76}Ge) with a total active mass of 10.96 kg (125.5 moles of ^{76}Ge). Passive and active shieldings, as well as pulse-shape analysis (PSA), allow the reduction of background rate in the energy region of interest to ≈0.06 counts/yr · kg · keV. The energy resolution at 2039 keV is 4 keV. From the analysis of 24 kg×yr of data, a limit of $T_{1/2}^{0\nu} \geq 1.6 \times 10^{25}$ yr with 90% CL has been set for ^{76}Ge [52].

TABLE B
Best Reported $T_{1/2}^{0\nu}$ and m_ν Limits from Direct 2β Decay Experiments

Nuclide	Experimental limit $T_{1/2}^{0\nu}$ (yr) 68% CL	90% CL	Reference	Limit on m_ν (eV) after Ref. [74] 68% CL	90% CL	Range of m_ν limit (eV) 90% CL
^{76}Ge	2.8×10^{25}	1.6×10^{25}	[52]	0.29	0.38	0.33−2.5
	—	1.6×10^{25}	[53]	—	0.38	0.33−2.5
^{100}Mo	1.0×10^{23}	5.5×10^{22}	[48]	3.6	4.9	1.4−256
^{116}Cd	2.5×10^{23}	7.0×10^{22}	[49]	1.4	2.6	2.4−8.4
^{130}Te	—	1.4×10^{23}	[50]	—	1.9	1.1−6.4
^{136}Xe	—	4.4×10^{23}	[51]	—	2.2	0.8−5.2

Discussion

The half-life 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 B. The m_ν constraints are presented in two ways: (i) in Column 4, the m_ν limits are determined on the basis of NME calculation of Staudt et al.[7] [74]; and (ii) in Column 5, the ranges of m_ν limits are estimated by using all available NME calculations[8] (see Table I and Ref. [1] for detailed references).

It is obvious from Table B that ^{76}Ge studies, in which limits of $T_{1/2}^{0\nu} \geq 10^{25}$ yr have been reached, have placed the most stringent restrictions on the neutrino mass at the level of ∼0.5 eV. Even though the $T_{1/2}^{0\nu}$ limits with ^{116}Cd, ^{130}Te, and ^{136}Xe are much lower at around 10^{23} yr, the m_ν bounds are in the range of 2–3 eV [74], which are not so drastically different from the limit in the case of ^{76}Ge. (Because the $Q_{\beta\beta}$ value of ^{76}Ge (2039 keV) is low, its 2β phase space integral (and consequently $0\nu2\beta$ decay probability) is about seven times smaller than those of ^{116}Cd and ^{130}Te [13].)

These $0\nu2\beta$ results have already brought the most stringent restrictions on the right-handed admixtures in the weak interaction $\eta \simeq 10^{-7}$, $\lambda \simeq 10^{-5}$, and on the neutrino–Majoron coupling constant $g_M \simeq 10^{-4}$. However, on the basis of the current status of astroparticle physics (and neutrino physics, in particular) it is very desirable to improve the present level of sensitivity further by 1–2 orders of magnitude [8, 12, 28, 75].

[7] The NMEs of Ref. [74] were chosen because of the most extensive list of 2β candidate nuclei calculated in this work on the basis of the QRPA formalism, which allows to compare the sensitivity of different experiments to the m_ν within the same scale.

[8] We are using the second presentation following Ref. [28]: "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."

Future Projects

There are several reasons why improvements in sensitivity should be attempted for several nuclei: (i) The $0\nu2\beta$ decay is still an elusive phenomenon. Despite the progress in theoretical treatment, there are large discrepancies (up to three orders of magnitude) between calculated and already measured half-lives of $2\nu2\beta$ decay of ^{48}Ca, ^{76}Ge, ^{82}Se, ^{96}Zr, ^{100}Mo, ^{116}Cd, and ^{150}Nd (see Table A). It is unlikely that the predictive ability of the theory for an unobserved $0\nu2\beta$ decay can be much better than that for the $2\nu2\beta$ decay; therefore, several candidate nuclides should be studied. (ii) Research on 2β decay is at the frontier of modern technology. No one can *a priori* predict where the highest sensitivity would be reached. New advanced experimental techniques could bring an advantage to a particular 2β decay candidate. (iii) Studying a wide set of nuclei becomes even more important if $0\nu2\beta$ decay is observed in one experiment. Such a discovery has to be confirmed with other nuclides and by using another experimental technique, which should be properly developed by then. However, because of the extremely low background nature of the 2β decay experiments, such a development is a multistage and rather long process. For instance, the first valuable result with ^{76}Ge was obtained in 1970 as $T_{1/2}^{0\nu} \geq 10^{21}$ yr [76]. As a result of intensive R&D performed by several groups, this limit was advanced to $T_{1/2}^{0\nu} \geq 10^{25}$ yr in 2000 [52, 53]. Thus the improvement in sensitivity by four orders of magnitude was reached after 30 years of strong efforts.

Many projects have been proposed during the past few years with regard to these goals. An interesting approach to study 2β decay of ^{136}Xe was suggested [77, 78] in 1991, which makes use of the coincident detection of $^{136}Ba^{2+}$ ions (the final state of ^{136}Xe decay on the atomic level)[9] and the

[9] The idea of detecting $^{136}Ba^{2+}$ ions with the aim to determine the 2β decay rate of ^{136}Xe was presented for the first time in Ref. [79].

$0\nu2\beta$ signal with the energy of 2.5 MeV in a TPC filled with liquid or gaseous Xe. Resonance Ionization Spectroscopy (RIS) was proposed for the identification of $^{136}Ba^{2+}$ ions in the liquid Xe drift ionization chamber [80]. Recently, the EXO project has been considered [81], in which the coincident detection 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). Estimated sensitivity of such an apparatus to neutrino mass is ≈0.01 eV [81]. Another proposal (originating from Raghavan's idea [82]) is to dissolve ≈80 kg (≈1.5 tons) of enriched (natural) Xe in the liquid scintillator of the BOREXINO Counting Test Facility (CTF), where a $T_{1/2}^{0\nu}$ limit in the range of 10^{24}–10^{25} yr could be reached [83].

The project MOON aims to make both the study of $0\nu2\beta$ decay of ^{100}Mo and the real time studies of low-energy solar ν by inverse β decay [84]. The detector module will be composed of ≈60,000 plastic scintillators (6 m × 0.2 m × 0.25 cm), the light outputs from which are collected by 866,000 wavelength shifter fibers (1.2 mm diameter × 6 m long), viewed through clear fibers by 6800 16-anode photomultiplier tubes. 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 a foil with a thickness ≈50 mg/cm^2 and purified to the level of 1 μBq/kg for ^{232}Th and ^{238}U. The sensitivity of such a module to the neutrino mass could be of the order of $m_\nu \approx$ 0.05 eV [84].

The nucleus ^{160}Gd ($Q_{\beta\beta} = 1730$ keV) is an attractive candidate because of its favorable theoretical value of $T_{1/2}^{0\nu} \cdot \langle m_\nu \rangle^2 = 8.6 \times 10^{23}$ yr · eV^2 [74] and rather large natural abundance (21.9%), allowing the construction of a sensitive apparatus with natural $Gd_2SiO_5 : Ce$ crystal scintillators (GSO). An experiment using the GSO multicrystal array with a total mass of 1–2 tons (≈200–400 kg of ^{160}Gd) has been suggested with the projected sensitivity of $T_{1/2}^{0\nu} \approx 5 \times 10^{26}$ yr ($m_\nu \leq 0.07$ eV) [85]. Such an experimental technique could also be of great interest for solar neutrino spectroscopy with ^{160}Gd [86]. Hence, even a larger setup with ≈30 t of the GSO crystals (needed for the solar neutrino detection) could become available, enhancing the sensitivity of the by-product $0\nu2\beta$ decay study of ^{160}Gd to the level of $m_\nu \leq 0.02$ eV [85] at the same time.

The DCBA project is under development in KEK (Japan) [87]. 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 with three-dimensional reconstruction of tracks. With a passive source (50 mg/cm^2) of 18-kg-enriched ^{150}Nd ($Q_{\beta\beta} =$ 3367 keV), the projected sensitivity to the Majorana neutrino mass is ≈0.05 eV [87].

Using future large-scale Yb-loaded liquid scintillation detectors for solar neutrino spectroscopy (LENS [86]), it is proposed to search for $2\beta^-$ decay of ^{176}Yb ($Q_{\beta\beta} =$ 1087 keV) and $\varepsilon\beta^+$ decay of ^{168}Yb ($Q_{\beta\beta} = 1422$ keV). With about 20 tons of natural Yb (≈2.5 tons of ^{176}Yb) the limit $T_{1/2}^{0\nu} \geq 10^{26}$ yr could be set on $0\nu2\beta$ decay of ^{176}Yb ($m_\nu \leq$ 0.1 eV) [88].

There are two new approaches: induced 2β decay[10] and 2β decay of α and β unstable nuclei. In the first process, the 2ν mode is induced by neutrinos (antineutrinos) and positrons (electrons) for $2\beta^-$ ($2\beta^+$) decay,[11] while the 0ν mode is 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 is enhanced rapidly with the incident electron energy [92]. The second approach is the search for 2β decay of α or β unstable nuclei whose $Q_{\beta\beta}$ values are much higher than those for α or β stable 2β candidates.[12] The probability of $0\nu2\beta$ decay is proportional to the fifth power of $Q_{\beta\beta}$. Therefore, taking the cases of ^{19}B and ^{22}C ($Q_{\beta\beta} \simeq 43$ MeV [93]) as examples, their $0\nu2\beta$ decay rates would be 4×10^6 times faster than that for ^{76}Ge with $Q_{\beta\beta} \simeq 2$ MeV (for equal NMEs). However, because of the enormous difficulty of accumulating large amounts of fast-decaying parent nuclide and difficulties in detecting 2β decay in the presence of intensive β background, no reliable schemes of such experiments have been proposed till now. Not only the latest two proposals but also all projects mentioned above require a significant amount of R&D to demonstrate their feasibility.

There are two projects, NEMO-3 [94] and CUORICINO [95], under construction now. The NEMO-3 apparatus will allow direct detection of two electrons by a tracking device (6180 drift cells) and measurement of their energies by 1940 large blocks of plastic scintillators. Up to 10 kg of ^{100}Mo

---

[10] To our knowledge, 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 for the first time in connection with the background in geochemical 2β decay experiments [89]. Capture rates of solar ν's (earth's $\bar{\nu}$'s) estimated for the set of $2\beta^-$ ($2\beta^+$) nuclides yielded induced $T_{1/2}$ values in the range of 10^{27-29} yr (10^{28-30} yr) [89].

[11] The use of a reactor (accelerator) neutrino beam or an artificial radioactive ν_e source (similar to ^{51}Cr) to induce such a reaction has been proposed recently [90, 91].

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

(passive source with the equivalent thickness of ≈60 mg/cm^2) will be placed between two concentric cylindrical tracking volumes. The energy resolution of the calorimeter at 3 MeV is 8.8%. For 5 yr measuring time and with 7 kg of ^{100}Mo source, the sensitivity of the NEMO-3 detector would be on the level of $T_{1/2}^{0\nu} \geq 4 \times 10^{24}$ yr ($m_\nu \leq 0.3$–0.7 eV) [96].

The CUORICINO setup will contain 56 low-temperature bolometers made of TeO_2 crystals (750 g each) with a total mass of 42 kg cooled down to a temperature of ≈10 mK by the dilution refrigerator. The projected CUORICINO sensitivity is $T_{1/2}^{0\nu} \geq 10^{24}$–$10^{25}$ yr or $m_\nu \leq 0.1$–0.5 eV [95, 97]. The main goal of the CUORICINO setup is to be a pilot step for a future CUORE project, which would contain one thousand TeO_2 bolometers with total mass 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, because of the complexity of cryogenic technique (which requires the use of many different construction materials) the CUORE sensitivity is quoted by authors for different background rates (0.5–0.05 counts/yr · kg · keV at 2.5 MeV) and would be as high as $T_{1/2}^{0\nu} \geq (1-5) \times 10^{25}$ yr or $m_\nu \leq 0.05$–0.2 eV [95, 97].

Recently a realistic project CAMEO has been suggested [98], where the unique features (super-low background and large sensitive volume) of the CTF (already existing device) and the BOREXINO setup (under construction) could be used to study ^{116}Cd. It is supposed that ≈100 kg of enriched $^{116}CdWO_4$ crystal scintillators would be placed in the liquid scintillator of the CTF. The calculated sensitivity of the CAMEO experiment (in terms of the $T_{1/2}^{0\nu}$ limit) is ≈10^{26} yr, which translates into $m_\nu \leq 0.06$ eV. Similarly, the constraint on the neutrino mass could be pushed down to $m_\nu \leq 0.02$ eV [98] with one ton of $^{116}CdWO_4$ crystals located in the BOREXINO apparatus.

In addition, three large-scale projects involving ^{76}Ge are under discussion. The MAJORANA proposal [99] will use around 500 kg of HP Ge semiconductor detectors (enriched in ^{76}Ge) in a more or less standard setup, where all known methods of background reduction would be applied.

The GENIUS project [100] intends to operate 1000 kg of high-purity Ge (enriched in ^{76}Ge) detectors placed in a tank (12 m diameter × 12 m high) with about 1000 t of extremely high-purity liquid nitrogen (required demands on its radioactive contamination are ≈10^{-15} g/g for ^{40}K, ^{238}U, and ^{232}Th and 0.05 mBq/m^3 for ^{222}Rn) serving simultaneously as a cooling medium and shielding for the detectors. With ≈7×10^{27} nuclei of ^{76}Ge, a sensitivity of $T_{1/2}^{0\nu} \geq \approx 10^{28}$ yr ($m_\nu \leq 0.015$–0.05 eV) could be reached [100].

To simplify the ^{76}Ge experiment, the GEM project has been proposed [101], in which 1000 kg of "naked" HP Ge detectors (enriched in ^{76}Ge) would be operating in the ultra-high-purity liquid nitrogen (40 t) contained in the copper vacuum cryostat. The latter is shielded by high-purity water to suppress external background. The projected sensitivity is $T_{1/2}^{0\nu} \geq 10^{28}$ yr, which corresponds to the neutrino mass constraints $m_\nu \leq 0.015$–0.05 eV [101].

Acknowledgment

We gratefully appreciate fruitful discussions with Professor F. Boehm and his suggestions, which helped us to improve the manuscript.

References

1. V. I. Tretyak and Yu. G. Zdesenko, Atomic Data and Nuclear Data Tables **61**, 43 (1995)
2. T. A. Kirsten, Rev. Mod. Phys. **71**, 1213 (1999)
3. J. Farine (SNO Collaboration), talk at III Int. Conf. on Non-Accelerator New Physics, NANP'01, 19–23 June 2001, Dubna, Russia; Q. R. Ahmad et al. (SNO Collaboration), available at http://www.sno.phy.queenssu.ca/sno/first_results
4. Y. Fukuda et al. (Super-Kamiokande Collaboration), Phys. Rev. Lett. **81**, 1562 (1998); **82**, 1810 (1999); **82**, 2430 (1999)
5. E. D. Church (for the LSND Collaboration), Nucl. Phys. A **663/664**, 799c (2000)
6. E. Fischbach, Ann. Phys. **247**, 213 (1996)
7. A. Abada, O. Pene, and J. Rodriguez-Quintero, Phys. Rev. D **59**, 077302 (1999)
8. H. V. Klapdor-Kleingrothaus, H. Pas, and A. Yu. Smirnov, Phys. Rev. D **63**, 073005 (2001)
9. S. M. Bilenky, C. Giunti, W. Grimus, B. Kayser, and S. T. Petcov, Phys. Lett. B **465**, 193 (1999)
10. J. Schechter and J. W. F. Valle, Phys. Rev. D **25**, 2951 (1982)
11. A. Faessler and F. Simkovic, J. Phys. G: Nucl. Part. Phys. **24**, 2139 (1998)

12. H. V. Klapdor-Kleingrothaus, Int. J. Mod. Phys. A **13**, 3953 (1998)

13. J. Suhonen and O. Civitarese, Phys. Rep. **300**, 123 (1998)

14. M. Doi, T. Kotani, H. Nishiura, and E. Takasugi, Prog. Theor. Phys. Suppl. **69**, 602 (1983)

15. M. Hirsch, H. V. Klapdor-Kleingrothaus, and O. Panella, Phys. Lett. B **374**, 7 (1996)

16. R. N. Mohapatra, Nucl. Phys. B (Proc. Suppl.) **77**, 376 (1999)

17. M. Hirsch, H. V. Klapdor-Kleingrothaus, and S. G. Kovalenko, Phys. Rev. D **54**, 4207 (1996)

18. N. Cabibbo, L. Maiani, and Y. Srivastava, Phys. Lett. B **139**, 459 (1984)

19. O. Panella, C. Carimallo, Y. N. Srivastava, and A. Widom, Phys. Rev. D **56**, 5766 (1997)

20. R. Mohapatra, Phys. Rev. D **34**, 3457 (1986)

21. J. D. Vergados, Phys. Lett. B **184**, 55 (1987)

22. M. Hirsch, H. V. Klapdor-Kleingrothaus, and S. G. Kovalenko, Phys. Rev. D **53**, 1329 (1996); Phys. Lett. B **372**, 181 (1996)

23. A. Faessler, S. Kovalenko, F. Simkovic, and J. Schwieger, Phys. Rev. Lett. **78**, 183 (1997)

24. A. Faessler, S. Kovalenko, and F. Simkovic, Phys. Rev. D **58**, 055004 (1998); **58**, 115004 (1998)

25. A. Wodecki, W. A. Kaminski, and F. Simkovic, Phys. Rev. D **60**, 115007 (1999)

26. M. Hirsch, H. V. Klapdor-Kleingrothaus, and S. G. Kovalenko, Phys. Lett. B **398**, 311 (1997); **403**, 291 (1997)

27. M. Hirsch, H. V. Klapdor-Kleingrothaus, St. Kolb, and S. G. Kovalenko, Phys. Rev. D **57**, 2020 (1998)

28. P. Vogel, nucl-th/0005020 9 May 2000; in *Current Aspects of Neutrino Physics*, edited by D. Caldwell (Springer-Verlag, Berlin/New York, 2000) chap. 8

29. E. Fireman, Phys. Rev. **74**, 1238 (1948)

30. Ya. B. Zel'dovich, S. Yu. Luk'ianov, and Ya. A. Smorodinskii, Usp. Fiz. Nauk **54**, 361 (1954)

31. H. Primakoff and S. P. Rosen, Rep. Prog. Phys. **12**, 121 (1959)

32. G. F. Dell'Antonio and E. Fiorini, Suppl. Nuovo Cim. **17**, 132 (1960)

33. E. Fiorini, Riv. Nuovo Cim. **2**, 1 (1972)

34. D. Bryman and C. Picciotto, Rev. Mod. Phys. **50**, 11 (1978)

35. Yu. G. Zdesenko, Sov. J. Part. Nucl. **11**, 542 (1980)

36. H. Primakoff and S. P. Rosen, Annu. Rev. Nucl. Part. Sci. **31**, 145 (1981)

37. M. Doi, T. Kotani, H. Nishiura, K. Okuda, and E. Takasugi, Prog. Th. Phys. **66**, 1739 (1981); **66**, 1765 (1981)

38. See [Hax84] in the REFERENCES FOR TABLES

39. M. G. Schepkin, Sov. Phys. Usp. **27**, 555 (1984)

40. M. Doi, T. Kotani, and E. Takasugi, Prog. Theor. Phys. Suppl. **83**, 1 (1985)

41. J. D. Vergados, Phys. Rep. **133**, 1 (1986)

42. F. T. Avignone III and R. L. Brodzinski, Prog. Part. Nucl. Phys. **21**, 99 (1988)

43. A. Faessler, Prog. Part. Nucl. Phys. **21**, 183 (1988)

44. T. Tomoda, Rep. Prog. Phys. **54**, 53 (1991)

45. F. Boehm and P. Vogel, *Physics of Massive Neutrinos*, 2nd ed. (Cambridge Univ. Press, Cambridge, UK, 1992)

46. M. Moe and P. Vogel, Annu. Rev. Nucl. Part. Sci. **44**, 247 (1994)

47. See [Ell92] in the REFERENCES FOR TABLES

48. See [Eji01] in the REFERENCES FOR TABLES

49. See [Dan00] in the REFERENCES FOR TABLES

50. See [Ale00] in the REFERENCES FOR TABLES

51. See [Lue98] in the REFERENCES FOR TABLES

52. See [Bau99] in the REFERENCES FOR TABLES

53. See [Gon00] in the REFERENCES FOR TABLES

54. See [Tur91] in the REFERENCES FOR TABLES

55. See [Bal96] in the REFERENCES FOR TABLES

56. See [Bru00] in the REFERENCES FOR TABLES

57. See [Vas90a] in the REFERENCES FOR TABLES

58. See [Mil90] in the REFERENCES FOR TABLES

59. See [Bro93] in the REFERENCES FOR TABLES

60. See [Aal96] in the REFERENCES FOR TABLES

61. See [Gun97] in the REFERENCES FOR TABLES

62. See [Arn98] in the REFERENCES FOR TABLES

63. See [Arn99] in the REFERENCES FOR TABLES

64. See [Vas90b] in the REFERENCES FOR TABLES

65. See [Eji91] in the REFERENCES FOR TABLES

66. See [Das95] in the REFERENCES FOR TABLES

67. See [Als97] in the REFERENCES FOR TABLES

68. See [Sil97] in the REFERENCES FOR TABLES

69. See [Eji95] in the REFERENCES FOR TABLES

70. See [Dan95] in the REFERENCES FOR TABLES

71. See [Arn96] in the REFERENCES FOR TABLES

72. See [Art95] in the REFERENCES FOR TABLES

73. C. E. Aalseth, F. T. Avignone III, R. L. Brodzinski, J. I. Collar, E. Garcia, D. Gonzalez, F. Hasenbalg, W. K. Hensley, I. V. Kirpichnikov, A. A. Klimenko, H. S. Miley, A. Morales, J. Morales, A. Ortiz de Solorzano, S. B. Osetrov, V. S. Pogosov, J. Puimedon, J. H. Reeves, A. Salinas, M. L. Sarsa, A. A. Smolnikov, A. S. Starostin, A. G. Tamanyan, A. A. Vasenko, S. I. Vasiliev, and J. A. Villar, Phys. Rev. C **59**, 2108 (1999)

74. See [Sta90] in the REFERENCES FOR TABLES

75. K. Zuber, Phys. Rep. **305**, 295 (1998)

76. E. Fiorini, A. Pullia, G. Bertolini, F. Cappellani, and G. Restelli, Lett. Nuovo Cimento **3**, 149 (1970)

77. M. K. Moe, Phys. Rev. C **44**, 931 (1991)

78. M. Miyajima, S. Sasaki, and H. Tawara, KEK Proc. **91–5**, 19 (1991)

79. L. W. Mitchel and N. Winograd, Bull. Am. Phys. Soc. **31**, 1219 (1986)

80. M. Miyajima, S. Sasaki, H. Tawara, and E. Shibamura, AIP Conf. Proc. **338**, 253 (1997)

81. M. Danilov, R. DeVoe, A. Dolgolenko, G. Giannini, G. Gratta, P. Picchi, A. Piepke, F. Pietropaolo, P. Vogel, J.-L. Vuilleumier, Y.-F. Wang, and O. Zeldovich, Phys. Lett. B **480**, 12 (2000)

82. R. S. Raghavan, Phys. Rev. Lett. **72**, 1411 (1994)

83. B. Caccianiga and M. G. Giammarchi, Astropart. Phys. **14**, 15 (2000)

84. H. Ejiri, J. Engel, R. Hazama, P. Krastev, N. Kudomi, and R. G. H. Robertson, Phys. Rev. Lett. **85**, 2917 (2000)

85. See [Dan01] in the REFERENCES FOR TABLES

86. M. Cribier (for the LENS Collaboration), Nucl. Phys. B (Proc. Suppl.) **87**, 195 (2000)

87. N. Ishihara, T. Inagaki, T. Ohama, K. Omata, S. Takeda, Y. Yamada, T. Emura, R. Itoh, Y. Kato, Y. Sakamoto, K. Shimada, N. Tamura, and S. Kitamura, Nucl. Instrum. Meth. A **443**, 101 (2000); **373**, 325 (1996)

88. K. Zuber, Phys. Lett. B **485**, 23 (2000)

89. G. Bozoki and K. Lande, Il Nuovo Cim. B **12**, 65 (1972)

90. S. V. Semenov, Yu. V. Gaponov, and R. U. Khafizov, Phys. At. Nucl. **61**, 1277 (1998)

91. L. V. Inzhechik, Yu. V. Gaponov, and S. V. Semenov, Phys. At. Nucl. **61**, 1282 (1998)

92. K. Muto, Czech. J. Phys. **48**, 197 (1998)

93. G. Audi and A. H. Wapstra, Nucl. Phys. A **595**, 409 (1995)

94. F. Piquemal (for the NEMO Collaboration), Nucl. Phys. B (Proc. Suppl.) **77**, 352 (1999)

95. E. Fiorini, Phys. Rep. **307**, 309 (1998)

96. NEMO Collaboration, hep-ex/0006031 26 Jun 2000

97. G. Gervasio (for the CUORE Collaboration), Nucl. Phys. A **663&664**, 873c (2000)

98. G. Bellini, B. Caccianiga, M. Chen, F. A. Danevich, M. G. Giammarchi, V. V. Kobychev, B. N. Kropivyansky, E. Meroni, L. Miramonti, A. S. Nikolayko, L. Oberauer, O. A. Ponkratenko, V. I. Tretyak, S. Yu. Zdesenko, and Yu. G. Zdesenko, Phys. Lett. B **493**, 216 (2000)

99. MAJORANA project website: http://majorana.pnl.gov

100. H. V. Klapdor-Kleingrothaus, J. Hellmig, and M. Hirsch, J. Phys. G: Nucl. Part. Phys. **24**, 483 (1998)

101. Yu. G. Zdesenko, O. A. Ponkratenko, and V. I. Tretyak, nucl-ex/0106021 26 Jun 2001; J. Phys. G: Nucl. Part. Phys., in press (2001)

Published online November 26, 2001

POLICIES

Literature Coverage

All available experimental papers, including refereed journal articles (which were strongly preferred), conference proceedings, preprints, and theses, were covered up to April, 2001. If the same data have been described in several papers, we give only the most extensive and recent reference. We present in the table all known positive results on 2β searches, whereas, in the case of limits on $T_{1/2}$, we give only the most stringent current experimental bounds. We quote theoretical half-lives for the most popular neutrino mass mechanism only and for a few theoretical models, giving a sense of the theoretical uncertainties. The sources with the most extensive lists of calculated nuclei were used, enabling a comparison with theoretical values for different 2β isotopes obtained by the same approach. Additional theoretical calculations are referenced in the Introduction; among them, recent theoretical reviews [11, 13] represent intensive sources of $T_{1/2}$ calculations for 2β decay resulting from other mechanisms such as right-handed currents, etc. Theoretical results published before 1995, which were included in the previous issue of these tables [1], were removed from the present issue. However, we have added several relevant theoretical calculations from before 1995 which were missed in our previous publication.

Data Presentation

All values of half-lives in the Table are rounded to the second decimal place. We regard this as the accuracy achievable with current experimental techniques.

Uncertainties

The full uncertainty is calculated as the square root of the sum of squares of systematic and statistical uncertainties (if both were presented in the original paper).

Confidence Levels

Confidence level (CL) is given *only* if it was quoted in the original paper. If several limits on the half-life were calculated for different CL in the article, only the limit with the higher CL is chosen for presentation in Table I. No efforts have been made to recalculate all data for the same confidence level.

In the current updated version of the 2β tables, we do not repeat formulas for energy and angular distributions of electrons in various modes of 2β decay, nor show the set of graphs representing various 2β decay data; they as well as older experimental and theoretical results can be found in the previous issue of the tables [1].

EXPLANATION OF TABLES

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

In Table I, the most stringent known experimental limits or positive results for 2β decay half-lives are given for transitions from parent ground states to daughter ground and excited states. Listed are 69 double β unstable nuclides present in natural isotopic composition of elements; these include 7 for which neither experimental nor theoretical results have yet been reported. The cutoff date for this compilation is April, 2001.

Theoretical estimates of half-lives are presented for comparison. For 0ν decay, the theoretical half-lives are given for the (light) neutrino mass mechanism with $m_\nu = 1$ eV. For 0ν decay with Majoron emission, the neutrino–Majoron coupling constant is set to $g_M = 1 \times 10^{-5}$.

A	Mass number
Z	Atomic number
X, Y	Element symbols
ΔM_A in keV	Mass difference between parent and daughter atoms (with uncertainty in parentheses) taken from [Aud95]; if recent experimental measurements of ΔM_A are known, the results are given in addition together with the reference source
δ in %	Abundance of parent nuclide (with uncertainty in parentheses) taken from [Ros98]
Type of result	
Exp.	Experimental values
Th.	Theoretical estimates
Decay channel	
$2\beta^-$	Double electron decay
$2\beta^+$	Double positron decay
$\varepsilon\beta^+$	Electron capture and β^+ decay
$K\beta^+$	Electron capture from K shell and β^+ decay
2ε	Double electron capture
$2K$	Double electron capture from K shell
$2L$	Double electron capture from L shell
KL	Double electron capture in which one electron is captured from the K shell and another from the L shell
$J_n^\pi(E$ (level))	Level of daughter nucleus with spin J, parity π, and ordinal number n; the level energy in keV is given in parentheses [ToI78, ToI96]
g.s.	Ground state
$2_1^+, 0_1^+, \ldots$	Excited levels of daughter nucleus
Decay mode	
2ν	Two-neutrino mode of process
0ν	Neutrinoless mode of process
$0\nu(m_\nu)$	Neutrinoless decay due to nonzero neutrino mass
$0\nu(\lambda), 0\nu(\eta)$	Neutrinoless decay due to right-handed currents
0νM1	Neutrinoless mode with emission of Majoron; the distribution of the sum of electron initial energies is given by the formula $F(T) = (T^4 + 10T^3 + 40T^2 + 60T + 30)T(T_0 - T)^{\mathrm{SI}}$ with spectral index SI = 1
0νM3	Neutrinoless mode with double Majoron emission (or emission of vector or charged Majorons, etc.); SI = 3 in the formula for $F(T)$
0νM7	Neutrinoless mode with Majoron(s) emission with spectral index SI = 7 in the formula for $F(T)$
$T_{1/2}$ (yr)	The 2β decay half-life in years

EXPLANATION OF TABLES continued

CL or Theor.	For experimental results, confidence level (CL) is given; for theoretical values, the approach model in which the result was obtained, is quoted:
GSM	Generalized Seniority Model
HFB	Hartree–Fock–Bogoliubov model
IBM	Interacting Boson Model
IQM	Independent Quasiparticle Model
MCM	Multiple Commutator Model
OEM	Operator Expansion Method
PSE	Phase Space Estimate (with Nuclear Matrix Element = 1)
pSU(3)	Pseudo SU(3) model for deformed nuclei
QCM	Quark Confinement Model
QRPA	(One of the modification of the) Quasiparticle Random Phase Approximation
RPA	Random Phase Approximation
SM	Shell Model
SSDH	Single State Dominance Hypothesis
SU(4)	SU(4) approach
Reference	The data source keyed to the list of References for Tables
Note	Additional information is given as a footnote corresponding to the given letter

TABLE II. List of Known 2β Unstable Nuclides Absent in Natural Isotopic Composition of Elements

Table II contains the list of 19 other known 2β unstable nuclides [ToI96] which are absent in natural isotopic composition of elements because of short half-life decays through other channels. Only "conventional" 2β decaying candidate nuclides are listed: for these, the intermediate nucleus $(A, Z \pm 1)$ has larger mass than initial (A, Z) and final $(A, Z \pm 2)$ nuclei.

Parent nuclide	A, Z, and element symbol of 2β unstable nuclide
Main channel of decay and $T_{1/2}$	Principal decay channel and observed half-life of the parent nuclide, from [ToI96]
α	Alpha decay
$^{14}_{6}$C	Decay with emission of $^{14}_{6}$C cluster
sf	Spontaneous fission
yr, d, ...	Half-life given in years, days, ...
Potential 2β transition and daughter nuclide	Possible 2β decay channels, and A, Z and element symbol of daughter nuclide
ΔM_A	Mass difference between parent and daughter atoms in keV (with uncertainty in parentheses) taken from [Aud95].

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$X$-{}^{A}_{Z\pm2}$Y ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Reference	Note
${}^{36}_{18}$Ar$-{}^{36}_{16}$S	Exp.	2ε			–			
433.5(0.4)	Th.	2ε	g.s.	2ν	$= 1.7 \times 10^{29}$	SM	Nak96	
0.3365(0.0030)								
${}^{40}_{20}$Ca$-{}^{40}_{18}$Ar	Exp.	2ε	g.s.	0ν	$> 3.0 \times 10^{21}$	90	Bel99a	
193.78(0.29)				2ν	$> 5.9 \times 10^{21}$	90	Bel99a	
96.941(0.156)	Th.	2ε	g.s.		$= 1.2 \times 10^{33}$	SM	Chi84	
${}^{46}_{20}$Ca$-{}^{46}_{22}$Ti	Exp.	$2\beta^-$	g.s.	0ν	$> 1.0 \times 10^{17}$	90	Bel99a	
990.4(2.4)	Th.	$2\beta^-$			–			A
0.004(0.003)								
${}^{48}_{20}$Ca$-{}^{48}_{22}$Ti	Exp.	$2\beta^-$	g.s.	0ν	$> 2.0 \times 10^{21}$	80	Bar70	B
4272(4)					$> 9.5 \times 10^{21}$	76	You91	C
0.187(0.021)					$> 1.5 \times 10^{21}$	90	Bru00	
				2ν	$> 3.6 \times 10^{19}$		Bar70	
					$= 4.3^{+2.8}_{-1.8} \times 10^{19}$		Bal96	
					$= 4.2^{+3.3}_{-1.3} \times 10^{19}$		Bru00	
				0νM1	$> 7.2 \times 10^{20}$	90	Bar70	D
			2^+_1(984)	0ν	$> 1.0 \times 10^{21}$	90	Bar70	D
			0^+_1(2997)	0ν	$> 8.0 \times 10^{18}$	95	Alb86	
	Th.	$2\beta^-$	g.s.	0ν	$= 3.2 \times 10^{24}$	SM	Hax84	A
					$= 2.8 \times 10^{25}$	QRPA	Pan96	
					$= 2.3 \times 10^{24}$	QRPA	Bar99a	
					$= 8.8 \times 10^{24}$	SM	Cau99	
				2ν	$= 6.1 \times 10^{18}$	SM	Tsu84	
					$= 5.0 \times 10^{20}$	SU(4)	Rum95	
					$\leq 1.0 \times 10^{20}$	SM	Pov95	
					$= 3.9 \times 10^{19}$	SM	Cau99	
${}^{50}_{24}$Cr$-{}^{50}_{22}$Ti	Exp.	$\varepsilon\beta^+$	g.s.	$0\nu + 2\nu$	$> 1.8 \times 10^{17}$	68	Nor85	
1171.4(1.2)	Th.	$\varepsilon\beta^+$, 2ε			–			
4.345(0.013)								
${}^{54}_{26}$Fe$-{}^{54}_{24}$Cr	Exp.	$2K$	g.s.	0ν	$> 4.4 \times 10^{20}$	68	Bik98	
679.9(0.5)		KL	g.s.	0ν	$> 4.1 \times 10^{20}$	68	Bik98	
5.845(0.035)		$2L$	g.s.	0ν	$> 5.0 \times 10^{20}$	68	Bik98	
	Th.	2ε	g.s.	2ν	$= 1.5 \times 10^{27}$	SM	Nak96	
${}^{58}_{28}$Ni$-{}^{58}_{26}$Fe	Exp.	$\varepsilon\beta^+$	g.s.	$0\nu + 2\nu$	$> 7.0 \times 10^{20}$	68	Vas93	
1925.8(0.7)			2^+_1(811)	$0\nu + 2\nu$	$> 4.0 \times 10^{20}$	68	Vas93	
68.0769(0.0089)		$\varepsilon\beta^+$, 2ε	2^+_1(811)	$0\nu + 2\nu$	$> 4.0 \times 10^{19}$	90	Bel82	
			2^+_2(1675)	$0\nu + 2\nu$	$> 4.0 \times 10^{19}$	90	Bel82	
		2ε	g.s. + 2^+_1(811)	0ν	$> 2.1 \times 10^{19}$	68	Nor84	
	Th.	$\varepsilon\beta^+$	g.s.	2ν	$= 8.6 \times 10^{25}$	SM	Nak96	A
		2ε		2ν	$= 6.1 \times 10^{24}$	SM	Nak96	
${}^{64}_{30}$Zn$-{}^{64}_{28}$Ni	Exp.	$\varepsilon\beta^+$	g.s.	$0\nu + 2\nu$	$> 2.3 \times 10^{18}$	68	Nor85	
1096.4(0.9)					$= (1.1 \pm 0.9) \times 10^{19}$		Bik95	E
48.63(0.60)		2ε		$0\nu + 2\nu$	$> 8.0 \times 10^{15}$		Ber53	
	Th.	$\varepsilon\beta^+$, 2ε			–			

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$**X**$-{}_{Z\pm2}^{A}$**Y** ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Reference	Note
${}^{70}_{30}$**Zn**$-{}^{70}_{32}$**Ge**	Exp.	$2\beta^-$	g.s.	0ν	$> 4.8 \times 10^{14}$		Fre52	F
1000.9(3.4)	Th.	$2\beta^-$	g.s.	2ν	$= 2.5 \times 10^{21} - 6.4 \times 10^{23}$	QRPA	Bob00	A
0.62(0.03)								
${}^{76}_{32}$**Ge**$-{}^{76}_{34}$**Se**	Exp.	$2\beta^-$	g.s.	0ν	$> 1.6 \times 10^{25}$	90	Bau99	G
2038.7(0.5)					$> 1.6 \times 10^{25}$	90	Gon00	
2038.58(0.31) [Hyk93]				2ν	$= (9.0 \pm 1.0) \times 10^{20}$	68	Vas90a	
2039.006(0.050) [Dou01]					$= 1.1^{+0.6}_{-0.3} \times 10^{21}$	95	Mil90	
7.61(0.38)					$= 8.4^{+1.0}_{-0.8} \times 10^{20}$	95	Bro93	H
					$= (1.1 \pm 0.2) \times 10^{21}$		Aal96	
					$= (1.8 \pm 0.1) \times 10^{21}$		Gun97	
				0νM1	$> 7.9 \times 10^{21}$	90	Gun97	
				0νM3	$> 5.9 \times 10^{21}$	90	Gun97	
				0νM7	$> 6.6 \times 10^{21}$	90	Gun97	
			$2^+_1(559)$	0ν	$> 8.2 \times 10^{23}$	90	Mai94	
				$0\nu + 2\nu$	$> 1.1 \times 10^{21}$	90	Bar95a	
			$0^+_1(1122)$	0ν	$> 2.0 \times 10^{22}$	68	Bus90	
				$0\nu + 2\nu$	$> 6.2 \times 10^{21}$	90	Vas00	
			$2^+_2(1216)$	$0\nu + 2\nu$	$> 1.4 \times 10^{21}$	90	Bar95a	
	Th.	$2\beta^-$	g.s.	0ν	$= 1.7 \times 10^{24}$	SM	Hax84	A
					$= 6.2 \times 10^{24}$	QCM	Suh91	
					$= 1.9 \times 10^{25}$	SM	Cau96	
					$= 1.8 \times 10^{25}$	QRPA	Pan96	
					$= 9.5 \times 10^{24}$	QRPA	Sim97	
					$= (2.0 - 2.9) \times 10^{24}$	QRPA	Aun98	
					$= 3.2 \times 10^{24}$	QRPA	Bar99a	
					$= 1.8 \times 10^{25}$	SM	Cau99	
					$= 4.2 \times 10^{24}$	QRPA	Sim99	
					$= (3.2 - 7.4) \times 10^{24}$	QRPA	Sto00	
					$= 5.0 \times 10^{24}$	QRPA	Suh00a	
					$= (6.9 - 9.6) \times 10^{25}$	QRPA	Bob01	
					$= (2.9 - 4.0) \times 10^{24}$	QRPA	Sto01	
				2ν	$= 4.2 \times 10^{20}$	SM	Hax84	
					$= 3.0 \times 10^{21}$	SU(4)	Rum95	
					$= 2.2 \times 10^{21}$	SM	Cau96	
					$= 7.7 \times 10^{20}$	MCM	Aun96	
					$= 5.0 \times 10^{21}$	SU(4)	Rum98	
					$= 2.6 \times 10^{21}$	SM	Cau99	
					$= 6.7 \times 10^{20} - 5.9 \times 10^{22}$	QRPA	Bob00	
					$= 1.3 \times 10^{21}$	QRPA	Kan01	
				0νM1	$= 4.3 \times 10^{24}$	QRPA	Hir96	
					$= 1.7 \times 10^{25}$	QRPA	Sim99	
			$2^+_1(559)$	2ν	$= 2.4 \times 10^{24}$	QRPA	Sto94	
					$= 7.8 \times 10^{25}$	MCM	Aun96	
					$= 1.0 \times 10^{26}$	MCM	Toi97	
					$= (2.4 - 4.3) \times 10^{26}$	QRPA	Sch98	
			$0^+_1(1122)$	0ν	$= 5.6 \times 10^{26}$	QRPA	Suh00a	
				2ν	$= 7.5 \times 10^{21}$	MCM	Aun96	
					$= (1.0 - 3.1) \times 10^{23}$	MCM	Toi97	
			$2^+_2(1216)$	2ν	$= 1.3 \times 10^{29}$	MCM	Aun96	
					$= 7.2 \times 10^{27} - 2.2 \times 10^{28}$	MCM	Toi97	

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$**X**$-{}^{A}_{Z\pm2}$**Y** ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Reference	Note
${}^{74}_{34}$**Se**$-{}^{74}_{32}$**Ge**	Exp.	$\varepsilon\beta^+$, 2ε			–			
1209.4(0.6)	Th.	$\varepsilon\beta^+$, 2ε			–			
1209.53(0.48) [Hyk93]								
0.89(0.04)								
${}^{80}_{34}$**Se**$-{}^{80}_{36}$**Kr**	Exp.	$2\beta^-$			–			
133.9(3.7)	Th.	$2\beta^-$	g.s.	2ν	$= 6.3\times10^{29} - 6.0\times10^{32}$	QRPA	Bob00	A
49.61(0.41)								
${}^{82}_{34}$**Se**$-{}^{82}_{36}$**Kr**	Exp.	$2\beta^-$	all modes		$= (1.4\pm0.3)\times10^{20}$		Kir69	I
2995.1(2.0)					$= (2.8\pm0.9)\times10^{20}$		Sri73	I
2995.8(1.5) [Nxu93]					$= (1.5\pm0.2)\times10^{20}$		Kir83b	J
8.73(0.22)					$= 9.7^{+3.6}_{-4.5}\times10^{19}$		Mar85	I
					$= (1.0\pm0.4)\times10^{20}$		Man86	J
					$= (1.3\pm0.1)\times10^{20}$		Kir86	J
					$< (1.7\pm0.2)\times10^{20}$		Lin86	I
					$= 1.0^{+0.3}_{-0.4}\times10^{20}$		Mur87	I
					$= (1.2\pm0.1)\times10^{20}$		Lin88a	I
					$= 1.0\times10^{20}$		Man91	J
			g.s.	0ν	$> 2.7\times10^{22}$	68	Ell92	
				2ν	$= 1.1^{+0.3}_{-0.1}\times10^{20}$	68	Ell92	
					$= (8.3\pm1.2)\times10^{19}$		Arn98	
				0νM1	$> 2.4\times10^{21}$	90	Arn98	
				0νM3	$> 6.3\times10^{20}$	90	Arn00	
				0νM7	$> 1.1\times10^{20}$	90	Arn00	
			$2^+_1(777)$	0ν	$> 2.8\times10^{21}$	90	Arn98	
				$0\nu+2\nu$	$> 1.4\times10^{21}$	90	Suh97a	
			$2^+_2(1475)$	$0\nu+2\nu$	$> 1.6\times10^{21}$	90	Suh97a	
			$0^+_1(2172)$	$0\nu+2\nu$	$> 3.0\times10^{21}$	90	Suh97a	
	Th.	$2\beta^-$	g.s.	0ν	$= 5.8\times10^{23}$	SM	Hax84	A
					$= 2.4\times10^{24}$	SM	Cau96	
					$= 2.8\times10^{24}$	QRPA	Pan96	
					$= (7.7-8.1)\times10^{23}$	QRPA	Aun98	
					$= 7.5\times10^{23}$	QRPA	Bar99a	
					$= 1.1\times10^{24}$	QRPA	Sim99	
					$= 2.4\times10^{24}$	SM	Cau99	
					$= 1.8\times10^{24}$	QRPA	Suh00a	
					$= (5.6-7.6)\times10^{23}$	QRPA	Sto01	
				2ν	$= 2.6\times10^{19}$	SM	Hax84	
					$= 3.0\times10^{20}$	SU(4)	Rum95	
					$= 5.0\times10^{19}$	SM	Cau96	
					$= 4.5\times10^{19}$	MCM	Aun96	
					$= 3.9\times10^{18} - 9.8\times10^{19}$	QRPA	Suh97a	
					$= 2.6\times10^{20}$	SU(4)	Rum98	
					$= 3.7\times10^{19}$	SM	Cau99	
					$= 2.0\times10^{19} - 1.2\times10^{21}$	QRPA	Bob00	
					$= 1.0\times10^{20}$	QRPA	Kan01	
				0νM1	$= 6.0\times10^{23}$	QRPA	Hir96	
					$= 2.3\times10^{24}$	QRPA	Sim99	
			$2^+_1(777)$	2ν	$= 2.0\times10^{23}$	QRPA	Sto94	
					$= 3.3\times10^{26}$	MCM	Aun96	
					$> 5.3\times10^{24}$	QRPA	Suh97a	
					$= (1.0-2.4)\times10^{24}$	QRPA	Sch98	

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$**X**$-{}^{A}_{Z\pm2}$**Y** ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Reference	Note
			$2^+_2(1475)$	2ν	$= 6.3 \times 10^{24}$	MCM	Aun96	
					$= (2.8 \pm 0.4) \times 10^{24}$	QRPA	Suh97a	
			$0^+_1(2172)$	0ν	$= 1.1 \times 10^{27}$	QRPA	Suh00a	
				2ν	$= 1.5 \times 10^{21}$	MCM	Aun96	
					$= (1.9 \pm 0.2) \times 10^{21}$	QRPA	Suh97a	
${}^{78}_{36}$**Kr**$-{}^{78}_{34}$**Se**	Exp.	$2\beta^+$	g.s.	$0\nu + 2\nu$	$> 2.0 \times 10^{21}$	68	Sae94	
2866(7)		$K\beta^+$	g.s.	0ν	$> 5.1 \times 10^{21}$	68	Sae94	
0.35(0.01)				2ν	$> 1.1 \times 10^{20}$	68	Sae94	
		$2K$	g.s.	2ν	$> 2.3 \times 10^{20}$	90	Gav00a	
	Th.	$\varepsilon\beta^+$	g.s.	2ν	$= 6.2 \times 10^{21}$	MCM	Aun96	A
					$= 1.0 \times 10^{24}$	SU(4)	Rum98	
			$0^+_1(1499)$	2ν	$= 3.8 \times 10^{28}$	MCM	Aun96	
		2ε	g.s.	2ν	$= 3.7 \times 10^{21}$	MCM	Aun96	
					$= 8.2 \times 10^{21} - 6.8 \times 10^{22}$	MCM	Toi97	
					$= 6.2 \times 10^{23}$	SU(4)	Rum98	
			$0^+_1(1499)$	2ν	$= 3.7 \times 10^{24}$	MCM	Aun96	
					$= 4.7 \times 10^{24} - 2.1 \times 10^{27}$	MCM	Toi97	
${}^{86}_{36}$**Kr**$-{}^{86}_{38}$**Sr**	Exp.	$2\beta^-$			–			
1255.6(2.4)	Th.	$2\beta^-$	g.s.	2ν	$= 2.2 \times 10^{23} - 9.9 \times 10^{24}$	QRPA	Bob00	A
17.30(0.22)								
${}^{84}_{38}$**Sr**$-{}^{84}_{36}$**Kr**	Exp.	$\varepsilon\beta^+$	g.s.	0ν	$> 7.3 \times 10^{13}$		Fre52	F
1786.8(3.6)	Th.	$\varepsilon\beta^+$, 2ε			–			A
0.56(0.01)								
${}^{94}_{40}$**Zr**$-{}^{94}_{42}$**Mo**	Exp.	$2\beta^-$	g.s.	0ν	$> 1.9 \times 10^{19}$	90	Arn99	
1144.1(2.0)				2ν	$> 1.1 \times 10^{17}$	90	Arn99	
17.38(0.28)				0νM1	$> 2.3 \times 10^{18}$	90	Arn99	
			$2^+_1(871)$	$0\nu + 2\nu$	$> 1.3 \times 10^{19}$	68	Nor87	
	Th.	$2\beta^-$	g.s.	2ν	$= 3.1 \times 10^{22} - 6.6 \times 10^{24}$	QRPA	Bob00	A
${}^{96}_{40}$**Zr**$-{}^{96}_{42}$**Mo**	Exp.	$2\beta^-$	all modes		$= (3.9 \pm 0.9) \times 10^{19}$	68	Kaw93	I,K
3350.4(2.9)			g.s.	0ν	$> 1.0 \times 10^{21}$	90	Arn99	
2.80(0.09)				2ν	$= 2.1^{+0.8}_{-0.4} \times 10^{19}$		Arn99	
				0νM1	$> 3.5 \times 10^{20}$	90	Arn99	
				0νM3	$> 6.3 \times 10^{19}$	90	Arn00	
				0νM7	$> 2.4 \times 10^{19}$	90	Arn00	
			$2^+_1(778)$	0ν	$> 3.9 \times 10^{20}$	90	Arn99	
				$0\nu + 2\nu$	$> 7.9 \times 10^{19}$	90	Bar96b	
			$0^+_1(1148)$	$0\nu + 2\nu$	$> 6.8 \times 10^{19}$	90	Bar96b	
			$2^+_2(1498)$	$0\nu + 2\nu$	$> 6.1 \times 10^{19}$	90	Bar96b	
			$2^+_3(1626)$	$0\nu + 2\nu$	$> 5.4 \times 10^{19}$	90	Bar96b	
			$4^+_1(1628)$	$0\nu + 2\nu$	$> 1.8 \times 10^{18}$	68	Nor87	
	Th.	$2\beta^-$	g.s.	0ν	$= 2.7 \times 10^{25}$	QRPA	Pan96	A
					$= (3.6 - 6.0) \times 10^{23}$	QRPA	Aun98	
					$= 1.6 \times 10^{24}$	QRPA	Sim99	
					$= 7.6 \times 10^{23}$	QRPA	Suh00b	
					$= 6.3 \times 10^{23} - 1.0 \times 10^{24}$	QRPA	Sto01	
				2ν	$= 1.0 \times 10^{19}$	SU(4)	Rum95	

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$**X**$-{}^{A}_{Z\pm2}$**Y** ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Reference	Note
					$= 3.9 \times 10^{19}$	QRPA	Sto95	
					$= 5.8 \times 10^{17} - 3.9 \times 10^{18}$	MCM	Bar96b	
					$= (4.2 - 4.4) \times 10^{19}$	MCM	Toi97	
					$= 1.1 \times 10^{19}$	SU(4)	Rum98	
					$= 4.5 \times 10^{18} - 6.1 \times 10^{20}$	QRPA	Bob00	
				0νM1	$= 2.8 \times 10^{24}$	QRPA	Sim99	
			$2^+_1(778)$	2ν	$= 6.4 \times 10^{22}$	QRPA	Sto95	
					$= 3.3 \times 10^{19} - 2.2 \times 10^{22}$	MCM	Bar96b	
					$= (3.8 - 4.8) \times 10^{21}$	MCM	Toi97	
					$= (1.1 - 1.4) \times 10^{21}$	QRPA	Sch98	
			$0^+_1(1148)$	0ν	$= 5.6 \times 10^{24}$	QRPA	Suh00b	
				2ν	$= 3.8 \times 10^{21}$	QRPA	Sto95	
					$= 2.1 \times 10^{20} - 1.3 \times 10^{21}$	MCM	Bar96b	
					$= (2.4 - 2.7) \times 10^{21}$	MCM	Toi97	
			$0^+_2(1330)$	0ν	$= 9.3 \times 10^{26}$	QRPA	Suh00b	
			$2^+_2(1498)$	2ν	$= 5.1 \times 10^{23} - 1.0 \times 10^{26}$	MCM	Bar96b	
					$= (6.0 - 6.3) \times 10^{24}$	MCM	Toi97	
${}^{92}_{42}$**Mo**$-{}^{92}_{40}$**Zr**	Exp.	$\varepsilon\beta^+$	g.s.	$0\nu + 2\nu$	$> 1.9 \times 10^{20}$	90	Bar97	
1649.1(3.7)		$\varepsilon\beta^+, 2\varepsilon$	$2^+_1(934)$	$0\nu + 2\nu$	$> 3.0 \times 10^{18}$	90	Bel82	
14.84(0.35)			$0^+_1(1383)$	$0\nu + 2\nu$	$> 4.0 \times 10^{18}$	90	Bel82	
			$4^+_1(1495)$	$0\nu + 2\nu$	$> 6.0 \times 10^{18}$	90	Bel82	
		2ε	$2^+_1(934)$	$0\nu + 2\nu$	$> 8.9 \times 10^{20}$	90	Bar97	
			$0^+_1(1383)$	$0\nu + 2\nu$	$> 8.1 \times 10^{20}$	90	Bar97	
	Th.	$\varepsilon\beta^+$	g.s.	2ν	$= 2.4 \times 10^{25}$	MCM	Aun95	A
		2ε	g.s.	2ν	$= 3.0 \times 10^{22}$	MCM	Aun95	
					$= 4.6 \times 10^{22} - 3.3 \times 10^{24}$	SM	Suh97b	
			$0^+_1(1383)$	2ν	$= 2.4 \times 10^{29}$	MCM	Aun95	
					$= 1.5 \times 10^{28} - 3.1 \times 10^{30}$	SM	Suh97b	
${}^{98}_{42}$**Mo**$-{}^{98}_{44}$**Ru**	Exp.	$2\beta^-$	g.s.	0ν	$> 1.0 \times 10^{14}$		Fre52	F
112(6)	Th.	$2\beta^-$	g.s.	2ν	$= 4.1 \times 10^{30} - 1.5 \times 10^{31}$	QRPA	Bob00	A
24.13(0.31)								
${}^{100}_{42}$**Mo**$-{}^{100}_{44}$**Ru**	Exp.	$2\beta^-$	g.s.	$0\nu(m_\nu)$	$> 5.5 \times 10^{22}$	90	Eji01	
3034(6)				$0\nu(\lambda)$	$> 4.2 \times 10^{22}$	90	Eji01	
9.63(0.23)				$0\nu(\eta)$	$> 4.9 \times 10^{22}$	90	Eji01	
				2ν	$= 3.3^{+2.0}_{-1.0} \times 10^{18}$	90	Vas90b	
					$= 1.2^{+0.5}_{-0.3} \times 10^{19}$	90	Eji91	
					$= (9.5 \pm 1.0) \times 10^{18}$		Das95	
					$= 7.6^{+2.2}_{-1.4} \times 10^{18}$		Als97	
					$= 6.8^{+0.8}_{-0.9} \times 10^{18}$		Sil97	
					$= 8.5 \times 10^{18}$		Ash99	L
				0νM1	$> 5.4 \times 10^{21}$	68	Eji96	
				0νM3	$> 1.6 \times 10^{20}$	90	Arn00	
				0νM7	$> 4.1 \times 10^{19}$	90	Arn00	
			$2^+_1(540)$	0ν	$> 1.4 \times 10^{22}$	68	Eji96	
				$0\nu + 2\nu$	$> 1.6 \times 10^{21}$	90	Bar95b	
			$0^+_1(1130)$	$0\nu + 2\nu$	$> 1.2 \times 10^{21}$	90	Blu92	
					$= 6.1^{+1.8}_{-1.1} \times 10^{20}$	68	Bar95b	

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$X$-{}^{A}_{Z\pm2}$Y ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Reference	Note
					$= 9.3^{+2.8}_{-1.7} \times 10^{20}$		Bar99b	
					$= 5.9^{+1.8}_{-1.3} \times 10^{20}$		Bra01	
			$4_1^+(1227)$	0ν	$> 6.3 \times 10^{20}$		Kud92	
				2ν	$> 5.1 \times 10^{19}$		Kud92	
			$2_2^+(1362)$	$0\nu + 2\nu$	$> 1.3 \times 10^{21}$	90	Bar95b	
			$0_2^+(1741)$	$0\nu + 2\nu$	$> 1.3 \times 10^{21}$	90	Bar95b	
	Th.	$2\beta^-$	g.s.	0ν	$= 3.6 \times 10^{27}$	QRPA	Pan96	A
					$= 2.6 \times 10^{23}$	QRPA	Sim97	
					$= 5.8 \times 10^{23}$	QRPA	Bar99a	
					$= 4.4 \times 10^{23}$	QRPA	Sim99	
					$= (1.1 - 1.3) \times 10^{23}$	QRPA	Sto01	
				2ν	$= (1.1 - 2.2) \times 10^{19}$	pSU(3)	Hir95a	
					$= 2.0 \times 10^{19}$	SU(4)	Rum95	
					$= 1.2 \times 10^{19}$	QRPA	Sto95	
					$= (4.4 - 8.6) \times 10^{18}$	SSDH	Civ98	
					$= 4.1 \times 10^{18}$	SU(4)	Rum98	
					$= (2.9 - 7.2) \times 10^{18}$	MCM	Suh98	
					$= 5.0 \times 10^{18} - 1.7 \times 10^{22}$	QRPA	Bob00	
					$= 7.6 \times 10^{18}$	SSDH	Sem00	
				0νM1	$= 2.4 \times 10^{23}$	QRPA	Hir96	
					$= 9.1 \times 10^{23}$	QRPA	Sim99	
			$2_1^+(540)$	2ν	$= 5.5 \times 10^{25} - 2.4 \times 10^{26}$	pSU(3)	Hir95a	
					$= 3.4 \times 10^{22}$	QRPA	Sto95	
					$= (1.0 - 1.1) \times 10^{22}$	QRPA	Sch98	
					$= 5.3 \times 10^{20} - 1.3 \times 10^{21}$	MCM	Suh98	
			$0_1^+(1130)$	2ν	$= 1.6 \times 10^{21}$	pSU(3)	Hir95a	
					$= 2.1 \times 10^{21}$	QRPA	Sto95	
					$= 5.4 \times 10^{19} - 1.3 \times 10^{20}$	MCM	Suh98	
			$2_2^+(1362)$	2ν	$= (1.2 - 3.0) \times 10^{24}$	MCM	Suh98	
${}^{96}_{44}$Ru$-{}^{96}_{42}$Mo	Exp.	$2\beta^+$	g.s.	$0\nu + 2\nu$	$> 3.1 \times 10^{16}$	68	Nor85	
2719(8)		$\varepsilon\beta^+$	g.s.	$0\nu + 2\nu$	$> 6.7 \times 10^{16}$	68	Nor85	
5.54(0.14)			$2_1^+(778)$	$0\nu + 2\nu$	$> 6.0 \times 10^{16}$	68	Nor85	
			$0_1^+(1148)$	$0\nu + 2\nu$	$> 4.5 \times 10^{16}$	68	Nor85	
			$2_2^+(1498)$	$0\nu + 2\nu$	$> 5.5 \times 10^{16}$	68	Nor85	
			$2_3^+(1626)$	$0\nu + 2\nu$	$> 5.3 \times 10^{16}$	68	Nor85	
			$4_1^+(1628)$	$0\nu + 2\nu$	$> 5.3 \times 10^{16}$	68	Nor85	
	Th.	$\varepsilon\beta^+$	g.s.	2ν	$= 8.6 \times 10^{22}$	SU(4)	Rum98	A
		2ε	g.s.	2ν	$= 1.4 \times 10^{22}$	SU(4)	Rum98	
${}^{104}_{44}$Ru$-{}^{104}_{46}$Pd	Exp.	$2\beta^-$			–			
1300(4)	Th.	$2\beta^-$			–			A
18.62(0.27)								
${}^{102}_{46}$Pd$-{}^{102}_{44}$Ru	Exp.	$\varepsilon\beta^+$, 2ε			–			
1172.0(2.6)	Th.	$\varepsilon\beta^+$, 2ε			–			
1.02(0.01)								
${}^{110}_{46}$Pd$-{}^{110}_{48}$Cd	Exp.	$2\beta^-$	all modes		$> 6.0 \times 10^{17}$		Win52	
2000(11)			g.s.	2ν	$> 6.0 \times 10^{16}$		Win52	M
11.72(0.09)				0νM1	$> 6.0 \times 10^{16}$		Win52	M
	Th.	$2\beta^-$	g.s.	2ν	$= 1.6 \times 10^{20}$	QRPA	Sto94	A

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}\mathbf{X}-{}^{A}_{Z\pm2}\mathbf{Y}$ ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Reference	Note
					$= (1.2 - 1.8) \times 10^{20}$	SSDH	Civ98	
					$= 1.6 \times 10^{20}$	SSDH	Sem00	
			$2^+_1(658)$	2ν	$= 8.4 \times 10^{25}$	QRPA	Sto94	
${}^{106}_{48}\mathbf{Cd}-{}^{106}_{46}\mathbf{Pd}$	Exp.	$2\beta^+$	g.s.	$0\nu + 2\nu$	$> 2.4 \times 10^{20}$	90	Bel99b	
2771(8)			$2^+_1(512)$	$0\nu + 2\nu$	$> 1.6 \times 10^{20}$	90	Bel99b	
1.25(0.06)		$\varepsilon\beta^+$	g.s.	0ν	$> 3.7 \times 10^{20}$	90	Bel99b	
				2ν	$> 4.1 \times 10^{20}$	90	Bel99b	
			$2^+_1(512)$	$0\nu + 2\nu$	$> 2.6 \times 10^{20}$	90	Bel99b	
			$2^+_2(1128)$	$0\nu + 2\nu$	$> 1.4 \times 10^{20}$	90	Bel99b	
			$0^+_1(1134)$	$0\nu + 2\nu$	$> 1.1 \times 10^{20}$	90	Bel99b	
		2ε	g.s. $+ 2^+_1(512)$	0ν	$> 1.5 \times 10^{17}$	68	Nor84	
			$2^+_1(512)$	$0\nu + 2\nu$	$> 3.5 \times 10^{18}$	90	Bar96c	
			$2^+_2(1128)$	$0\nu + 2\nu$	$> 5.1 \times 10^{18}$	90	Bar96c	
				2ν	$> 4.9 \times 10^{19}$	90	Bel99b	
			$0^+_1(1134)$	$0\nu + 2\nu$	$> 6.2 \times 10^{18}$	90	Bar96c	
				2ν	$> 7.3 \times 10^{19}$	90	Bel99b	
			$1, 2^+(2741)$	2ν	$> 3.0 \times 10^{19}$	90	Bel99b	
		$2K$	g.s.	2ν	$> 5.8 \times 10^{17}$	90	Geo95a	
	Th.	$2\beta^+$	g.s.	2ν	$= 3.3 \times 10^{25}$	QRPA	Bar96c	A
					$= 9.5 \times 10^{25} - 1.8 \times 10^{27}$	QRPA	Suh01	
		$\varepsilon\beta^+$	g.s.	2ν	$= 8.3 \times 10^{20}$	QRPA	Bar96c	
					$= 1.3 \times 10^{22}$	SU(4)	Rum98	
					$= 2.4 \times 10^{21} - 4.4 \times 10^{22}$	QRPA	Suh01	
			$0^+_1(1134)$	2ν	$= 1.7 \times 10^{26}$	QRPA	Bar96c	
					$= (5.1 - 5.8) \times 10^{26}$	QRPA	Suh01	
		2ε	g.s.	2ν	$= 1.0 \times 10^{20}$	QRPA	Bar96c	
					$= (2.0 - 2.1) \times 10^{20}$	MCM	Toi97	
					$= (2.0 - 5.3) \times 10^{21}$	SSDH	Civ98	
					$= 1.7 \times 10^{21}$	SU(4)	Rum98	
					$= 3.0 \times 10^{20} - 5.5 \times 10^{21}$	QRPA	Suh01	
			$0^+_1(1134)$	2ν	$= 1.0 \times 10^{23}$	QRPA	Bar96c	
					$= 1.0 \times 10^{23}$	MCM	Aun96	
					$= 1.0 \times 10^{22} - 1.4 \times 10^{23}$	MCM	Toi97	
					$= (3.0 - 3.4) \times 10^{23}$	QRPA	Suh01	
${}^{108}_{48}\mathbf{Cd}-{}^{108}_{46}\mathbf{Pd}$	Exp.	2ε	g.s.	0ν	$> 3.3 \times 10^{16}$	90	Geo95a	
269(6)		$2K$	g.s.	2ν	$> 4.1 \times 10^{17}$	90	Geo95a	
0.89(0.03)	Th.	2ε			–			
${}^{114}_{48}\mathbf{Cd}-{}^{114}_{50}\mathbf{Sn}$	Exp.	$2\beta^-$	g.s.	0ν	$> 2.0 \times 10^{20}$	90	Geo95a	
536.8(3.3)				2ν	$> 9.2 \times 10^{16}$	99	Geo95a	
28.73(0.42)	Th.	$2\beta^-$	g.s.	2ν	$= 2.8 \times 10^{24} - 1.2 \times 10^{25}$	SSDH	Civ98	A
					$= 1.3 \times 10^{25}$	SSDH	Sem00	
${}^{116}_{48}\mathbf{Cd}-{}^{116}_{50}\mathbf{Sn}$	Exp.	$2\beta^-$	g.s.	0ν	$> 7.0 \times 10^{22}$	90	Dan00	
2805.0(3.8)				2ν	$> 1.8 \times 10^{19}$	99	Dan95	
7.49(0.18)					$= 2.6^{+0.9}_{-0.5} \times 10^{19}$	68	Eji95	
					$= 2.7^{+1.0}_{-0.7} \times 10^{19}$	68	Dan95	
					$= (3.8 \pm 0.4) \times 10^{19}$		Arn96	
					$= 2.6^{+0.7}_{-0.4} \times 10^{19}$		Dan00	
				0νM1	$> 3.7 \times 10^{21}$	90	Dan00	

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$**X**$-{}^{A}_{Z\pm2}$**Y** ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Reference	Note
				0νM3	$> 5.9 \times 10^{20}$	90	Dan00	
				0νM7	$> 4.1 \times 10^{19}$	90	Arn00	
			$2^+_1(1294)$	0ν	$> 1.3 \times 10^{22}$	90	Dan00	
				$0\nu + 2\nu$	$> 2.4 \times 10^{21}$	90	Pie94	
			$0^+_1(1757)$	0ν	$> 7.0 \times 10^{21}$	90	Dan00	
				$0\nu + 2\nu$	$> 2.1 \times 10^{21}$	90	Pie94	
			$0^+_2(2027)$	$0\nu + 2\nu$	$> 2.1 \times 10^{21}$	90	Pie94	
			$2^+_2(2112)$	$0\nu + 2\nu$	$> 1.7 \times 10^{20}$	68	Bar90	
			$2^+_3(2225)$	$0\nu + 2\nu$	$> 1.0 \times 10^{20}$	68	Bar90	
	Th.	$2\beta^-$	g.s.	0ν	$= 4.9 \times 10^{24}$	QRPA	Pan96	A
					$= 6.9 \times 10^{23}$	QRPA	Sim97	
					$= 4.0 \times 10^{23} - 1.3 \times 10^{24}$	QRPA	Aun98	
					$= 1.0 \times 10^{24}$	QRPA	Sim99	
					$= 1.5 \times 10^{24}$	QRPA	Suh00b	
					$= 7.8 \times 10^{23} - 1.1 \times 10^{24}$	QRPA	Sto01	
				2ν	$= 1.0 \times 10^{19}$	SU(4)	Rum95	
					$= 5.1 \times 10^{19}$	MCM	Aun96	
					$= (1.5 \pm 0.4) \times 10^{19}$	SSDH	Bha98	
					$= (1.3 - 2.3) \times 10^{19}$	SSDH	Civ98	
					$= 1.2 \times 10^{19}$	SU(4)	Rum98	
					$= 1.2 \times 10^{19}$	SSDH	Sem00	
				0νM1	$= 5.3 \times 10^{23}$	QRPA	Hir96	
					$= 2.3 \times 10^{24}$	QRPA	Sim99	
			$2^+_1(1294)$	2ν	$= 3.4 \times 10^{23}$	QRPA	Sto94	
					$= 1.1 \times 10^{24}$	MCM	Aun96	
					$= (1.0 - 1.7) \times 10^{24}$	QRPA	Bha98	
					$= (1.1 - 1.3) \times 10^{23}$	QRPA	Sch98	
			$0^+_1(1757)$	0ν	$= 2.0 \times 10^{27}$	QRPA	Suh00b	
				2ν	$= 1.1 \times 10^{22}$	MCM	Aun96	
					$= (2.3 \pm 0.6) \times 10^{23}$	SSDH	Bha98	
			$0^+_2(2027)$	0ν	$= 5.4 \times 10^{28}$	QRPA	Suh00b	
			$2^+_2(2112)$	2ν	$= 4.6 \times 10^{27}$	MCM	Aun96	
					$= 6.6 \times 10^{23} - 1.0 \times 10^{24}$	QRPA	Bha98	
${}^{112}_{50}$**Sn**$-{}^{112}_{48}$**Cd**	Exp.	$\varepsilon\beta^+$	g.s.	0ν	$> 6.1 \times 10^{13}$		Fre52	F
1922(4)	Th.	$\varepsilon\beta^+, 2\varepsilon$			–			A
0.97(0.01)								
${}^{122}_{50}$**Sn**$-{}^{122}_{52}$**Te**	Exp.	$2\beta^-$	g.s.	0ν	$> 5.8 \times 10^{13}$		Fre52	F
366.2(2.8)	Th.	$2\beta^-$			–			A
4.63(0.03)								
${}^{124}_{50}$**Sn**$-{}^{124}_{52}$**Te**	Exp.	$2\beta^-$	g.s.	0ν	$> 2.4 \times 10^{17}$	95	Kal52	
2287.0(1.5)				2ν	$> 1.0 \times 10^{17}$		Kal52	N
5.79(0.05)				0νM1	$> 1.0 \times 10^{17}$		Kal52	N
			$2^+_1(603)$	$0\nu + 2\nu$	$> 4.1 \times 10^{19}$	95	Smo85	
			$2^+_2(1326)$	$0\nu + 2\nu$	$> 2.0 \times 10^{18}$	68	Nor87	
			$0^+_2(1657)$	$0\nu + 2\nu$	$> 2.2 \times 10^{18}$	68	Nor87	
	Th.	$2\beta^-$	g.s.	0ν	$= 4.6 \times 10^{23} - 1.1 \times 10^{24}$	QRPA	Aun98	A
					$= 3.4 \times 10^{24}$	SM	Cau99	
				2ν	$= 7.8 \times 10^{19}$	MCM	Aun96	
					$= 2.9 \times 10^{20}$	SM	Cau99	

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$X$-{}_{Z\pm2}^{A}$Y ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Reference	Note
			$2^+_1(603)$	2ν	$= 6.5 \times 10^{26}$	MCM	Aun96	
			$0^+_1(1156)$	2ν	$= 2.7 \times 10^{21}$	MCM	Aun96	
			$2^+_2(1326)$	2ν	$= 1.7 \times 10^{27}$	MCM	Aun96	
${}^{120}_{52}$**Te**$-{}^{120}_{50}$**Sn**	Exp.	$\varepsilon\beta^+$	g.s.	0ν	$> 4.2 \times 10^{12}$		Fre52	F
1698(10)	Th.	$\varepsilon\beta^+$, 2ε			–			
0.09(0.01)								
${}^{128}_{52}$**Te**$-{}^{128}_{54}$**Xe**	Exp.	$2\beta^-$	all modes		$= (1.5 \pm 0.2) \times 10^{24}$		Hen75	I
867.2(1.5)					$> 8.0 \times 10^{24}$	95	Kir83a	I
867.2(1.0) [Dyc90]					$= (1.4 \pm 0.4) \times 10^{24}$		Man86	J
31.74(0.08)					$> 5.0 \times 10^{24}$		Kir86	J
					$= (1.8 \pm 0.7) \times 10^{24}$		Lin88b	I
					$= 2.0 \times 10^{24}$		Man91	J
					$= (7.7 \pm 0.4) \times 10^{24}$	68	Ber92	I
					$= (7.2 \pm 0.3) \times 10^{24}$		Cru93	I,O
					$= (2.2 \pm 0.3) \times 10^{24}$		Tak96	I
			g.s.	0ν	$> 8.6 \times 10^{22}$	90	Ale00	
			$2^+_1(443)$	$0\nu + 2\nu$	$> 4.7 \times 10^{21}$	68	Bel87	
	Th.	$2\beta^-$	g.s.	0ν	$= 4.0 \times 10^{24}$	SM	Hax84	A
					$= 1.5 \times 10^{26}$	QRPA	Pan96	
					$= 1.1 \times 10^{25}$	QRPA	Sim97	
					$= 7.3 \times 10^{24}$	QRPA	Bar99a	
					$= 4.9 \times 10^{25}$	SM	Cau99	
					$= 2.5 \times 10^{25}$	QRPA	Sim99	
					$= (1.4 - 1.9) \times 10^{25}$	QRPA	Sto01	
				2ν	$= 8.8 \times 10^{22}$	SM	Hax84	
					$= 9.2 \times 10^{22}$	IBM	Sch85	
					$= 4.0 \times 10^{24}$	SU(4)	Rum95	
					$= 5.6 \times 10^{23}$	MCM	Aun96	
					$= (1.7 - 2.9) \times 10^{25}$	SSDH	Civ98	
					$= 4.1 \times 10^{23}$	SU(4)	Rum98	
					$= 5.0 \times 10^{23}$	SM	Cau99	
					$= 1.3 \times 10^{25}$	SSDH	Sem00	
				0νM1	$= 4.9 \times 10^{25}$	QRPA	Hir96	
					$= 3.6 \times 10^{26}$	QRPA	Sim99	
			$2^+_1(443)$	2ν	$= 5.9 \times 10^{30}$	QRPA	Sto94	
					$= 1.6 \times 10^{30}$	MCM	Aun96	
${}^{130}_{52}$**Te**$-{}^{130}_{54}$**Xe**	Exp.	$2\beta^-$	all modes		$= 1.4 \times 10^{21}$		Ing50	I
2528.9(2.1)					$= (8.2 \pm 0.6) \times 10^{20}$		Tak66	I
2528.8(1.3) [Dyc90]					$= 6.2 \times 10^{20}$		Kir67	I
34.08(0.62)					$= (3.0 \pm 0.4) \times 10^{20}$		Ger68	I
					$= (2.2 \pm 0.7) \times 10^{21}$		Kir68	I
					$= (2.0 \pm 0.3) \times 10^{21}$		Ale69	I
					$= (2.8 \pm 0.3) \times 10^{21}$		Sri72a	I
					$= 2.5 \times 10^{21}$		Sri72b	I
					$= (1.0 \pm 0.1) \times 10^{21}$		Hen75	I
					$= (2.6 \pm 0.3) \times 10^{21}$		Kir83a	I
					$= (2.6 \pm 0.2) \times 10^{21}$		Kir83b	J
					$= (7.0 \pm 2.0) \times 10^{20}$		Man86	J
					$= (1.5 - 2.8) \times 10^{21}$		Kir86	J

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$X$-{}_{Z\pm2}^{A}$Y ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Reference	Note
					$= (1.0 \pm 0.3) \times 10^{21}$		Ric86	I
					$< (1.3 \pm 0.1) \times 10^{21}$		Lin86	I
					$= (7.5 \pm 0.3) \times 10^{20}$		Lin88a	I
					$= 8.0 \times 10^{20}$		Man91	J
					$= (2.7 \pm 0.1) \times 10^{21}$	68	Ber92	I
					$= (7.9 \pm 1.0) \times 10^{20}$		Tak96	I
			g.s.	0ν	$> 1.4 \times 10^{23}$	90	Ale00	
				2ν	$> 3.0 \times 10^{20}$	90	Ale00	
				0νM1	$> 1.4 \times 10^{21}$	90	Ale00	
				0νM3	$> 7.0 \times 10^{20}$	90	Ale00	
			$2^+_1(536)$	0ν	$> 9.7 \times 10^{22}$	90	Ale00	
				$0\nu + 2\nu$	$> 4.5 \times 10^{21}$	68	Bel87	
					$> 1.6 \times 10^{21}$	90	Bar01	
			$2^+_2(1122)$	$0\nu + 2\nu$	$> 2.7 \times 10^{21}$	90	Bar01	
			$0^+_1(1794)$	$0\nu + 2\nu$	$> 2.3 \times 10^{21}$	90	Bar01	
	Th.	$2\beta^-$	g.s.	0ν	$= 1.6 \times 10^{23}$	SM	Hax84	A
					$= 2.1 \times 10^{24}$	QRPA	Pan96	
					$= (4.6 - 5.2) \times 10^{23}$	QRPA	Aun98	
					$= 3.3 \times 10^{23}$	QRPA	Bar99a	
					$= 5.8 \times 10^{24}$	SM	Cau99	
					$= 1.5 \times 10^{24}$	QRPA	Sim99	
					$= 9.8 \times 10^{23} - 1.1 \times 10^{24}$	QRPA	Sto01	
				2ν	$= 1.7 \times 10^{19}$	SM	Hax84	
					$= 1.7 \times 10^{19}$	IBM	Sch85	
					$= 7.0 \times 10^{20}$	SU(4)	Rum95	
					$= 2.6 \times 10^{20}$	MCM	Aun96	
					$= 9.4 \times 10^{19}$	SU(4)	Rum98	
					$= 2.3 \times 10^{20}$	SM	Cau99	
				0νM1	$= 4.9 \times 10^{23}$	QRPA	Hir96	
					$= 3.9 \times 10^{24}$	QRPA	Sim99	
			$2^+_1(536)$	2ν	$= 2.6 \times 10^{24}$	QRPA	Sto94	
					$= 2.7 \times 10^{23}$	MCM	Aun96	
					$= 3.0 \times 10^{22} - 1.4 \times 10^{23}$	MCM	Toi97	
			$2^+_2(1122)$	2ν	$= 1.0 \times 10^{28}$	MCM	Aun96	
					$= 2.0 \times 10^{25} - 3.2 \times 10^{26}$	MCM	Toi97	
			$0^+_1(1794)$	2ν	$= 3.3 \times 10^{20}$	MCM	Aun96	
					$= (2.6 - 7.1) \times 10^{20}$	MCM	Toi97	
${}^{124}_{54}$Xe$-{}^{124}_{52}$Te *2865.6(2.2)* *0.09(0.01)*	Exp.	$2\beta^+$	g.s.	0ν	$> 4.2 \times 10^{17}$	68	Bar89b	
				2ν	$> 2.0 \times 10^{14}$		Bar89b	
		$K\beta^+$	g.s.	0ν	$> 1.2 \times 10^{18}$	68	Bar89b	
				2ν	$> 4.8 \times 10^{16}$	68	Bar89b	
		$K\beta^+$	$2^+_1(603)$	0ν	$> 4.2 \times 10^{17}$	68	Bar89b	
		$2K$	g.s.	2ν	$> 1.1 \times 10^{17}$	90	Gav98	
	Th.	$2\beta^+$	g.s.	0ν	$= (3.4 - 4.3) \times 10^{27}$	QRPA	Aun98	A
		$\varepsilon\beta^+$	g.s.	2ν	$= 2.3 \times 10^{24}$	MCM	Aun96	
					$= 8.2 \times 10^{22}$	SU(4)	Rum98	
			$0^+_1(1156)$	2ν	$= 1.0 \times 10^{28}$	MCM	Aun96	
		2ε	g.s.	2ν	$= 3.9 \times 10^{23}$	MCM	Aun96	
					$= 7.0 \times 10^{21}$	SU(4)	Rum98	
			$0^+_1(1156)$	2ν	$= 5.3 \times 10^{24}$	MCM	Aun96	

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$X$-{}_{Z\pm2}^{A}$Y ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Reference	Note
${}^{126}_{54}$**Xe**$-{}^{126}_{52}$**Te**	Exp.	2ε			–			
897(6)	Th.	2ε			–			
0.09(0.01)								
${}^{134}_{54}$**Xe**$-{}^{134}_{56}$**Ba**	Exp.	$2\beta^-$	g.s.	0ν	$> 8.2 \times 10^{19}$	68	Bar89b	
830.1(3.0)				2ν	$> 1.1 \times 10^{16}$		Bar89b	
10.44(0.10)	Th.	$2\beta^-$			–			A
${}^{136}_{54}$**Xe**$-{}^{136}_{56}$**Ba**	Exp.	$2\beta^-$	g.s.	$0\nu(m_\nu)$	$> 4.4 \times 10^{23}$	90	Lue98	
2468(7)				$0\nu(\lambda)$	$> 2.6 \times 10^{23}$	90	Vui93	
8.87(0.16)				2ν	$> 8.1 \times 10^{20}$	90	Gav00b	
				0νM1	$> 7.2 \times 10^{21}$	90	Lue98	
			$2^+_1(819)$	0ν	$> 6.5 \times 10^{21}$	90	Bel91	
	Th.	$2\beta^-$	g.s.	0ν	$= 1.2 \times 10^{25}$	SM	Cau96	A
					$= 2.8 \times 10^{24}$	QRPA	Pan96	
					$= 3.4 \times 10^{23}$	QRPA	Sim97	
					$= (2.8 - 9.3) \times 10^{23}$	QRPA	Aun98	
					$= 1.2 \times 10^{25}$	SM	Cau99	
					$= 1.0 \times 10^{25}$	QRPA	Sim99	
					$= (5.6 - 6.2) \times 10^{24}$	QRPA	Sto01	
				2ν	$= 1.0 \times 10^{21}$	SU(4)	Rum95	
					$= 2.0 \times 10^{21}$	SM	Cau96	
					$= 1.3 \times 10^{20}$	MCM	Aun96	
					$= 1.1 \times 10^{20}$	SU(4)	Rum98	
					$= 2.1 \times 10^{21}$	SM	Cau99	
				0νM1	$= 2.2 \times 10^{24}$	QRPA	Hir96	
					$= 2.8 \times 10^{25}$	QRPA	Sim99	
			$2^+_1(819)$	2ν	$= 4.7 \times 10^{23}$	QRPA	Sto94	
					$= 2.4 \times 10^{24}$	MCM	Aun96	
			$2^+_2(1551)$	2ν	$= 5.1 \times 10^{26}$	MCM	Aun96	
			$0^+_1(1579)$	2ν	$= 2.5 \times 10^{21}$	MCM	Aun96	
${}^{130}_{56}$**Ba**$-{}^{130}_{54}$**Xe**	Exp.	$2\beta^+, \varepsilon\beta^+, 2\varepsilon$	all modes		$> 4.0 \times 10^{21}$		Bar96a	I,P
2611(7)	Th.	$\varepsilon\beta^+$	g.s.	2ν	$= 3.1 \times 10^{24}$	MCM	Aun96	A
0.106(0.001)					$= 2.2 \times 10^{23}$	SU(4)	Rum98	
			$0^+_1(1794)$	2ν	$= 1.2 \times 10^{28}$	MCM	Aun96	
		2ε	g.s.	2ν	$= 4.7 \times 10^{23}$	MCM	Aun96	
					$= 7.5 \times 10^{21}$	SU(4)	Rum98	
			$0^+_1(1794)$	2ν	$= 5.4 \times 10^{23}$	MCM	Aun96	
${}^{132}_{56}$**Ba**$-{}^{132}_{54}$**Xe**	Exp.	2ε	all modes		$> 3.0 \times 10^{20}$		Bar96a	I,P
839.9(3.2)	Th.	2ε			–			
0.101(0.001)								
${}^{136}_{58}$**Ce**$-{}^{136}_{56}$**Ba**	Exp.	$2\beta^+$	g.s.	0ν	$> 6.9 \times 10^{17}$	68	Ber97	
2400(50)				2ν	$> 1.8 \times 10^{16}$	90	Dan01	
0.185(0.002)		$K\beta^+$	g.s.	0ν	$> 3.8 \times 10^{16}$	90	Dan01	
				2ν	$> 1.8 \times 10^{15}$	90	Dan01	
		$2K$	g.s.	0ν	$> 6.0 \times 10^{15}$	90	Dan01	
				2ν	$> 7.0 \times 10^{13}$	90	Dan01	

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$**X**$-{}^{A}_{Z\pm2}$**Y** ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Refer- ence	Note
	Th.	$2\beta^+$	g.s.	0ν	$= (2.6-2.7)\times10^{29}$	QRPA	Aun98	A
		$\varepsilon\beta^+$	g.s.	2ν	$= 6.0\times10^{23}$	SU(4)	Rum98	
		2ε	g.s.	2ν	$= (3.2-5.1)\times10^{21}$	SSDH	Civ98	
					$= 9.6\times10^{21}$	SU(4)	Rum98	
${}^{138}_{58}$**Ce**$-{}^{138}_{56}$**Ba**	Exp.	$2K$	g.s.	0ν	$> 1.8\times10^{15}$	90	Dan01	
693(10)				2ν	$> 9.0\times10^{13}$	90	Dan01	
0.251(0.002)	Th.	2ε			–			
${}^{142}_{58}$**Ce**$-{}^{142}_{60}$**Nd**	Exp.	$2\beta^-$	g.s.	0ν	$> 1.5\times10^{19}$	68	Ber97	Q
1416.9(2.1)				2ν	$> 1.6\times10^{17}$	90	Dan01	
11.114(0.051)	Th.	$2\beta^-$			–			A
${}^{146}_{60}$**Nd**$-{}^{146}_{62}$**Sm**	Exp.	$2\beta^-$			–			Q
70.2(2.9)	Th.	$2\beta^-$			–			A
17.2(0.3)								
${}^{148}_{60}$**Nd**$-{}^{148}_{62}$**Sm**	Exp.	$2\beta^-$	$2^+_1(550)$	$0\nu+2\nu$	$> 3.0\times10^{18}$	90	Bel82	Q
1928.8(1.9)			$2^+_2(1454)$	$0\nu+2\nu$	$> 2.7\times10^{18}$	90	Bel82	
5.7(0.1)	Th.	$2\beta^-$			–			A
${}^{150}_{60}$**Nd**$-{}^{150}_{62}$**Sm**	Exp.	$2\beta^-$	g.s.	$0\nu(m_\nu)$	$> 1.7\times10^{21}$	95	Kli86	
3367.5(2.2)				$0\nu(\lambda)$	$> 1.1\times10^{21}$	95	Kli86	
5.6(0.2)				0ν	$> 1.2\times10^{21}$	90	Sil97	
				2ν	$> 1.8\times10^{19}$	95	Kli86	
					$= 1.9^{+0.7}_{-0.4}\times10^{19}$		Art95	
					$= (6.8\pm0.8)\times10^{18}$		Sil97	
				0νM1	$> 2.8\times10^{20}$	90	Sil97	
			$2^+_1(334)$	$0\nu+2\nu$	$> 9.1\times10^{19}$	90	Arp99	
			$0^+_1(741)$	$0\nu+2\nu$	$> 1.0\times10^{20}$	90	Arp99	
			$4^+_1(773)$	$0\nu+2\nu$	$> 2.0\times10^{19}$	90	Arp94	
			$2^+_2(1046)$	$0\nu+2\nu$	$> 1.4\times10^{20}$	90	Arp96	
			$2^+_3(1194)$	$0\nu+2\nu$	$> 2.7\times10^{18}$	90	Bel82	
			$0^+_2(1256)$	$0\nu+2\nu$	$> 2.0\times10^{20}$	90	Arp99	
	Th.	$2\beta^-$	g.s.	0ν	$= 8.7\times10^{22}$	QRPA	Sim99	A
				2ν	$= 6.7\times10^{18}$	pSU(3)	Hir95b	
					$= 1.0\times10^{19}$	SU(4)	Rum95	
					$= 2.0\times10^{18}$	SU(4)	Rum98	
				0νM1	$= 3.3\times10^{22}$	QRPA	Hir96	
					$= 1.4\times10^{23}$	QRPA	Sim99	
			$2^+_1(334)$	2ν	$= 7.2\times10^{24}$	pSU(3)	Hir95b	
			$0^+_1(741)$	2ν	$= \infty$	pSU(3)	Hir95b	
			$0^+_2(1256)$	2ν	$= 4.3\times10^{22}$	pSU(3)	Hir95b	
${}^{144}_{62}$**Sm**$-{}^{144}_{60}$**Nd**	Exp.	$\varepsilon\beta^+$, 2ε			–			Q
1781.1(1.8)	Th.	$\varepsilon\beta^+$, 2ε			–			
3.07(0.07)								
${}^{154}_{62}$**Sm**$-{}^{154}_{64}$**Gd**	Exp.	$2\beta^-$	$2^+_1(123)$	$0\nu+2\nu$	$> 2.3\times10^{18}$	68	Der96	
1251.0(1.3)	Th.	$2\beta^-$	g.s.	0ν	$= 7.8\times10^{25}$	IQM	Kar85	A
22.75(0.29)				2ν	$= 1.6\times10^{20}$	IQM	Kar85	

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$X$-{}^{A}_{Z\pm2}$Y ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Refer-ence	Note
${}^{152}_{64}$**Gd**$-{}^{152}_{62}$**Sm**	Exp.	2ε			–			Q
55.6(1.2)	Th.	2ε			–			
0.20(0.01)								
${}^{160}_{64}$**Gd**$-{}^{160}_{66}$**Dy**	Exp.	$2\beta^-$	g.s.	0ν	$> 1.3 \times 10^{21}$	90	Dan01	
1729.7(1.3)				2ν	$> 1.9 \times 10^{19}$	90	Dan01	
21.86(0.19)				0νM1	$> 3.5 \times 10^{18}$	90	Dan01	
				0νM3	$> 1.3 \times 10^{19}$	90	Dan01	
			$2^+_1(87)$	0ν	$> 1.3 \times 10^{21}$	90	Dan01	
				2ν	$> 2.1 \times 10^{19}$	90	Dan01	
	Th.	$2\beta^-$			–			A
${}^{156}_{66}$**Dy**$-{}^{156}_{64}$**Gd**	Exp.	$\varepsilon\beta^+$, 2ε			–			Q
2011(6)	Th.	2ε	g.s.	2ν	$= 2.7 \times 10^{22}$	pSU(3)	Cer99	
0.06(0.01)			$0^+_1(1050)$	2ν	$= 8.3 \times 10^{24}$	pSU(3)	Cer99	
			$0^+_2(1168)$	2ν	$= 1.1 \times 10^{25}$	pSU(3)	Cer99	
${}^{158}_{66}$**Dy**$-{}^{158}_{64}$**Gd**	Exp.	2ε			–			Q
283.3(2.4)	Th.	2ε			–			
0.10(0.01)								
${}^{162}_{68}$**Er**$-{}^{162}_{66}$**Dy**	Exp.	$\varepsilon\beta^+$, 2ε			–			Q
1844.5(2.8)	Th.	2ε	g.s.	2ν	$= 2.9 \times 10^{22}$	pSU(3)	Cer99	
0.14(0.01)			$0^+_1(1400)$	2ν	$= 3.7 \times 10^{27}$	pSU(3)	Cer99	
${}^{164}_{68}$**Er**$-{}^{164}_{66}$**Dy**	Exp.	2ε			–			Q
24.1(2.5)	Th.	2ε			–			
1.61(0.03)								
${}^{170}_{68}$**Er**$-{}^{170}_{70}$**Yb**	Exp.	$2\beta^-$	$2^+_1(84)$	$0\nu + 2\nu$	$> 3.2 \times 10^{17}$	68	Der96	Q
653.6(1.7)	Th.	$2\beta^-$			–			A
14.93(0.27)								
${}^{168}_{70}$**Yb**$-{}^{168}_{68}$**Er**	Exp.	$\varepsilon\beta^+$, 2ε			–			Q
1422.1(3.7)	Th.	2ε	g.s.	2ν	$= 2.0 \times 10^{23}$	pSU(3)	Cer99	
0.13(0.01)			$0^+_1(1217)$	2ν	$= 5.4 \times 10^{33}$	pSU(3)	Cer99	
${}^{176}_{70}$**Yb**$-{}^{176}_{72}$**Hf**	Exp.	$2\beta^-$	$2^+_1(88)$	$0\nu + 2\nu$	$> 1.6 \times 10^{17}$	68	Der96	Q
1086.7(1.9)	Th.	$2\beta^-$			–			A
12.76(0.41)								
${}^{174}_{72}$**Hf**$-{}^{174}_{70}$**Yb**	Exp.	$\varepsilon\beta^+$, 2ε			–			Q
1101.1(2.3)	Th.	$\varepsilon\beta^+$, 2ε			–			
0.16(0.01)								
${}^{180}_{74}$**W**$-{}^{180}_{72}$**Hf**	Exp.	2ε	g.s.	0ν	$> 5.0 \times 10^{16}$	90	Geo95a	Q
146(5)	Th.	2ε			–			
0.12(0.01)								
${}^{186}_{74}$**W**$-{}^{186}_{76}$**Os**	Exp.	$2\beta^-$	g.s.	0ν	$> 2.7 \times 10^{20}$	90	Geo95a	Q
488.0(1.7)				2ν	$> 5.9 \times 10^{17}$	90	Geo95a	
28.43(0.19)			$2^+_1(137)$	0ν	$> 2.4 \times 10^{20}$	90	Geo95a	

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\varepsilon\beta^+$; 2ε)

See page 93 for Explanation of Tables

${}^{A}_{Z}$X$-{}^{A}_{Z\pm2}$Y ΔM_A in keV δ in %	Type of result	Decay channel	Level of daughter nucleus	Decay mode	$T_{1/2}$ (yr)	CL in % or Theor. Model	Refer-ence	Note
	Th.	$2\beta^-$			–			A
${}^{184}_{76}$Os$-{}^{184}_{74}$W	Exp.	$\varepsilon\beta^+$	g.s.	0ν	$> 9.9 \times 10^{9}$		Fre52	F,Q
1451.5(1.4)	Th.	$\varepsilon\beta^+, 2\varepsilon$			–			
0.02(0.01)								
${}^{192}_{76}$Os$-{}^{192}_{78}$Pt	Exp.	$2\beta^-$	g.s.	0ν	$> 9.8 \times 10^{12}$		Fre52	F,Q
413.5(3.0)	Th.	$2\beta^-$			–			A
40.78(0.19)								
${}^{190}_{78}$Pt$-{}^{190}_{76}$Os	Exp.	$\varepsilon\beta^+$	g.s.	0ν	$> 3.1 \times 10^{11}$		Fre52	F,Q
1383(6)	Th.	$\varepsilon\beta^+, 2\varepsilon$			–			
0.014(0.001)								
${}^{198}_{78}$Pt$-{}^{198}_{80}$Hg	Exp.	$2\beta^-$	g.s.	0ν	$> 3.2 \times 10^{14}$		Fre52	F,Q
1047(3)	Th.	$2\beta^-$			–			A
7.163(0.055)								
${}^{196}_{80}$Hg$-{}^{196}_{78}$Pt	Exp.	2ε	g.s.	0ν	$> 2.5 \times 10^{18}$	68	Buk90	Q
819.7(3.0)			2^+_1(356)	$0\nu + 2\nu$	$> 2.5 \times 10^{18}$	68	Buk90	
0.15(0.01)	Th.	2ε			–			
${}^{204}_{80}$Hg$-{}^{204}_{82}$Pb	Exp.	$2\beta^-$			–			
416.3(1.5)	Th.	$2\beta^-$			–			A
6.87(0.15)								
${}^{232}_{90}$Th$-{}^{232}_{92}$U	Exp.	$2\beta^-$			–			Q
842.2(2.5)	Th.	$2\beta^-$			–			A
100								
${}^{238}_{92}$U$-{}^{238}_{94}$Pu	Exp.	$2\beta^-$	all modes		$= (2.0 \pm 0.6) \times 10^{21}$	68	Tur91	R,Q
1145.0(1.3)	Th.	$2\beta^-$	g.s.	0ν	$= 5.7 \times 10^{24}$	IQM	Kar85	A
99.2745(0.0106)				2ν	$= 1.2 \times 10^{19}$	IQM	Kar85	

A Additional theoretical results—published before 1995—can be found in [Tre95].

B An ordinary β^- decay ^{48}Ca(0^+)$\rightarrow{}^{48}$Sc($6^+, 5^+, 4^+$) is also possible ($Q_\beta = 278(5)$ keV [Aud95]). The half-life of the most probable transition ($0^+ \rightarrow 5^+$) was calculated as 7.6×10^{20} yr [War85] and as $1.1^{+0.8}_{-0.6} \times 10^{21}$ yr [Aun99]. The experimental limit is $T_{1/2}({}^{48}\text{Ca}, \beta^-) > 6.0 \times 10^{18}$ yr with 95% CL [Alb85].

C The results of this experiment were criticized in [Dan94] because of possibly improper background reduction which was, most probably, caused by the incorrect operation of the active shield. The reestimated $T^{0\nu}_{1/2}$ value is $\simeq 4 \times 10^{20}$ yr [Dan94].

D This result was obtained in [Bar89a] using the experimental data of [Bar70].

E The indication of a positive effect with $T_{1/2}({}^{64}\text{Zn}, \varepsilon\beta^+\ \ 0\nu + 2\nu\ \ \text{g.s.} - \text{g.s.}) = (1.1 \pm 0.9) \times 10^{19}$ yr was claimed in Ref. [Bik95] on the basis of observed 511 keV peak. However, no attempts were made to estimate systematic effects which could cause this peak (for example, radioactive impurities of the sample used).

F Calculated in [Tre95] on the basis of the results of [Fre52] with corrections on the decay energy and the natural abundance of the isotope.

G By using another statistical approach, the value $T^{0\nu}_{1/2} > 5.7 \times 10^{25}$ yr with 90% CL was obtained, which, however, was criticized in [Avi00].

H This is the final result of the experiment. The previous value $T^{2\nu}_{1/2} = 9.2^{+0.7}_{-0.4} \times 10^{20}$ yr [Avi91] often cited in literature was based on near half of the total statistics [Bro93].

I The result of a geochemical experiment.

J Recommended value based on latest geochemical experiments.

K An ordinary β^- decay ^{96}Zr(0^+) → ^{96}Nb(6^+) is also possible ($Q_\beta = 164(4)$ keV [Aud95]). In geochemical experiments, only an excess amount of daughter isotope is measured but not the way of its production. Thus the observed [Kaw93] excess of ^{96}Mo can be caused not only by 2β decay ^{96}Zr → ^{96}Mo but also by the chain of single β decays ^{96}Zr → ^{96}Nb → ^{96}Mo. Experimental limit for β^- decay of ^{96}Zr is $T_{1/2}(^{96}\mathrm{Zr}, \beta^-) > 3.8 \times 10^{19}$ yr with 90% CL [Arp94].

L Preliminary result.

M This result was obtained in [Bar87] using the experimental data of [Win52].

N This result was obtained in [Bar87] using the experimental data of [Kal52].

O The experimental data of [Ber92] were reestimated in [Cru93] using the experimental measurements of thick-target yields of I isotope from proton interactions in Te.

P Using the experimental data of [Sri76].

Q The parent 2β isotope is (potentially) α radioactive. The corresponding Q_α values and half-lives are given below. Theoretical $T_{1/2}$ values are taken from Refs. [Poe86] (evaluation with semiempirical formula), [Alb88] (microscopical approach), and calculated here on the base of the cluster model of Ref. [Buc91].

	Q_α, keV [Aud95]	$T_{1/2}^{\alpha,\ \mathrm{exp}}$, yr		$T_{1/2}^{\alpha,\ \mathrm{calc}}$, yr [Poe86]	[Alb88]	[Buc91]
$^{142}_{58}$Ce	1299.6(3.5)	$> 5 \times 10^{16}$	[Mac61]	–	3.8×10^{27}	4.6×10^{27}
$^{146}_{60}$Nd	1182.2(2.2)	–	–	–	–	2.0×10^{34}
$^{148}_{60}$Nd	598.6(3.1)	–	–	–	–	6.8×10^{70}
$^{144}_{62}$Sm	76(19)	–	–	–	–	7.4×10^{311}
$^{152}_{64}$Gd	2204.6(1.4)	$= 1.08 \times 10^{14}$	[ToI96]	1.0×10^{14}	–	9.0×10^{13}
$^{156}_{66}$Dy	1758(6)	$> 1 \times 10^{18}$	[Rie58]	5.0×10^{24}	4.3×10^{24}	2.6×10^{24}
$^{158}_{66}$Dy	874.8(2.4)	–	–	–	–	2.6×10^{58}
$^{162}_{68}$Er	1646.0(3.5)	$> 1.4 \times 10^{14}$	[Por56]	4.0×10^{29}	2.2×10^{29}	2.1×10^{29}
$^{164}_{68}$Er	1304.1(2.5)	–	–	–	9.2×10^{39}	1.1×10^{40}
$^{170}_{68}$Er	50.2(2.4)	–	–	–	–	1.0×10^{442}
$^{168}_{70}$Yb	1951(4)	$> 1.3 \times 10^{14}$	[Por56]	5.0×10^{24}	1.9×10^{24}	1.8×10^{24}
$^{176}_{70}$Yb	571(4)	–	–	2.5×10^{96}	–	1.4×10^{94}
$^{174}_{72}$Hf	2494.8(2.5)	$= 2.0 \times 10^{15}$	[ToI96]	6.3×10^{16}	–	3.4×10^{16}
$^{180}_{74}$W	2516(5)	$> 7.4 \times 10^{16}$ 90% CL	[Geo95b]	2.5×10^{18}	7.5×10^{17}	8.3×10^{17}
$^{186}_{74}$W	1123(7)	$> 6.5 \times 10^{18}$ 90% CL	[Geo95b]	2.5×10^{57}	–	8.7×10^{55}
$^{184}_{76}$Os	2964(4)	$> 5.6 \times 10^{13}$ 95% CL	[Spe76]	5.0×10^{13}	2.1×10^{13}	3.0×10^{13}
$^{192}_{76}$Os	362.2(3.8)	–	–	1.3×10^{154}	–	8.1×10^{148}
$^{190}_{78}$Pt	3249(6)	$= 6.5 \times 10^{11}$	[ToI96]	6.3×10^{11}	–	5.2×10^{11}
$^{198}_{78}$Pt	87.0(3.9)	–	–	6.3×10^{391}	–	4.9×10^{377}
$^{196}_{80}$Hg	2027.3(3.8)	$> 1 \times 10^{14}$	[Mac61]	1.3×10^{33}	1.0×10^{32}	2.8×10^{32}
$^{232}_{90}$Th	4082.8(1.4)	$= 1.405 \times 10^{10}$	[ToI96]	2.0×10^{10}	–	3.6×10^{10}
$^{238}_{92}$U	4269.8(2.9)	$= 4.468 \times 10^{9}$	[ToI96]	6.3×10^{9}	–	1.5×10^{10}

For six daughter isotopes, α radioactivity has been observed experimentally:

	Q_α, keV [Aud95]	$T_{1/2}^{\alpha,\ \mathrm{exp}}$, yr [ToI96]
$^{144}_{60}$Nd	1905.2(1.8)	2.29×10^{15}
$^{146}_{62}$Sm	2528.9(2.9)	1.03×10^{8}
$^{148}_{62}$Sm	1986.0(1.2)	7×10^{15}
$^{186}_{76}$Os	2822.0(1.7)	2.0×10^{15}
$^{232}_{92}$U	5413.55(0.14)	68.9
$^{238}_{94}$Pu	5593.20(0.19)	87.7

R The result of a radiochemical experiment.

TABLE II. List of Known 2β Unstable Nuclides Absent in Natural Isotopic Composition of Elements[a]

See page 94 for Explanation of Tables

Parent nuclide	Main channel of decay and $T_{1/2}$		Potential 2β transition and daughter nuclide		ΔM_A, keV
$^{148}_{64}$Gd[b]	α	74.6 yr	$2\beta^+ + \varepsilon\beta^+ + 2\varepsilon$	$^{148}_{62}$Sm	3066.3(2.0)
$^{150}_{64}$Gd	α	1.79×10^6 yr	$\varepsilon\beta^+ + 2\varepsilon$	$^{150}_{62}$Sm	1289(6)
$^{154}_{66}$Dy	α	3.0×10^6 yr	$2\beta^+ + \varepsilon\beta^+ + 2\varepsilon$	$^{154}_{64}$Gd	3316(8)
$^{216}_{84}$Po	α	0.145 s	$2\beta^-$	$^{216}_{86}$Rn	1534(8)
$^{212}_{86}$Rn	α	23.9 m	$\varepsilon\beta^+ + 2\varepsilon$	$^{212}_{84}$Po	1711.3(3.0)
$^{214}_{86}$Rn	α	0.27 μs	2ε	$^{214}_{84}$Po	149(9)
$^{220}_{86}$Rn	α	55.6 s	$2\beta^-$	$^{220}_{88}$Ra	344(10)
$^{218}_{88}$Ra	α	25.6 μs	$\varepsilon\beta^+ + 2\varepsilon$	$^{218}_{86}$Rn	1432(11)
$^{226}_{88}$Ra	$\alpha + ^{14}_{6}$C	1600 yr	$2\beta^-$	$^{226}_{90}$Th	477(5)
$^{224}_{90}$Th	α	1.05 s	$\varepsilon\beta^+ + 2\varepsilon$	$^{224}_{88}$Ra	1171(12)
$^{230}_{92}$U	α	20.8 d	2ε	$^{230}_{90}$Th	746(5)
$^{236}_{94}$Pu	α + sf	2.858 yr	2ε	$^{236}_{92}$U	452.9(2.0)
$^{244}_{94}$Pu[c]	α + sf	8.08×10^7 yr	$2\beta^-$	$^{244}_{96}$Cm	1352(5)
$^{242}_{96}$Cm	α + sf	162.8 d	2ε	$^{242}_{94}$Pu	86.1(0.9)
$^{248}_{96}$Cm	α + sf	3.40×10^5 yr	$2\beta^-$	$^{248}_{98}$Cf	153(7)
$^{254}_{98}$Cf	sf + α	60.5 d	$2\beta^-$	$^{254}_{100}$Fm	436(12)
$^{252}_{100}$Fm	α + sf	25.39 h	2ε	$^{252}_{98}$Cf	783(7)
$^{260}_{100}$Fm	sf	~4 ms	$2\beta^-$	$^{260}_{102}$No	~0.7 MeV[d]
$^{258}_{102}$No	sf + α	~1.2 ms	$\varepsilon\beta^+ + 2\varepsilon$	$^{258}_{100}$Fm	1050(280)

[a] Only "conventional" 2β decaying candidate nuclides are listed: for these, the mass of an intermediate nucleus $(A, Z \pm 1)$ is larger than that of initial (A, Z) and final $(A, Z \pm 2)$ nuclei.

[b] Theoretical calculations [Sta91]: $T^{0\nu}_{1/2} \cdot \langle m_\nu \rangle^2 = 1.6 \times 10^{28}$ yr $\cdot$ eV^2, $T^{2\nu}_{1/2} \geq 2.2 \times 10^{26}$ yr.

[c] Result of radiochemical experiments [Moo92]: $T_{1/2}$($^{244}_{94}$Pu, all $2\beta^-$ modes) $> 1.1 \times 10^{18}$ yr with 95% CL. Theoretical calculations [Sta90]: $T^{0\nu}_{1/2} \cdot \langle m_\nu \rangle^2 = 5.7 \times 10^{23}$ yr $\cdot$ eV^2, $T^{2\nu}_{1/2} = 9.3 \times 10^{21} - 6.9 \times 10^{22}$ yr. Calculations [Cas94] predict that $2\nu 2\beta$ decay of $^{244}_{94}$Pu is forbidden.

[d] Estimated from the data of Ref. [ToI96].

REFERENCES FOR TABLES

Aal96 C. E. Aalseth, F. T. Avignone III, R. L. Brodzinski, J. I. Collar, E. Garcia, D. Gonzales, F. Hasenbalg, W. K. Hensley, I. V. Kirpichnikov, A. A. Klimenko, H. S. Miley, A. Morales, J. Morales, A. Ortiz de Solorzano, S. B. Osetrov, V. S. Pogosov, J. Puimedon, J. H. Reeves, C. Saenz, A. Salinas, M. L. Sarsa, A. A. Smolnikov, A. S. Starostin, A. G. Tamanyan, A. A. Vasenko, S. I. Vasiliev, and J. A. Villar, Nucl. Phys. B (Proc. Suppl.) **48**, 223 (1996).

Alb85 D. E. Alburger and J. B. Cumming, Phys. Rev. C **32**, 1358 (1985).

Alb86 D. E. Alburger and J. B. Cumming, Phys. Rev. C **33**, 2169 (1986).

Alb88 B. Al-Bataina and J. Janecke, Phys. Rev. C **37**, 1667 (1988).

Ale69 E. C. Alexander, Jr., B. Srinivasan, and O. K. Manuel, Earth Planet. Sci. Lett. **5**, 478 (1969).

Ale00 A. Alessandrello, C. Brofferio, O. Cremonesi, E. Fiorini, A. Giuliani, A. Nucciotti, M. Pavan, G. Pessina, S. Pirro, E. Previtali, M. Vanzini, L. Zanotti, C. Bucci, and C. Pobes, Phys. Lett. B **486**, 13 (2000).

Als97 M. Alston-Garnjost, B. L. Dougherty, R. W. Kenney, R. D. Tripp, J. M. Krivicich, H. W. Nicholson, C. S. Sutton, B. D. Dieterle, S. D. Foltz, C. P. Leavitt, R. A. Reeder, J. D. Baker, and A. J. Caffrey, Phys. Rev. C **55**, 474 (1997).

Arn96 R. Arnold, C. Augier, A. Barabash, D. Blum, V. Brudanin, J. E. Campagne, D. Dassie, V. Egorov, R. Eschbach, J. L. Guyonnet, F. Hubert, Ph. Hubert, S. Jullian, O. Kochetov, I. Kisel, V. N. Kornoukov, V. Kovalenko, D. Lalanne, F. Laplanche, F. Leccia, I. Linck, C. Longuemare, F. Mauger, P. Mennrath, H. W. Nicholson, A. Nozdrin, F. Piquemal, O. Purtov, J.-L. Reyss, F. Scheibling, J. Suhonen, C. S. Sutton, G. Szklarz, V. I. Tretyak, V. Umatov, I. Vanushin, A. Vareille, Yu. Vasilyev, Ts. Vylov, and V. Zerkin, Z. Phys. C **72**, 239 (1996).

Arn98 R. Arnold, C. Augier, J. Baker, A. Barabash, D. Blum, V. Brudanin, A. J. Caffrey, J. E. Campagne, E. Caurier, D. Dassie, V. Egorov, R. Eschbach, T. Filipova, R. Gurriaran, J. L. Guyonnet, F. Hubert, Ph. Hubert, S. Jullian, I. Kisel, O. Kochetov, V. N. Kornoukhov, V. Kovalenko, D. Lalanne, F. Laplanche, F. Leccia, I. Linck, C. Longuemare, Ch. Marquet, F. Mauger, P. Mennrath, H. W. Nicholson, I. Pilugin, F. Piquemal, O. Purtov, J.-L. Reyss, X. Sarazin, F. Scheibling, J. Suhonen, C. S. Sutton, G. Szklarz, V. Timkin, R. Torres, V. I. Tretyak, V. Umatov, I. Vanyushin, A. Vareille, Yu. Vasilyev, Ts. Vylov, and V. Zerkin, Nucl. Phys. A **636**, 209 (1998).

Arn99 R. Arnold, C. Augier, J. Baker, A. Barabash, D. Blum, V. Brudanin, A. J. Caffrey, J. E. Campagne, E. Caurier, D. Dassie, V. Egorov, T. Filipova, R. Gurriaran, J. L. Guyonnet, F. Hubert, Ph. Hubert, S. Jullian, I. Kisel, O. Kochetov, V. N. Kornoukhov, V. Kovalenko, D. Lalanne, F. Laplanche, F. Leccia, I. Linck, C. Longuemare, Ch. Marquet, F. Mauger, H. W. Nicholson, I. Pilugin, F. Piquemal, J.-L. Reyss, X. Sarazin, F. Scheibling, J. Suhonen, C. S. Sutton, G. Szklarz, V. Timkin, R. Torres, V. I. Tretyak, V. Umatov, I. Vanyushin, A. Vareille, Yu. Vasilyev, and Ts. Vylov, Nucl. Phys. A **658**, 299 (1999).

Arn00 R. Arnold, C. Augier, J. Baker, A. Barabash, D. Blum, V. Brudanin, A. J. Caffrey, J. E. Campagne, E. Caurier, D. Dassie, V. Egorov, T. Filipova, R. Gurriaran, J. L. Guyonnet, F. Hubert, Ph. Hubert, S. Jullian, I. Kisel, O. Kochetov, V. N. Kornoukhov, V. Kovalenko, D. Lalanne, F. Laplanche, F. Leccia, I. Linck, C. Longuemare, Ch. Marquet, F. Mauger, H. W. Nicholson, I. Pilugin, F. Piquemal, J.-L. Reyss, X. Sarazin, F. Scheibling, J. Suhonen, C. S. Sutton, G. Szklarz, V. Timkin, R. Torres, V. Umatov, I. Vanyushin, A. Vareille, V. Vasilyev, and Ts. Vylov, Nucl. Phys. A **678**, 341 (2000).

Arp94 C. Arpesella, A. S. Barabash, E. Bellotti, C. Brofferio, E. Fiorini, P. P. Sverzellati, and V. I. Umatov, Europhys. Lett. **27**, 29 (1994).

Arp96 C. Arpesella, E. Bellotti, E. Fiorini, L. Miramonti, and P. P. Sverzellati, Nucl. Phys. B (Proc. Suppl.) **48**, 247 (1996).

Arp99 C. Arpesella, E. Bellotti, N. Ferrari, and L. Zanotti, Nucl. Phys. B (Proc. Suppl.) **70**, 249 (1999).

Art95 V. Artemiev, E. Brakchman, A. Karelin, V. Kirichenko, A. Klimenko, O. Kozodaeva, V. Lubimov, A. Mitin, S. Osetrov, V. Paramokhin, A. Pomansky, A. Smolnikov, T. Tsvetkova, S. Vasilyev, and O. Zeldovich, Phys. Lett. B **345**, 564 (1995).

Ash99 V. D. Ashitkov, A. S. Barabash, S. G. Belogurov, G. Carugno, S. I. Konovalov, F. Massera, I. O. Pilugin, G. Puglierin, R. R. Saakyan, V. N. Stekhanov, V. I. Umatov, and I. A. Vanushin, Phys. At. Nucl. **62**, 2044 (1999).

REFERENCES FOR TABLES continued

Aud95 G. Audi and A. H. Wapstra, Nucl. Phys. A **595**, 409 (1995).

Aun95 M. Aunola, J. Suhonen, A. S. Barabash, V. I. Umatov, R. Gurriaran, F. Hubert, and Ph. Hubert, JETP Lett. **62**, 706 (1995).

Aun96 M. Aunola and J. Suhonen, Nucl. Phys. A **602**, 133 (1996).

Aun98 M. Aunola and J. Suhonen, Nucl. Phys. A **643**, 207 (1998).

Aun99 M. Aunola, J. Suhonen, and T. Siiskonen, Europhys. Lett. **46**, 577 (1999).

Avi91 F. T. Avignone III, R. L. Brodzinski, C. K. Guerard, I. V. Kirpichnikov, H. S. Miley, V. S. Pogosov, J. H. Reeves, A. S. Starostin, and A. G. Tamanyan, Phys. Lett. B **256**, 559 (1991).

Avi00 F. T. Avignone III, C. E. Aalseth, and R. L. Brodzinski, Phys. Rev. Lett. **85**, 465 (2000).

Bal96 A. Balysh, A. De Silva, V. I. Lebedev, K. Lou, M. K. Moe, M. A. Nelson, A. Piepke, A. Pronskiy, M. A. Vient, and P. Vogel, Phys. Rev. Lett. **77**, 5186 (1996).

Bar70 R. K. Bardin, P. J. Gollon, J. D. Ullman, and C. S. Wu, Nucl. Phys. A **158**, 337 (1970).

Bar87 A. S. Barabash, preprint ITEP 56 (Moscow, 1987).

Bar89a A. S. Barabash, Phys. Lett. B **216**, 257 (1989).

Bar89b A. S. Barabash, V. V. Kuzminov, V. M. Lobashev, V. M. Novikov, B. M. Ovchinnikov, and A. A. Pomansky, Phys. Lett. B **223**, 273 (1989).

Bar90 A. S. Barabash, A. V. Kopylov, and V. I. Cherehovsky, Phys. Lett. B **249**, 186 (1990).

Bar95a A. S. Barabash, A. V. Derbin, L. A. Popeko, and V. I. Umatov, Z. Phys. A **352**, 231 (1995).

Bar95b A. S. Barabash, F. T. Avignone III, J. I. Collar, C. K. Guerard, R. J. Arthur, R. L. Brodzinski, H. S. Miley, J. H. Reeves, J. R. Meier, K. Ruddick, and V. I. Umatov, Phys. Lett. B **345**, 408 (1995).

Bar96a A. S. Barabash and R. R. Saakyan, Phys. At. Nucl. **59**, 179 (1996).

Bar96b A. S. Barabash, R. Gurriaran, F. Hubert, Ph. Hubert, J. L. Reyss, J. Suhonen, and V. I. Umatov, J. Phys. G Nucl. Part. Phys. **22**, 487 (1996).

Bar96c A. S. Barabash, V. I. Umatov, R. Gurriaran, F. Hubert, Ph. Hubert, M. Aunola, and J. Suhonen, Nucl. Phys. A **604**, 115 (1996).

Bar97 A. S. Barabash, R. Gurriaran, F. Hubert, Ph. Hubert, and V. I. Umatov, Z. Phys. A **357**, 351 (1997).

Bar99a C. Barbero, F. Krmpotic, A. Mariano, and D. Tadic, Nucl. Phys. A **650**, 485 (1999).

Bar99b A. S. Barabash, R. Gurriaran, F. Hubert, Ph. Hubert, and V. I. Umatov, Phys. At. Nucl. **62**, 2039 (1999).

Bar01 A. S. Barabash, F. Hubert, Ph. Hubert, and V. I. Umatov, Eur. Phys. J. A **11**, 143 (2001).

Bau99 L. Baudis, A. Dietz, G. Heusser, H. V. Klapdor-Kleingrothaus, I. V. Krivosheina, St. Kolb, B. Majorovits, V. F. Melnikov, H. Pas, F. Schwamm, H. Strecker, V. Alexeev, A. Balysh, A. Bakalyarov, S. T. Belyaev, V. I. Lebedev, and S. Zhukov, Phys. Rev. Lett. **83**, 41 (1999).

Bel82 E. Bellotti, E. Fiorini, C. Liguori, A. Pullia, A. Sarracino, and L. Zanotti, Lett. Nuovo Cim. **33**, 273 (1982).

Bel87 E. Bellotti, C. Cattadori, O. Cremonesi, E. Fiorini, C. Liguori, A. Pullia, P. P. Sverzellati, and L. Zanotti, Europhys. Lett. **3**, 889 (1987).

Bel91 E. Bellotti, O. Cremonesi, E. Fiorini, G. Gervasio, S. Ragazzi, L. Rossi, J. Szarka, P. P. Sverzellati, T. Tabarelli, and L. Zanotti, J. Phys. G Nucl. Part. Phys. **17**, s231 (1991).

Bel99a P. Belli, R. Bernabei, C. J. Dai, F. Grianti, H. L. He, G. Ignesti, A. Incicchitti, H. H. Kuang, J. M. Ma, F. Montecchia, O. A. Ponkratenko, D. Prosperi, V. I. Tretyak, and Yu. G. Zdesenko, Nucl. Phys. B **563**, 97 (1999).

Bel99b P. Belli, R. Bernabei, A. Incicchitti, C. Arpesella, V. V. Kobychev, O. A. Ponkratenko, V. I. Tretyak, and Yu. G. Zdesenko, Astropart. Phys. **10**, 115 (1999).

Ber53 A. Berthelot, R. Chaminade, C. Levi, and L. Papineau, Compt. Rend. **236**, 1769 (1953).

Ber92 T. Bernatowicz, J. Brannon, R. Brazzle, R. Cowsik, C. Hohenberg, and F. Podosek, Phys. Rev. Lett. **69**, 2341 (1992).

Ber97 R. Bernabei, P. Belli, A. Incicchitti, D. Prosperi, C. Bacci, F. De Notaristefani, G. J. Davies, and C. J. Dai, Nuovo Cim. A **110**, 189 (1997).

REFERENCES FOR TABLES continued

Bha98 M. Bhattacharya, A. Garcia, M. M. Hindi, E. B. Norman, C. E. Ortiz, N. I. Kaloskamis, C. N. Davids, O. Civitarese, and J. Suhonen, Phys. Rev. C **58**, 1247 (1998).

Bik95 I. Bikit, M. Krmar, J. Slivka, I. Anicin, M. Veskovic, and Lj. Conkic, Appl. Radiat. Isot. **46**, 455 (1995).

Bik98 I. Bikit, M. Krmar, J. Slivka, M. Veskovic, Lj. Conkic, and I. Anicin, Phys. Rev. C **58**, 2566 (1998).

Blu92 D. Blum, J. Busto, J. E. Campagne, D. Dassie, F. Hubert, Ph. Hubert, M. C. Isaac, C. Izac, S. Jullian, V. N. Kouts, B. N. Kropivyansky, D. Lalanne, T. Lamhamdi, F. Laplanche, F. Leccia, I. Linck, C. Longuemare, P. Mennrath, F. Natchez, F. Scheibling, G. Szklarz, V. I. Tretyak, and Yu. G. Zdesenko, Phys. Lett. B **275**, 506 (1992).

Bob00 A. Bobyk, W. A. Kaminski, and P. Zareba, Nucl. Phys. A **669**, 221 (2000).

Bob01 A. Bobyk, W. A. Kaminski, and F. Simkovic, Phys. Rev. C **63**, 051301 (2001).

Bra01 L. De Braeckeleer, M. Hornish, A. Barabash, and V. Umatov, Phys. Rev. Lett. **86**, 3510 (2001).

Bro93 R. L. Brodzinski, F. T. Avignone, J. I. Collar, H. Courant, E. Garcia, C. K. Guerard, W. K. Hensley, I. V. Kirpichnikov, H. S. Miley, A. Morales, J. Morales, R. Nunez-Lagos, S. B. Osetrov, V. S. Pogosov, A. A. Pomansky, J. Puimedon, J. H. Reeves, K. Ruddick, C. Saenz, A. Salinas, M. L. Sarsa, A. A. Smolnikov, A. S. Starostin, A. G. Tamanyan, S. I. Vasiliev, and J. A. Villar, Nucl. Phys. B (Proc. Suppl.) **31**, 76 (1993).

Bru00 V. B. Brudanin, N. I. Rukhadze, Ch. Briancon, V. G. Egorov, V. E. Kovalenko, A. Kovalik, A. V. Salamatin, I. Stekl, V. V. Tsoupko-Sitnikov, Ts. Vylov, and P. Cermak, Phys. Lett. B **495**, 63 (2000).

Buc91 B. Buck, A. C. Merchant, and S. M. Perez, J. Phys. G Nucl. Part. Phys. **17**, 1223 (1991).

Buk90 E. Bukhner, I. N. Vishnevskii, F. A. Danevich, Yu. G. Zdesenko, Kh. V. Klapdor, B. N. Kropivyanskii, V. N. Kuts, A. Piepke, V. I. Tretyak, G. Heusser, J. Schneider, and H. Strecker, Sov. J. Nucl. Phys. **52**, 193 (1990).

Bus90 J. Busto, D. Dassie, O. Helene, Ph. Hubert, P. Larrieu, F. Leccia, P. Mennrath, M. M. Aleonard, and J. Chevallier, Nucl. Phys. A **513**, 291 (1990).

Cas94 O. Castanos, J. G. Hirsch, O. Civitarese, and P. O. Hess, Nucl. Phys. A **571**, 276 (1994).

Cau96 E. Caurier, F. Nowacki, A. Poves, and J. Retamosa, Phys. Rev. Lett. **77**, 1954 (1996).

Cau99 E. Caurier, F. Nowacki, A. Poves, and J. Retamosa, Nucl. Phys. A **654**, 973c (1999).

Cer99 V. E. Ceron and J. G. Hirsch, Phys. Lett. B **471**, 1 (1999).

Chi84 Ching Cheng-rui, Ho Tso-hsiu, and Zhao Wei-qin, Comm. Theor. Phys. **3**, 517 (1984).

Civ98 O. Civitarese and J. Suhonen, Phys. Rev. C **58**, 1535 (1998).

Cru93 M. T. F. da Cruz, D. W. Bardayan, Y. Chan, A. Garcia, M. M. Hindi, R.-M. Larimer, K. T. Lesko, E. B. Norman, Della F. Rossi, R. G. Stokstad, F. E. Wietfeldt, and I. Zlimen, Phys. Rev. C **48**, 3106 (1993).

Dan94 F. A. Danevich, Ph.D. Thesis, Inst. for Nucl. Research (Kiev, 1994).

Dan95 F. A. Danevich, A. Sh. Georgadze, V. V. Kobychev, B. N. Kropivyansky, V. N. Kuts, A. S. Nikolaiko, V. I. Tretyak, and Yu. Zdesenko, Phys. Lett. B **344**, 72 (1995).

Dan00 F. A. Danevich, A. Sh. Georgadze, V. V. Kobychev, B. N. Kropivyansky, A. S. Nikolaiko, O. A. Ponkratenko, V. I. Tretyak, S. Yu. Zdesenko, Yu. G. Zdesenko, P. G. Bizzeti, T. F. Fazzini, and P. R. Maurenzig, Phys. Rev. C **62**, 045501 (2000).

Dan01 F. A. Danevich, V. V. Kobychev, O. A. Ponkratenko, V. I. Tretyak, and Yu. G. Zdesenko, Nucl. Phys. A **694**, 375 (2001).

Das95 D. Dassie, R. Eschbach, F. Hubert, Ph. Hubert, M. C. Isaac, C. Izac, F. Leccia, P. Mennrath, A. Vareille, C. Longuemare, F. Mauger, F. Danevich, V. Kouts, V. I. Tretyak, Yu. Vassilyev, Yu. Zdesenko, A. S. Barabash, V. N. Kornoukov, Yu. B. Lepikhin, V. I. Umatov, I. A. Vanushin, C. Augier, D. Blum, J. E. Campagne, S. Jullian, D. Lalanne, F. Laplanche, F. Natchez, G. Pichenot, G. Szklarz, R. Arnold, J. L. Guyonnet, T. Lamhamdi, I. Linck, F. Piquemal, F. Scheibling, V. Brudanin, V. Egorov, O. Kochetov, A. Nozdrin, Ts. Vylov, Sh. Zaparov, H. W. Nicholson, and C. S. Sutton, Phys. Rev. D **51**, 2090 (1995).

Der96 A. V. Derbin, A. I. Egorov, V. N. Muratova, and S. V. Bakhlanov, Phys. At. Nucl. **59**, 2037 (1996).

Dou01 G. Douysset, T. Fritioff, and C. Carlberg, Phys. Rev. Lett. **86**, 4259 (2001).

Dyc90 G. R. Dyck, M. H. Sidky, J. G. Hykawy, C. A. Lander, K. S. Sharma, R. C. Barber, and H. E. Duckworth, Phys. Lett. B **245**, 343 (1990).

REFERENCES FOR TABLES continued

Eji91 H. Ejiri, K. Fushimi, T. Kamada, H. Kinoshita, H. Kobiki, H. Ohsumi, K. Okada, H. Sano, T. Shibata, T. Shima, N. Tanabe, J. Tanaka, T. Taniguchi, T. Watanabe, and N. Yamamoto, Phys. Lett. B **258**, 17 (1991).

Eji95 H. Ejiri, K. Fushimi, R. Hazama, M. Kawasaki, V. Kouts, N. Kudomi, K. Kume, K. Nagata, H. Ohsumi, K. Okada, H. Sano, T. Senoo, T. Shibata, T. Shima, J. Tanaka, and Yu. Zdesenko, J. Phys. Soc. Jpn. **64**, 339 (1995).

Eji96 H. Ejiri, K. Fushimi, K. Hayashi, R. Hazama, T. Kishimoto, N. Kudomi, K. Kume, K. Nagata, H. Ohsumi, K. Okada, T. Shima, and J. Tanaka, Nucl. Phys. A **611**, 85 (1996).

Eji01 H. Ejiri, K. Fushimi, K. Hayashi, T. Kishimoto, N. Kudomi, K. Kume, H. Kuramoto, K. Matsuoka, H. Ohsumi, K. Takahisa, and S. Yoshida, Phys. Rev. C **63**, 065501 (2001).

Ell92 S. R. Elliott, A. A. Hahn, M. K. Moe, M. A. Nelson, and M. A. Vient, Phys. Rev. C **46**, 1535 (1992).

Fre52 J. H. Fremlin and M. C. Walters, Proc. Phys. Soc. A **65**, 911 (1952).

Gav98 Ju. M. Gavriljuk, V. V. Kuzminov, N. Yu. Osetrova, S. S. Ratkevich, and G. V. Volchenko, Phys. At. Nucl. **61**, 1287 (1998).

Gav00a Ju. M. Gavriljuk, V. V. Kuzminov, N. Ya. Osetrova, and S. S. Ratkevich, Phys. At. Nucl. **63**, 2201 (2000).

Gav00b Ju. M. Gavriljuk, V. V. Kuzminov, N. Ya. Osetrova, and S. S. Ratkevich, Phys. Rev. C **61**, 035501 (2000).

Geo95a A. Sh. Georgadze, F. A. Danevich, Yu. G. Zdesenko, V. V. Kobychev, B. N. Kropivyanskii, V. N. Kuts, A. S. Nikolaiko, and V. I. Tretyak, Phys. At. Nucl. **58**, 1093 (1995).

Geo95b A. Sh. Georgadze, F. A. Danevich, Yu. G. Zdesenko, V. V. Kobychev, B. N. Kropivyanskii, V. N. Kuts, V. V. Muzalevskii, A. S. Nikolaiko, O. A. Ponkratenko, and V. I. Tretyak, JETP Lett. **61**, 882 (1995).

Ger68 E. K. Gerling, J. A. Shukolyukov, and G. Sh. Ashkinadze, Sov. J. Nucl. Phys. **6**, 226 (1968).

Gon00 D. Gonzalez, C. E. Aalseth, F. T. Avignone III, R. L. Brodzinski, S. Cebrian, E. Garcia, W. K. Hensley, I. G. Irastorza, I. V. Kirpichnikov, A. A. Klimenko, H. S. Miley, A. Morales, J. Morales, A. Ortiz de Solorzano, S. B. Osetrov, V. S. Pogosov, J. Puimedon, J. H. Reeves, M. L. Sarsa, S. Scopel, A. A. Smolnikov, A. G. Tamanyan, A. A. Vasenko, S. I. Vasiliev, and J. A. Villar, Nucl. Phys. B (Proc. Suppl.) **87**, 278 (2000).

Gun97 M. Gunther, J. Hellmig, G. Heusser, M. Hirsch, H. V. Klapdor-Kleingrothaus, B. Maier, H. Pas, F. Petry, Y. Ramachers, H. Strecker, M. Vollinger, A. Balysh, S. T. Belyaev, A. Demehin, A. Gurov, I. Kondratenko, D. Kotel'nikov, V. I. Lebedev, and A. Muller, Phys. Rev. D **55**, 54 (1997).

Hax84 W. C. Haxton and G. J. Stephenson, Jr., Prog. Part. Nucl. Phys. **12**, 409 (1984).

Hen75 E. W. Hennecke, O. K. Manuel, and D. D. Sabu, Phys. Rev. C **11**, 1378 (1975).

Hir95a J. G. Hirsch, O. Castanos, P. O. Hess, and O. Civitarese, Phys. Rev. C **51**, 2252 (1995).

Hir95b J. G. Hirsch, O. Castanos, P. O. Hess, and O. Civitarese, Nucl. Phys. A **589**, 445 (1995).

Hir96 M. Hirsch, H. V. Klapdor-Kleingrothaus, S. G. Kovalenko, and H. Pas, Phys. Lett. B **372**, 8 (1996).

Hyk93 J. G. Hykawy, J. N. Nxumalo, P. P. Unger, C. A. Lander, R. D. Peters, R. C. Barber, K. S. Sharma, and H. E. Duckworth, Nucl. Instrum. Meth. A **329**, 423 (1993).

Ing50 M. G. Inghram and J. H. Reynolds, Phys. Rev **78**, 822 (1950).

Kal52 M. I. Kalkstein and W. F. Libby, Phys. Rev. **85**, 368 (1952).

Kan01 K. Kaneko and M. Hasegawa, Prog. Theor. Phys. **105**, 219 (2001).

Kar85 F. F. Karpeshin, Sov. J. Nucl. Phys. **41**, 530 (1985).

Kaw93 A. Kawashima, K. Takahashi, and A. Masuda, Phys. Rev. C **47**, 2452 (1993).

Kir67 T. Kirsten, W. Gentner, and O. Muller, Z. Naturforsch. A **22**, 1783 (1967).

Kir68 T. Kirsten, O. A. Schaeffer, E. Norton, and R. W. Stoenner, Phys. Rev. Lett. **20**, 1300 (1968).

Kir69 T. Kirsten and H. W. Muller, Earth Planet Sci. Lett. **6**, 271 (1969).

Kir83a T. Kirsten, H. Richter, and E. Jessberger, Phys. Rev. Lett. **50**, 474 (1983); Z. Phys. C **16**, 189 (1983).

Kir83b T. Kirsten, AIP Conference Proc. **96**, 396 (1983).

Kir86 T. Kirsten, E. Heusser, D. Kaether, J. Oehm, E. Pernicka, and H. Richter, *Proc. Int. Symp. on Nuclear Beta Decays and Neutrino. Osaka, Japan, June 1986* (World Scientific, Singapore, 1986), p. 81.

Kli86 A. A. Klimenko, A. A. Pomansky, and A. A. Smolnikov, Nucl. Instrum. Meth. B **17**, 445 (1986).

Kud92 N. Kudomi, H. Ejiri, K. Nagata, K. Okada, T. Shibata, T. Shima, and J. Tanaka, Phys. Rev. C **46**, 2132 (1992).

REFERENCES FOR TABLES continued

Lin86 W. J. Lin, O. K. Manuel, L. L. Oliver, and R. I. Thorpe, Nucl. Phys. A **457**, 285 (1986).

Lin88a W. J. Lin, O. K. Manuel, G. L. Cumming, D. Krstic, and R. I. Thorpe, Nucl. Phys. A **481**, 477 (1988).

Lin88b W. J. Lin, O. K. Manuel, S. Muangnoicharoen, and R. I. Thorpe, Nucl. Phys. A **481**, 484 (1988).

Lue98 R. Luescher, J. Farine, F. Boehm, J. Busto, K. Gabathuler, G. Gervasio, H. E. Henrikson, V. Jorgens, K. Lou, A. Paic, D. Schenker, A. Tadsen, M. Treichel, J.-L. Vuilleumier, J.-M. Vuilleumier, and H. Wong, Phys. Lett. B **434**, 407 (1998).

Mac61 R. D. Macfarlane and T. P. Kohman, Phys. Rev. **121**, 1758 (1961).

Mai94 B. Maier (for the Heidelberg-Moscow Collaboration), Nucl. Phys. B. (Proc. Suppl.) **35**, 358 (1994).

Man86 O. K. Manuel, *Proc. Int. Symp. on Nuclear Beta Decays and Neutrino. Osaka, Japan, June 1986* (World Scientific, Singapore, 1986), p. 71.

Man91 O.K. Manuel, J. Phys. G Nucl. Part. Phys. **17**, s221 (1991).

Mar85 K. Marti and S. V. S. Murty, Phys. Lett. B **163**, 71 (1985).

Mil90 H. S. Miley, F. T. Avignone, III, R. L. Brodzinski, J. I. Collar, and J. H. Reeves, Phys. Rev. Lett. **65**, 3092 (1990).

Moo92 K. J. Moody, R. W. Lougheed, and E. K. Hulet, Phys. Rev. C **46**, 2624 (1992).

Mur87 S. V. S. Murty and K. Marti, Geochim. Cosmochim. Acta **51**, 163 (1987).

Nak96 H. Nakada, T. Sebe, and K. Muto, Nucl. Phys. A **607**, 235 (1996).

Nor84 E. B. Norman and M. A. De Faccio, Phys. Lett. B **148**, 31 (1984).

Nor85 E. B. Norman, Phys. Rev. C **31**, 1937 (1985).

Nor87 E. B. Norman and D. M. Meekhof, Phys. Lett. B **195**, 126 (1987).

Nxu93 J. N. Nxumalo, J. G. Hykawy, P. P. Unger, C. A. Lander, R. C. Barber, K. S. Sharma, and H. E. Duckworth, Phys. Lett. B **302**, 13 (1993).

Pan96 G. Pantis, F. Simkovic, J. D. Vergados, and A. Faessler, Phys. Rev. C **53**, 695 (1996).

Pie94 A. Piepke, M. Beck, J. Bockholt, D. Glatting, G. Heusser, H. V. Klapdor-Kleingrothaus, B. Maier, F. Petry, U. Schmidt-Rohr, H. Strecker, M. Vollinger, A. S. Barabash, V. I. Umatov, A. Muller, and J. Suhonen, Nucl. Phys. A **577**, 493 (1994).

Poe86 D. N. Poenaru, W. Greiner, K. Depta, M. Ivascu, D. Mazilu, and A. Sandulescu, AT. DATA NUCL. DATA TABLES. **34**, 423 (1986).

Por56 W. Porschen and W. Riezler, Z. Naturforsch. A **11**, 143 (1956).

Pov95 A. Poves, R. P. Bahukutumbi, K. Langanke, and P. Vogel, Phys. Lett. B **361**, 1 (1995).

Ric86 J. F. Richardson, O. K. Manuel, B. Sinha, and R. I. Thorpe, Nucl. Phys. A **453**, 26 (1986).

Rie58 W. Riezler and G. Kauw, Z. Naturforsch. A **13**, 904 (1958).

Ros98 K. J. R. Rosman and P. D. P. Taylor, Pure and Appl. Chem. **70**, 217 (1998).

Rum95 O. A. Rumyantsev and M. G. Urin, JETP Lett. **61**, 361 (1995).

Rum98 O. A. Rumyantsev and M. H. Urin, Phys. Lett. B **443**, 51 (1998).

Sae94 C. Saenz, E. Cerezo, E. Garcia, A. Morales, J. Morales, R. Nunez-Lagos, A. Ortiz de Solorzano, J. Puimedon, A. Salinas, M. L. Sarsa, J. A. Villar, A. Klimenko, V. Kuzminov, N. Metlinsky, V. Novikov, A. Pomansky, and B. Pritychenko, Phys. Rev. C **50**, 1170 (1994).

Sch85 O. Scholten and Z. R. Yu, Phys. Lett. B **161**, 13 (1985).

Sch98 J. Schwieger, F. Simkovic, and A. Faessler, Phys. Rev. C **57**, 1738 (1998).

Sem00 S. V. Semenov, F. Simkovic, V. V. Khruschev, and P. Domin, Phys. At. Nucl. **63**, 1196 (2000).

Sil97 A. De Silva, M. K. Moe, M. A. Nelson, and M. A. Vient, Phys. Rev. C **56**, 2451 (1997).

Sim97 F. Simkovic, J. Schwieger, G. Pantis, and A. Faessler, Found. Phys. **27**, 1275 (1997).

Sim99 F. Simkovic, G. Pantis, J. D. Vergados, and A. Faessler, Phys. Rev. C **60**, 055502 (1999).

Smo85 A. A. Smolnikov, Ph.D. Thesis, Inst. for Nucl. Research (Moscow, 1985).

Spe76 R. F. Sperlein and R. L. Wolke, J. Inorg. Nucl. Chem. **38**, 27 (1976).

Sri72a B. Srinivasan, E. C. Alexander, Jr., and O. K. Manuel, Econ. Geol. **67**, 592 (1972).

Sri72b B. Srinivasan, E. C. Alexander, Jr., and O. K. Manuel, J. Inorg. Nucl. Chem. **34**, 2381 (1972).

REFERENCES FOR TABLES continued

Sri73 B. Srinivasan, E. C. Alexander, Jr., R. D. Beaty, D. E. Sinclair, and O. K. Manuel, Econ. Geol. **68**, 252 (1973).

Sri76 B. Srinivasan, Earth Planet. Sci. Lett. **31**, 129 (1976).

Sta90 A. Staudt, K. Muto, and H. V. Klapdor-Kleingrothaus, Europhys. Lett. **13**, 31 (1990).

Sta91 A. Staudt, K. Muto, and H. V. Klapdor-Kleingrothaus, Phys. Lett. B **268**, 312 (1991).

Sto94 S. Stoica, Phys. Rev. C **49**, 2240 (1994).

Sto95 S. Stoica, Phys. Lett. B **350**, 152 (1995).

Sto00 S. Stoica and H. V. Klapdor-Kleingrothaus, Eur. Phys. J. A **9**, 345 (2000).

Sto01 S. Stoica and H. V. Klapdor-Kleingrothaus, Phys. Rev. C **63**, 064304 (2001).

Suh91 J. Suhonen, S. B. Khadkikar, and A. Faessler, Nucl. Phys. A **529**, 727 (1991).

Suh97a J. Suhonen, J. Toivanen, A. S. Barabash, I. A. Vanushin, V. I. Umatov, R. Gurriaran, F. Hubert, and Ph. Hubert, Z. Phys. A **358**, 297 (1997).

Suh97b J. Suhonen, P. C. Divari, L. D. Skouras, and I. P. Johnstone, Phys. Rev. C **55**, 714 (1997).

Suh98 J. Suhonen, Phys. At. Nucl. **61**, 1186 (1998).

Suh00a J. Suhonen, Phys. Lett. B **477**, 99 (2000).

Suh00b J. Suhonen, Phys. Rev. C **62**, 042501 (2000).

Suh01 J. Suhonen and O. Civitarese, Phys. Lett. B **497**, 221 (2001).

Tak66 N. Takaoka and K. Ogata, Z. Naturforsch. A **21**, 84 (1966).

Tak96 N. Takaoka, Y. Motomura, and K. Nagao, Phys. Rev. C **53**, 1557 (1996).

ToI78 C. M. Lederer, V. S. Shirley, et al., Eds., *Table of Isotopes*, 7th ed. (Wiley, New York, 1978).

ToI96 R. B. Firestone, V. S. Shirley et al., Eds., *Table of Isotopes*, 8th ed. (Wiley, New York, 1996).

Toi97 J. Toivanen and J. Suhonen, Phys. Rev. C **55**, 2314 (1997).

Tre95 V. I. Tretyak and Yu. G. Zdesenko, At. Data Nucl. Data Tables **61**, 43 (1995).

Tsu84 T. Tsuboi, K. Muto, and H. Horie, Phys. Lett. B **143**, 293 (1984).

Tur91 A. L. Turkevich, T. E. Economou, and G. A. Cowan, Phys. Rev. Lett. **67**, 3211 (1991).

Vas90a A. A. Vasenko, I. V. Kirpichnikov, V. A. Kuznetsov, A. S. Starostin, A. G. Djanyan, V. S. Pogosov, S. P. Shachysisyan, and A. G. Tamanyan, Mod. Phys. Lett. A **5**, 1299 (1990).

Vas90b S. I. Vasil'ev, A. A. Klimenko, S. B. Osetrov, A. A. Pomanskii, and A. A. Smol'nikov, JETP Lett. **51**, 622 (1990).

Vas93 S. I. Vasil'ev, A. A. Klimenko, S. B. Osetrov, A. A. Pomanskii, and A. A. Smol'nikov, JETP Lett. **57**, 631 (1993).

Vas00 S. I. Vasil'ev, A. A. Klimenko, S. B. Osetrov, and A. A. Smolnikov, JETP Lett. **72**, 279 (2000).

Vui93 J.-C. Vuilleumier, J. Busto, J. Farine, V. Jorgens, L. W. Mitchel, M. Treichel, J.-L. Vuilleumier, H. T. Wong, F. Boehm, P. Fisher, H. E. Henrikson, D. A. Imel, M. Z. Iqbal, B. M. O'Callaghan-Hay, J. Thomas, and K. Gabathuler, Phys. Rev. D **48**, 1009 (1993).

War85 E. K. Warburton, Phys. Rev. C **31**, 1896 (1985).

Win52 R. G. Winter, Phys. Rev. **85**, 687 (1952).

You91 Ke You, Yucan Zhu, Junguang Lu, Hanseng Sun, Weihua Tian, Wenheng Zhao, Zhipeng Zheng, Minghan Ye, Chengrui Ching, Tsohsiu Ho, Fengzhu Cui, Changjiang Yu, and Guojing Jiang, Phys. Lett. B **265**, 53 (1991).