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TABLES OF DOUBLE BETA DECAY DATA

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A compilation of data on double beta decay is presented. The tables contain the most stringent known experimental limits or positive results on half-lives for 2β transitions to ground and excited states of daughter nuclei for different channels ($2\beta^-$; $2\beta^+$, $\epsilon\beta^+$; 2ϵ) and modes (0ν; 2ν; $0\nu M$) of decay. Theoretical estimates are given for comparison. Formulas for energy and angular distributions of electrons in various modes of 2β decay are presented as a supplement. © 1995 Academic Press, Inc.

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INTRODUCTION

Research in double beta (2β) decay has been very active during the past decade, in part triggered by a revived interest in the neutrino mass. A great number of results have been obtained at a level of precision which seemed unattainable during the early history of investigations beginning from the theoretical prediction of 2β decay by M. Goeppert-Mayer in 1935 [Goe35] and W. H. Furry in 1939 [Fur39] and the first experimental work of E. Fireman in 1948 [Fir48].

We distinguish between the following decay modes: neutrinoless double beta decay ($0\nu2\beta$), a process that violates lepton number conservation and thus is of current interest as it may provide evidence for new physics, and two-neutrino double beta decay ($2\nu2\beta$), a higher order transition allowed by conservation laws.

The following are some highlights of recent developments in this field:

- a half-life limit greater than 10^{24} y for $0\nu2\beta$ decay of ^{76}Ge [Cal90, Kir92, Kla93a];
- a limit of $T^{0\nu}_{1/2}$ greater than 10^{23} y for ^{136}Xe [Vui93] and 10^{22} y for ^{82}Se [Ell92], ^{100}Mo [Als93], ^{116}Cd [Dan93], and ^{130}Te [Ale94b];
- observation of $2\nu2\beta$ decay of ^{76}Ge [Vas90a, Mil90, Bro93, Bal94], ^{82}Se [Ell87a], ^{100}Mo [Vas90b, Eji91, Ell91, Das94], ^{116}Cd [Kum94, Dan95, Das95], and ^{150}Nd [Art93, Ell93] in direct counting experiments;
- a large-scale experiment on ^{76}Ge with enriched high-purity (HP) Ge detectors [Kla93a];
- development of a low-temperature, high-energy resolution bolometer with a TeO_2 crystal to study the 2β decay of ^{130}Te [Ale92];
- further progress in the theoretical interpretation of the double beta decay phenomenon [Eng88, Gro90, Tom91, Boe92, Kla93b].

These achievements are related to the special role 2β decay plays as a tool to study fundamental properties: it provides a unique and very sensitive probe for nonzero neutrino mass, right-handed admixtures in the weak interaction, and possible Majoron couplings. Double beta decay, therefore, can provide information on new physics beyond the standard model and continues to be an interesting and important field of research.

The goal of the present article is to collect systematically the known experimental limits and positive results on values of 2β decay half-lives and decay energies and also to give some further information useful to people working in this field of research. In the following two sections we briefly discuss the present status of 2β decay. We do not aim to repeat the material contained in numerous excellent reviews [Zel54, Del60, Laz67, Fio72, Bry78, Zde80a, Pri81, Doi81, Hax84, Sch84, Doi85, Ver86, Avi88, Fae88, Mut88, Cal89, Gro90, Tom91, Moe91a, Boe92, Kla93b, Moe93, Moe94b] but rather wish to draw attention to recent developments in 2β decay research.

Theoretical Situation

Significant limits for neutrino mass, right-handed admixtures (and other parameters, for example, masses of supersymmetrical particles [Sin88]) from measured limits on $0\nu2\beta$ decay rates are possible only if the nuclear matrix elements which enter the half-life formulas can be calculated reliably. Since the $0\nu2\beta$ decay has not been observed up to now, it is impossible to check the theoretical $0\nu2\beta$ rates directly; rather we must resort to the $2\nu2\beta$ decay data to test the assumptions made in nuclear structure calculations.

Three main approaches have been used for the most part to calculate nuclear matrix elements: the nuclear shell model, the quasiparticle random phase approximation (QRPA), and the operator expansion method (OEM). Full-scale computations in the shell model [Hax81, Hax82, Hax84, Tsu84, Cau90, Pan90, Hax93, Ret95] were unattainable because the number of basis states in the model space increases explosively for nuclei heavier than ^{48}Ca and various simplifications had to be introduced. From this point of view, the QRPA [Vog86, Gro86, Civ87, Tom87, Eng88, Mut88, Mut89, Sta90, Tom91, Pan92, Suh93a, Hir94a, Pan94] is more attractive insofar as a new vacuum is determined for quasiparticles, and the nuclear wave function can be described in terms of a small number of quasiparticle degrees of freedom.

Calculations in the framework of the QRPA revealed that the $2\nu2\beta$ decay rates could be strongly suppressed by taking into account the ground-state correlations in nuclei which are enhanced by the particle–particle interaction. Predicted $2\nu2\beta$ decay rates are found to be very sensitive to the value of the strength of the particle–particle interaction g_{pp}, and calculated half-lives can be tuned to agree with all experimental data in the region of $g_{pp} \sim 1$. Several attempts were made to remove or at least decrease these difficulties. In Sto92, the $2\nu2\beta$ nuclear matrix elements were calculated, taking into account the self-consistent self-energy corrections to the single-particle spectra. In this way, the QRPA instability around $g_{pp} \sim 1$ was avoided and a reasonably good agreement between calculated matrix elements and the experimental values was achieved. Investigating the high-order corrections on the QRPA nuclear matrix elements, the authors of Sto93 found that the higher order QRPA corrections display a weak dependence on the particle–particle strength g_{pp} and become important in the region of $g_{pp} \sim 1$, where QRPA values vanish.

As regards the $0\nu2\beta$ decay, QRPA calculations of 0ν rates are comparatively insensitive to various types of ground-state correlations (and to particle–particle correlations in particular). This is because in the neutrinoless mode the transitions are possible not only through intermediate states with $J^\pi = 1^+$ but mainly through other multipoles J^π whose corresponding matrix elements are much less affected by a change in g_{pp}. Most of the authors agree that computation of $0\nu2\beta$ decay rates can be quite reliable.

The tediousness of the calculation of matrix elements in the shell model and the drastic sensitivity of $2\nu2\beta$ decay rates to the value of g_{pp} in QRPA stimulated the development of alternative approaches. In the OEM [Chi88, Chi89, Gmi90, Wu91, Wu92, Hir94b], the intermediate 1^+ energy spectrum is not explicitly used in the calculation of the $2\nu2\beta$ decay amplitude. In this way the dependence on g_{pp} is strongly reduced and the 2ν nuclear matrix elements become comparatively constant in the physical region of g_{pp}. OEM assumptions are criticized in Eng92 as generating values of nuclear matrix elements which are too small. Instead, another approach eliminating the explicit summation over intermediate states is proposed [Eng92] for the exact evaluation of Green's function based on a Lanczos algorithm for inverting linear operators. This method removes the need for the Green's function approximation used in OEM.

Calculations of the 2β half-life for several heavy deformed nuclei were performed in Cas94 and Hir95. The pseudo-SU(3) shell model scheme and a summation procedure without closure approximation for 2ν were used in these works. References Mut88, Gro90, Tom91, Mut91, Boe92, Kla93b, Hax93, Moe93, and Moe94b may be consulted for a discussion and comparison of the calculations of matrix elements in the shell model, QRPA, and OEM.

The approach to calculating 2β decay rates in the framework of a relativistic quark confinement model was developed in Ver85, Lus85, Suh90, and Suh91.

The theoretical formulas for the energy and angular distributions of electrons in different modes and mechanisms of 2β decay are given in the Supplement.

Experimental Status

There are two different classes of direct double β decay experiments: (a) those with an active source (source = detector) and (b) those with a passive source. Both can again be divided into two kinds: experiments with detectors which measure only the energy and experiments which also track the electrons. In the first class of experiments the effect can be studied on the basis of only one property of 2β decay, namely the distribution of the total energy of the electrons. In the experiments with a passive source and energy detectors it is possible to use time coincidence between the two electrons and to measure the single- and sum-energy distributions. Full information about all properties of 2β decay events can be obtained in the most complete class of these experiments—ones which measure time coincidence, tracks and vertex of the electrons, and also energy and angular distributions.

Below, we briefly discuss some of the recent and most sensitive 2β decay experiments.

^{76}Ge. For the last six years the Max-Planck Institute in Heidelberg has collaborated with the Kurchatov Institute in Moscow on the most sensitive experiment to study ^{76}Ge by using HP Ge semiconductor detectors enriched in ^{76}Ge. Three HP Ge detectors (0.93, 2.76, and 2.3 kg active mass) enriched in ^{76}Ge to 86% with an energy resolution of 2.4 keV at 1.3 MeV were operational in the Gran Sasso Underground Laboratory (Italy). The background rate around 2 MeV was 0.23 counts/(y · keV · kg). From 1133 kg · d of operation time, the following half-life limit for the $0\nu2\beta$ decay of ^{76}Ge was obtained: $T_{1/2}^{0\nu} > 1.93 \times 10^{24}$ y (90% confidence level (CL)) [Kla93a]. This result corresponds to a neutrino mass less than 1.1 eV (we use theoretical values of $T_{1/2}^{0\nu} \cdot \langle m_\nu \rangle^2$ from Sta90 to calculate the limits on the neutrino mass). In addition the $2\nu2\beta$ decay of ^{76}Ge has been confirmed with high statistical accuracy: $T_{1/2}^{2\nu} = (1.42 \pm 0.03(\text{stat.}) \pm 0.13(\text{syst.})) \times 10^{21}$ y [Bal94].

There is another international project (IGEX) to study 2β decay of ^{76}Ge [Bro93] which is now under preparation. Three detectors, each composed of ~1 kg of germanium and one of ~2 kg enriched to 87.4% in ^{76}Ge, have been produced and tested to date. The goal of the IGEX project is to obtain five detectors of ~3 kg each.

^{82}Se. The $2\nu2\beta$ decay of ^{82}Se has been measured by the University of California Irvine group with a time projection chamber (TPC) placed in a magnetic field of ~700 G [Ell92]. The TPC records the electron tracks, and the energies and opening angle are determined from each track. Experimental observation of the $2\nu2\beta$ decay of ^{82}Se with $T_{1/2}^{2\nu} = 1.08^{+0.26}_{-0.06} \times 10^{20}$ y (68% CL) has been claimed after a 20,244-h run, and a limit of $T_{1/2}^{0\nu} > 2.7 \times 10^{22}$ y (68% CL) has been set for the $0\nu2\beta$ decay of ^{82}Se [Ell92].

^{100}Mo. Five groups have performed measurements with ^{100}Mo. In 1982 the Institute for Nuclear Research (INR) Kiev group used plastic scintillator–wafer stacks with sheets of ^{100}Mo [Zde82]. A limit of $T_{1/2}^{0\nu} > 2.2 \times 10^{21}$ y (90% CL) was set. Recently, a technique with semiconductor–wafer stacks was used by the LBL + MHC + UNM + INEL collaboration [Als93]. A limit of $T_{1/2}^{0\nu} > 4.4 \times 10^{22}$ y (68% CL) was reached in this work. Three other groups used apparatus with tracking and energy detectors and all have claimed discovery of the $2\nu2\beta$ decay of ^{100}Mo: The Moscow group reported $T_{1/2}^{2\nu} = (3.3^{+2.0}_{-1.0}) \times 10^{18}$ y (90% CL) [Vas90b], the Osaka group $T_{1/2}^{2\nu} = (1.15^{+0.30}_{-0.20}) \times 10^{19}$ y (68% CL) [Eji91], and the Irvine group $T_{1/2}^{2\nu} = (1.16^{+0.34}_{-0.08}) \times 10^{19}$ y (68% CL) [Ell91]. Recently, the Osaka and Irvine results were confirmed by the NEMO collaboration, which, with the help of the NEMO 2 apparatus with a good tracking device (square source ~1 m^2) and 2 × 64 plastic scintillators, obtained $T_{1/2}^{2\nu} = (0.95 \pm 0.04(\text{stat.}) \pm 0.09(\text{syst.})) \times 10^{19}$ y [Das94]. The NEMO collaboration is now building the NEMO 3 tracking detector, which is scaled up from the previous one by a factor of 20 in size (square source ~20 m^2) and by a factor of 1000 in sensitivity. With ~10 kg of ^{100}Mo they plan to reach a sensitivity limit of $T_{1/2}^{0\nu} \sim 10^{25}$ y.

The detector resolution will play a decisive role in distinguishing between allowed (in the standard model) $2\nu2\beta$ and forbidden $0\nu2\beta$ decays [Moe91b]. In Fig. 1 the sum energy distributions for the $0\nu2\beta$ decay of ^{100}Mo assuming $T_{1/2}^{0\nu} = 10^{24}$ and 10^{25} y are shown together with a tail from the $2\nu2\beta$ decay for $T_{1/2}^{2\nu} = 10^{19}$ y. These distributions were calculated for an energy resolution (FWHM) equal to 10, 15, and 20% at an energy of 1 MeV. It is clear that reaching a sensitivity of more than 10^{24} y with poor resolution (worse than 10%) appears very questionable, especially if we take into account the problems of low statistics (for instance, in 10 kg of ^{100}Mo only 42 (4.2) $0\nu2\beta$ decays will occur during a period of 1 y if $T_{1/2}^{0\nu} = 10^{24}$ (10^{25}) y).

^{116}Cd. ^{116}CdWO$_4$ crystal scintillators enriched in ^{116}Cd to 83% have been developed by the INR Kiev group [Dan89, Zde91]. The experiment was performed in the Solotvina Underground Laboratory with three enriched crystal scintillators ^{116}CdWO$_4$ (19, 14, and 13 cm^3) as well as with natural CdWO$_4$ (8, 9, and 57 cm^3) detectors. The energy resolution of the crystals was about 7.5% at 2.6 MeV and the background rate in the energy interval 2.7–2.9 MeV was equal to 0.57 counts/(y · keV · kg) [Dan93, Dan95]. After a 5822-h run a lower limit of $T_{1/2}^{0\nu} > 2.9 \times 10^{22}$ y (90% CL) was set, which corresponds

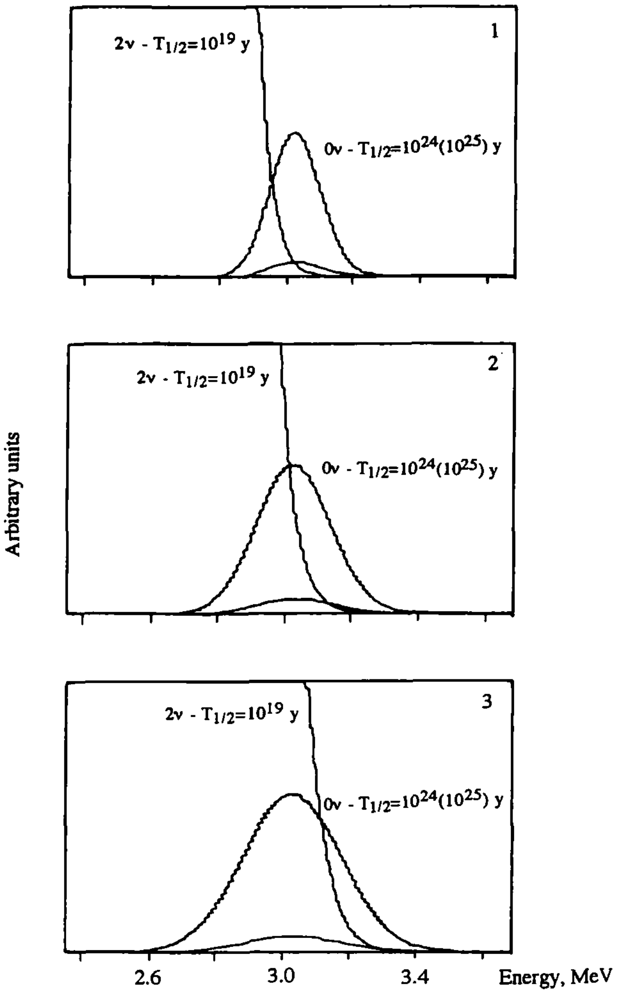

Figure 1. Distributions for the sum of electron energies in $0\nu2\beta$ and $2\nu2\beta$ decays of ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV) calculated for different resolution of the detector. The assumed dependence of the full width at half-maximum of the energy spread is FWHM(E) = FWHM(E_0)$\sqrt{E/E_0}$. Plots 1, 2, and 3 correspond to FWHM(E_0) = 100, 150, and 200 keV, respectively, for E_0 = 1 MeV. The higher (lower) of the two curves for the 0ν decay corresponds to the $T_{1/2}^{0\nu} = 10^{24}$ (10^{25}) y.

to $m_\nu < 4.1$ eV [Dan95]. By subtracting the spectra of natural CdWO$_4$ scintillators from the spectra of enriched ^{116}CdWO$_4$ detectors, indications of a $2\nu2\beta$ decay of ^{116}Cd were found with $T_{1/2}^{2\nu} = 2.7^{+0.5}_{-0.4}(\text{stat.})^{+0.9}_{-0.6}(\text{syst.}) \times 10^{19}$ y [Dan95]. INR (Kiev) and MPI (Heidelberg) have recently proposed [Dan95] a project for a large-scale experiment with ^{116}CdWO$_4$ crystal scintillators ($\sim$20 kg of ^{116}Cd) in which a limit of $T_{1/2}^{0\nu} > 10^{25}$ y is expected to be reached ($m_\nu < 0.3$ eV). ^{116}CdWO$_4$ crystals could also be used as the cryogenic thermal detectors. An energy resolution of $\sim$5 keV at 1 MeV has recently been obtained in the first tests with a CdWO$_4$ crystal of mass 58 g [Ale94a].

The $2\nu2\beta$ decay of ^{116}Cd was also observed by the Osaka group in a 1875-h measurement with ELEGANTS V ($T_{1/2}^{2\nu} = 2.6^{+0.9}_{-0.5} \times 10^{19}$ y (68% CL) [Kum94]) and by the NEMO collaboration with modified NEMO 2 installation during a 2460-h run ($T_{1/2}^{2\nu} = (3.6^{+0.6}_{-0.5}(\text{stat.}) \pm 0.3(\text{syst.})) \times 10^{19}$ y [Das95]).

^{130}Te. The Milano group has used crystalline TeO$_2$ (334 g) as a cryogenic thermal detector for 2β decay research in ^{130}Te [Ale94b]. The energy resolution of the crystal is about 10 keV at 1.3 MeV. After 9234 h of operation in the Gran Sasso Underground Laboratory the background rate near 2.53 MeV was 3.4 counts/(y·keV·kg). A limit of $T_{1/2}^{0\nu} > 1.8 \times 10^{22}$ y (90% CL) has been established for the $0\nu2\beta$ decay of ^{130}Te ($m_\nu < 5.2$ eV) [Ale94b]. In the near future, it will be possible to use four TeO$_2$ crystals (total mass $\approx$1.2 kg) to achieve a sensitivity limit of 10^{23} y ($m_\nu < 2.2$ eV) or to use an enriched ^{130}TeO$_2$ crystal to reach a level of 10^{24} y ($m_\nu < 0.7$ eV) after several years. It should be mentioned that the development of this technique is an important step in 2β decay research because it can be applied to different crystals containing the possible 2β active nuclei.

^{136}Xe. The Caltech (Pasadena), Institut de Physique (Neuchatel), and Paul Scherrer Institute (Villigen) collaboration [Vui93] has constructed a time projection chamber with an active volume of 180 liters, which has operated at 5 atm pressure of xenon enriched in ^{136}Xe to 62.5%. The energy resolution of the TPC is 6.6% at 1.6 MeV. The track reconstruction capability of the TPC provides a powerful means of background rejection. As a result, the background rate around 2.48 MeV (within a FWHM energy interval) is 0.01 counts/(y·keV·kg). From 6830 h of data taking in the Gotthard Underground Laboratory a limit of $T_{1/2}^{0\nu} > 3.4 \times 10^{23}$ y (90% CL) ($m_\nu < 2.5$ eV) has been set for the $0\nu2\beta$ decay of ^{136}Xe [Vui93]. In the near future and after some improvements of the apparatus this collaboration plans to reach a limit of $T_{1/2}^{0\nu} > 10^{24}$ y ($m_\nu < 1.5$ eV). One should note that the equipment developed in this work combines the advantages of both classes of direct 2β decay experiments: reasonably high efficiency plus tracking information. Naturally the next step in this direction—a large-volume liquid Xe TPC [Gir92] and a self-triggered drift chamber filled by liquid-enriched ^{136}Xe [Pro94]—has been proposed to enable a sensitivity level of $\sim 10^{25}$ y ($m_\nu < 0.5$ eV) to be reached. In order to surpass even this level of sensitivity, a new approach has been proposed which makes use of the coincident detection of ^{136}Ba^{2+} ions (resulting from the 2β decay of ^{136}Xe at the atomic level) and the $0\nu2\beta$ signal of ^{136}Xe with an energy of 2.5 MeV in a TPC filled with liquid Xe [Moe91b, Miy91]. Such an apparatus with 1000 kg of ^{136}Xe should be capable of

TABLE A

Limits on the Neutrino Mass from the Most Advanced Direct Experiments

Isotope	Experimental limit $T^{0\nu}_{1/2}$ in y at 68% (90%) CL	$T^{0\nu}_{1/2}\cdot\langle m_\nu\rangle^2$ in y·eV^2 and upper limit on m_ν in eV at 68% (90%) CL				
		[Hax84]	[Eng88]	[Eng89]	[Sta90]	[Tom91]
^{76}Ge	3.2 (1.9) × 10^{24} [Kla93a]	1.7 × 10^{24}	1.4 × 10^{25}	2.3 × 10^{24}	2.3 × 10^{24}	2.2 × 10^{24}
		0.7 (0.9)	2.1 (2.7)	0.8 (1.1)	0.8 (1.1)	0.8 (1.1)
^{82}Se	2.7 (—) × 10^{22} [Ell92]	5.8 × 10^{23}	5.6 × 10^{24}	9.2 × 10^{23}	6.0 × 10^{23}	6.0 × 10^{23}
		4.6 (—)	14.4 (—)	5.8 (—)	4.7 (—)	4.7 (—)
^{100}Mo	4.4 (—) × 10^{22} [Als93]	—	—	—	1.3 × 10^{24}	2.6 × 10^{23}
		—	—	—	5.4 (—)	2.4 (—)
^{116}Cd	5.4 (2.9) × 10^{22} [Dan95]	—	—	—	4.9 × 10^{23}	—
		—	—	—	3.0 (4.1)	—
^{130}Te	2.8 (1.8) × 10^{22} [Ale94b]	1.6 × 10^{23}	6.6 × 10^{23}	2.4 × 10^{23}	4.9 × 10^{23}	5.2 × 10^{23}
		2.4 (3.0)	4.9 (6.1)	2.9 (3.7)	4.2 (5.2)	4.3 (5.4)
^{136}Xe	6.4 (3.4) × 10^{23} [Vui93]	—	3.3 × 10^{24}	—	2.2 × 10^{24}	1.5 × 10^{24}
		—	2.3 (3.1)	—	1.9 (2.5)	1.5 (2.1)
^{150}Nd	— (2.1) × 10^{21} [Moe94a]	—	—	—	3.4 × 10^{22}	4.5 × 10^{22}
		—	—	—	— (4.0)	— (4.6)

Note. We use the recalculation for $g_A = 1.25$ [Moe94b] (if needed) of theoretical values of $T^{0\nu}_{1/2}\cdot\langle m_\nu\rangle^2$ from different works.

investigating the Majorana neutrino mass at the 0.01-eV level assuming zero background [Moe91b]. The first step in this direction has been taken by the KEK group [Miy94]: They have developed a collector of positive ions in liquid xenon and a time-of-flight mass spectrometer (TOFMS) for daughter Ba ions using the techniques of resonant ionization spectroscopy. The positive ion collector was operated for 847 h with 3 liters of natural liquid xenon; no ^{136}Ba^{2+} ions were detected by the TOFMS. Taking into account the full efficiency (<10^{-4}), the sensitivity for $T^{0\nu+2\nu}_{1/2}$ of ^{136}Xe is at the level of 10^{19} y. Now the KEK group plans to increase efficiency (and sensitivity) by two orders of magnitude [Miy94].

^{150}Nd. In an early experiment of the Moscow group, plastic scintillators with sheets of ^{150}Nd were used and a limit of $T^{0\nu}_{1/2} > 1.7 \times 10^{21}$ y (95% CL) ($m_\nu < 4.5$ eV) was established for the $0\nu2\beta$ decay of ^{150}Nd [Kli86]. The Irvine group doing a 6342-h TPC run with 11.2 g of ^{150}Nd

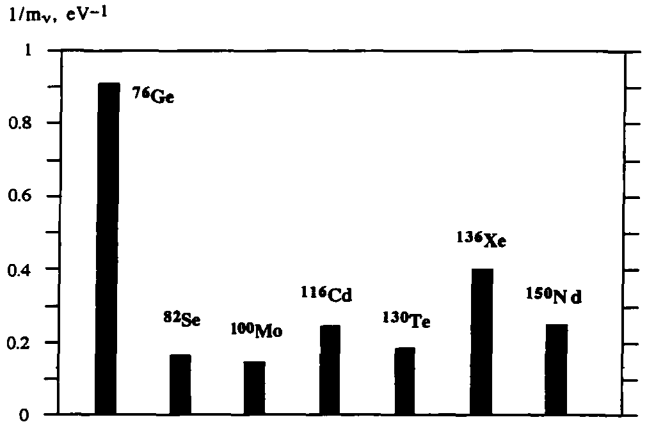

Figure 2. Sensitivity of the most advanced experiments to neutrino mass. Theoretical values of $T^{0\nu}_{1/2}\cdot\langle m_\nu\rangle^2$ [Sta90] and 90% CL experimental limits of $T^{0\nu}_{1/2}$ were used.

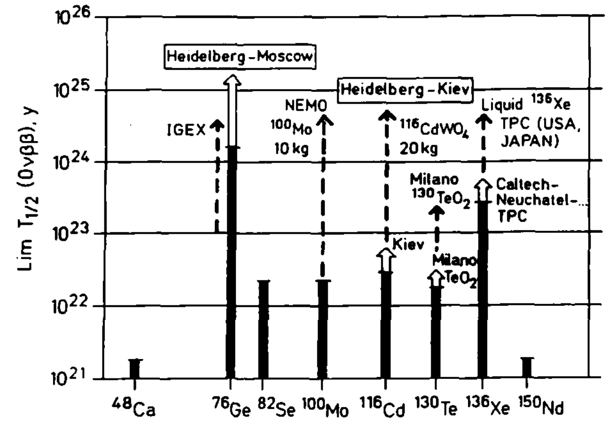

Figure 3. Present status and expected improvements for $T^{0\nu}_{1/2}$ half-life limits.

has set a limit of $T^{0\nu}_{1/2} > 2.1 \times 10^{21}$ y (90% CL), which corresponds to a neutrino mass $m_\nu < 4.0$ eV [Moe94a]. Due to the high sensitivity of the ^{150}Nd decay to the neutrino mass (large decay energy), a scaling up of the TPC with ~400 g of ^{150}Nd could push the limit on the neutrino mass down to 0.5 eV [Moe94a]. The two-neutrino 2β decay of ^{150}Nd was recently observed with $T^{2\nu}_{1/2} = (1.7^{+1.1}_{-0.5}(\text{stat.}) \pm 0.35(\text{syst.})) \times 10^{19}$ y [Art93] (the preliminary result of the Irvine group is $T^{2\nu}_{1/2} = 1.0 \times 10^{19}$ y [Ell93]).

The results of the recent and most advanced 2β decay experiments are summarized in Table A. It is clear that research in ^{76}Ge and ^{136}Xe has given us the most stringent limits on the Majorana neutrino mass ($\leqslant 1$–2 eV). Figure 2 shows the sensitivity of these experiments to the neutrino mass.

Figure 3, from Zde93, shows the actual status of the most advanced experiments, the expected improvements over current results, and the most realistic projects up to the year 1999.

In Table I we summarize the experimental and theoretical status for the 69 2β-unstable nuclides which are present in natural isotopic composition of elements. In Table II we list 19 other 2β-unstable isotopes which are absent in nature because of their decay through other channels. The graphs following these tables give an overview of selected data for the double beta-decaying isotopes listed in Table I.

SUPPLEMENT: ENERGY AND ANGULAR DISTRIBUTIONS OF ELECTRONS IN VARIOUS MODES OF 2β DECAY

In this supplement the theoretical formulas based on Doi81, Sch84, Moh88, Bur93a, and Car93 for the energy and angular distributions of electrons for different modes (0ν, 2ν, and modes with emission of Majorons) and mechanisms (two-nucleon $2n$, and Δ-isobar N^*) of 2β decay are given. In cases where formulas for the distribution of the single electron energy $F_1(T_1)$ or the sum of electron energies $F(T)$ were absent in the original articles, they were obtained from the basic distributions $F_{12\theta}(T_1, T_2, \cos\theta)$,

$$F_{12}(T_1, T_2) = \int_0^{\pi} F_{12\theta}(T_1, T_2, \cos\theta)\, d(\cos\theta), \quad (1)$$

$$F_1(T_1) = \int_0^{T_0 - T_1} F_{12}(T_1, T_2)\, dT_2, \quad (2)$$

$$F(T) = \int_0^{T} F_{12}(T - T_2, T_2)\, dT_2, \quad (3)$$

where T_i is the kinetic energy of the ith electron (in units of the electron mass m_0c^2), T_0 is the energy available for the 2β decay ($Q_{\beta\beta}$ for decay to the ground state and $Q_{\beta\beta} - E_{\text{level}}$ for decay to an excited state with energy E_{level} of the daughter nucleus) in the same units, $T = T_1 + T_2$, and θ is the angle between the electron directions. The momentum of the ith electron, P_i, which appears in the formulas below is given by $P_i = \sqrt{T_i(T_i + 2)}$ (in units of m_0c) and its velocity, β_i, by $\beta_i = P_i/E_i$ (in units of c), where $E_i = T_i + 1$. The Primakoff–Rosen (PR) approximation for the Fermi function, which takes into account the influence of the electric field of the nucleus on the emitted electrons, was used to obtain all the formulas analytically. It should be stressed here that the PR approximation is adequate for $2\beta^-$ decay but is not so reliable in the case of $2\beta^+$ decay; in Boe92, Doi92, and Doi93, exact distributions are compared with those calculated in the PR approximation.

1. $0\nu 2\beta$ Decay with Neutrino Mass, 0^+–0^+ Transition, and $2n$ Mechanism

$$F_{12\theta}(T_1, T_2, \cos\theta) = (T_1 + 1)^2 (T_2 + 1)^2 \times \delta(T_0 - T_1 - T_2)(1 - \beta_1\beta_2 \cos\theta), \quad (4)$$

$$F_{12}(T_1, T_2) = (T_1 + 1)^2 (T_2 + 1)^2 \times \delta(T_0 - T_1 - T_2), \quad (5)$$

$$F_1(T_1) = (T_1 + 1)^2 (T_0 + 1 - T_1)^2, \quad (6)$$

$$F(T) = \delta(T_0 - T). \quad (7)$$

Corresponding $F_1(T_1)$ and $F(T)$ distributions are shown in Fig. 4.1.

2. $0\nu 2\beta$ Decay with Right-Handed Currents, 0^+–0^+ Transition, and $2n$ Mechanism

The exact expression for $F_{12\theta}(T_1, T_2, \cos\theta)$ [Doi81, Sch84] is quite complicated and depends on different nuclear matrix elements. Therefore, the PR approximation and further simplifications recommended in Doi81, Sch84 were used:

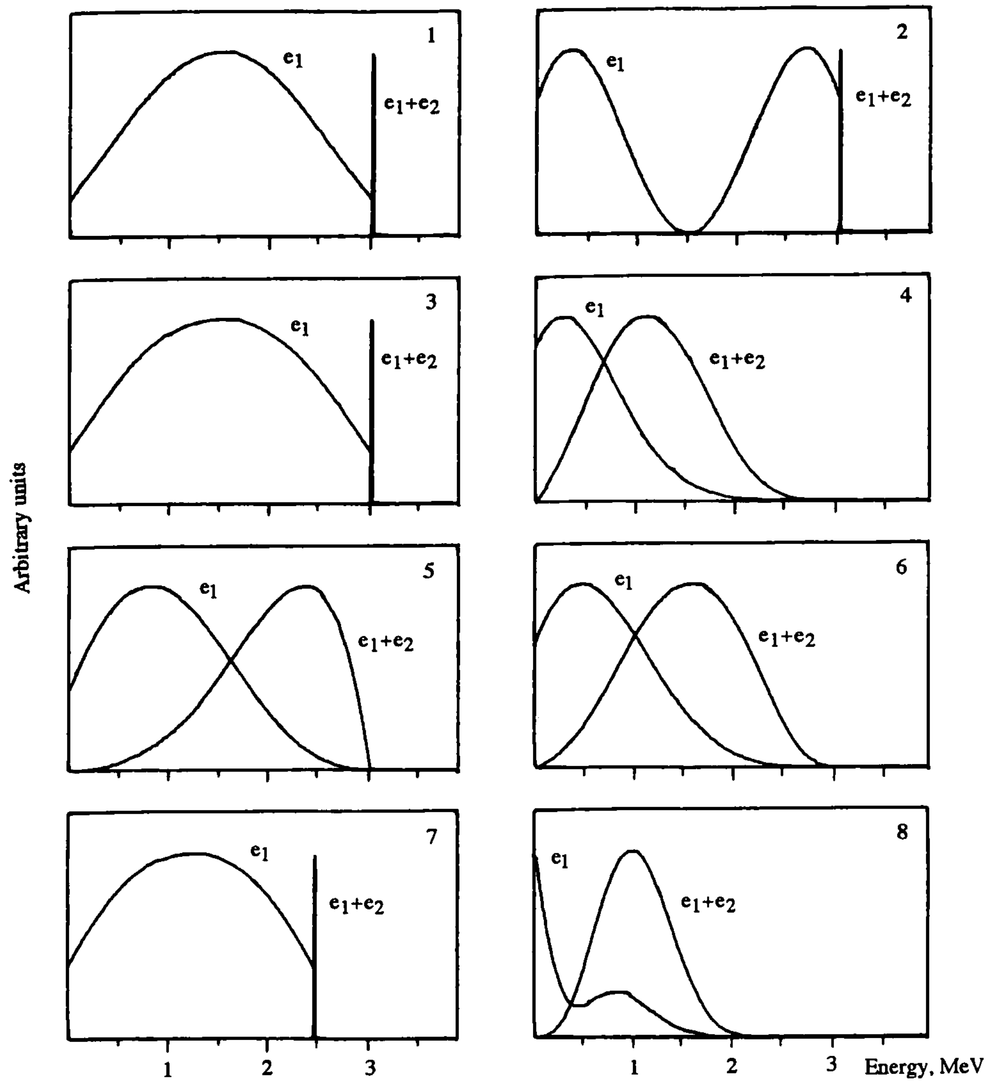

Figure 4. Theoretical distributions for the energy of a single electron (e_1) and for the sum of electron energies ($e_1 + e_2$) for ^{100}Mo ($Q_{\beta\beta}$ = 3034 keV, $E(2^+)$ = 540 keV) for different modes and mechanisms of 2β decay: (1) $0\nu2\beta$ decay with neutrino mass, 0^+–0^+ transition, $2n$ mechanism; (2) $0\nu2\beta$ decay with right-handed currents, 0^+–0^+ transition, $2n$ mechanism; (3) $0\nu2\beta$ decay with right-handed currents, 0^+–0^+ transition, N^* mechanism; (4) $2\nu2\beta$ decay, 0^+–0^+ transition, $2n$ mechanism; (5) $0\nu2\beta$ decay with Majoron emission, 0^+–0^+ transition, $2n$ mechanism; (6) $0\nu2\beta$ decay with double Majoron emission, 0^+–0^+ transition, $2n$ mechanism; (7) $0\nu2\beta$ decay with right-handed currents, 0^+–2^+ transition, $2n$ mechanism; (8) $2\nu2\beta$ decay, 0^+–2^+ transition, $2n$ mechanism and N^* mechanism.

$$F_{12\theta}(T_1, T_2, \cos\theta) = (T_1 + 1)^2(T_2 + 1)^2(T_1 - T_2)^2 \times \delta(T_0 - T_1 - T_2)(1 + \beta_1\beta_2\cos\theta), \quad (8)$$

$$F_{12}(T_1, T_2) = (T_1 + 1)^2(T_2 + 1)^2(T_1 - T_2)^2 \times \delta(T_0 - T_1 - T_2), \quad (9)$$

$$F_1(T_1) = (T_1 + 1)^2(T_0 + 1 - T_1)^2 \times (T_0 - 2T_1)^2, \quad (10)$$

$$F(T) = \delta(T_0 - T). \quad (11)$$

The $F_1(T_1)$ and $F(T)$ distributions are shown in Fig. 4.2.

3. $0\nu2\beta$ Decay with Right-Handed Currents, 0^+–0^+ Transition, and N^* Mechanism

$$F_{12\theta}(T_1, T_2, \cos\theta) = E_1E_2[2P_1^2P_2^2\cos^2\theta - P_1P_2\cos\theta[(E_1 + E_2)^2 + 4(E_1E_2 + 1)] + 3(E_1E_2 + 1)(P_1^2 + P_2^2)]\delta(T_0 - T_1 - T_2), \quad (12)$$

$$F_{12}(T_1, T_2) = E_1E_2[2P_1^2P_2^2 + 9(E_1E_2 + 1) \times (P_1^2 + P_2^2)]\delta(T_0 - T_1 - T_2), \quad (13)$$

$$F_1(T_1) = E_1E_2[2P_1^2P_2^2 + 9(E_1E_2 + 1) \times (P_1^2 + P_2^2)], \tag{14}$$

$$F(T) = \delta(T_0 - T), \tag{15}$$

with $T_2 = T_0 - T_1$. The $F_1(T_1)$ and $F(T)$ distributions are shown in Fig. 4.3.

4. 2ν2β Decay, 0⁺-0⁺ Transition, and 2*n* Mechanism

$$F_{12\theta}(T_1, T_2, \cos\theta) = (T_1 + 1)^2(T_2 + 1)^2 \times (T_0 - T_1 - T_2)^5(1 - \beta_1\beta_2\cos\theta), \tag{16}$$

$$F_{12}(T_1, T_2) = (T_1 + 1)^2(T_2 + 1)^2 \times (T_0 - T_1 - T_2)^5, \tag{17}$$

$$F_1(T_1) = (T_1 + 1)^2(T_0 - T_1)^6[(T_0 - T_1)^2 + 8(T_0 - T_1) + 28], \tag{18}$$

$$F(T) = (T^4 + 10T^3 + 40T^2 + 60T + 30) \times T(T_0 - T)^5. \tag{19}$$

The $F_1(T_1)$ and $F(T)$ distributions are shown in Fig. 4.4.

5. 0ν2β Decay with Emission of Majoron, 0⁺-0⁺ Transition, and 2*n* Mechanism

For 0ν2β decay with emission of Majoron [Gel81],

$$F_{12\theta}(T_1, T_2, \cos\theta) = (T_1 + 1)^2(T_2 + 1)^2 \times (T_0 - T_1 - T_2)(1 - \beta_1\beta_2\cos\theta), \tag{20}$$

$$F_{12}(T_1, T_2) = (T_1 + 1)^2 \times (T_2 + 1)^2(T_0 - T_1 - T_2), \tag{21}$$

$$F_1(T_1) = (T_1 + 1)^2[(T_0 + 1 - T_1)^4 - 4(T_0 + 1 - T_1) + 3], \tag{22}$$

$$F(T) = (T^4 + 10T^3 + 40T^2 + 60T + 30) \times T(T_0 - T). \tag{23}$$

The $F_1(T_1)$ and $F(T)$ distributions are shown in Fig. 4.5.

6. 0ν2β Decay with Double Majoron Emission, 0⁺-0⁺ Transition, and 2*n* Mechanism; Decay with Charged *L* = −2 Majoron and Massive Vector Majoron

For both decay with double Majoron emission [Moh88] and decay with emission of Majoron with lepton number −2 [Bur93a],

$$F_{12\theta}(T_1, T_2, \cos\theta) = (T_1 + 1)^2(T_2 + 1)^2 \times (T_0 - T_1 - T_2)^3(1 - \beta_1\beta_2\cos\theta), \tag{24}$$

$$F_{12}(T_1, T_2) = (T_1 + 1)^2 \times (T_2 + 1)^2(T_0 - T_1 - T_2)^3, \tag{25}$$

$$F_1(T_1) = (T_1 + 1)^2(T_0 - T_1)^4 \times [(T_0 - T_1)^2 + 6(T_0 - T_1) + 15], \tag{26}$$

$$F(T) = (T^4 + 10T^3 + 40T^2 + 60T + 30) \times T(T_0 - T)^3. \tag{27}$$

For the decay with emission of a vector Majoron with mass m [Car93]

$$F_{12\theta}(T_1, T_2, \cos\theta) = (T_1 + 1)^2(T_2 + 1)^2 \times [(T_0 - T_1 - T_2)^2 - m^2]^{3/2}(1 - \beta_1\beta_2\cos\theta). \tag{28}$$

In the $m = 0$ case this distribution (and all subsequent ones) reduces to the distribution for double Majoron emission. Corresponding $F_1(T_1)$ and $F(T)$ distributions are shown in Fig. 4.6.

7. 0ν2β Decay with Right-Handed Currents, 0⁺-2⁺ Transition, and 2*n* Mechanism

$$F_{12\theta}(T_1, T_2, \cos\theta) = E_1E_2[3P_1^2P_2^2\cos^2\theta - P_1P_2\cos\theta(10(E_1E_2 + 1) + P_1^2 + P_2^2) + 5(E_1E_2 + 1)(P_1^2 + P_2^2) - P_1^2P_2^2] \times \delta(T_0 - T_1 - T_2), \tag{29}$$

$$F_{12}(T_1, T_2) = E_1E_2(E_1E_2 + 1) \times (P_1^2 + P_2^2)\delta(T_0 - T_1 - T_2), \tag{30}$$

$$F_1(T_1) = E_1E_2(E_1E_2 + 1)(P_1^2 + P_2^2), \tag{31}$$

$$F(T) = \delta(T_0 - T), \tag{32}$$

with $T_2 = T_0 - T_1$. Corresponding $F_1(T_1)$ and $F(T)$ distributions are shown in Fig. 4.7.

8. 0ν2β Decay with Right-Handed Currents, 0⁺-2⁺ Transition, and *N** Mechanism

In this case the theoretical formulas are the same as for the 0ν2β decay with right-handed currents, 0⁺-0⁺ transition, and *N** mechanism (Eqs. 12–15), but the T_0 value would be different.

9. 2ν2β Decay, 0⁺-2⁺ Transition, 2*n* Mechanism, and *N** Mechanism

$$F_{12\theta}(T_1, T_2, \cos\theta) = (T_1 + 1)^2(T_2 + 1)^2(T_1 - T_2)^2 \times (T_0 - T_1 - T_2)^7(1 + \tfrac{1}{3}\beta_1\beta_2\cos\theta), \tag{33}$$

$$F_{12}(T_1, T_2) = (T_1 + 1)^2(T_2 + 1)^2 \times (T_1 - T_2)^2(T_0 - T_1 - T_2)^7, \tag{34}$$

$$F_1(T_1) = (T_1 + 1)^2(T_0 - T_1)^8[(T_0 - T_1)^4 - 6(T_1 - 1)(T_0 - T_1)^3 + 11(T_1^2 - 4T_1 + 1)(T_0 - T_1)^2 + 110T_1(T_1 - 1) \times (T_0 - T_1) + 495T_1^2], \tag{35}$$

$$F(T) = T^3(T^4 + 14T^3 + 84T^2 + 140T + 70)(T_0 - T)^7. \quad (36)$$

(The formula for $F_1(T_1)$ in Sch84 is slightly incorrect; we give the correct expression.) The formulas for N^* mechanism in this mode of decay are the same as those for the $2n$ mechanism. Corresponding $F_1(T_1)$ and $F(T)$ distributions are shown in Fig. 4.8.

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POLICIES

Literature Coverage All available experimental papers, including articles, conference proceedings, preprints, and theses, were covered up to January 1995. 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 and, in the case of limits on $T_{1/2}$, only the most stringent current experimental limit. We quote theoretical half-lives only for a few of the more successful theoretical models. The sources with the most extensive list 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.

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.

Errors Full error is calculated as the square root of the sum of squares of systematic and statistical errors (if both were presented in the original paper).

Confidence Levels Confidence level 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 effort has been made to recalculate all data for the same confidence level.

EXPLANATION OF TABLES

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β Processes ($2\beta^-$; $2\beta^+$; $\epsilon\beta^+$; 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 2β-unstable nuclides present in natural isotopic composition of elements; these include 15 for which neither experimental nor theoretical results have yet been reported. The cutoff date for this compilation is January 1995.

Theoretical estimates of half-lives are given for comparison. For 0ν decay, the theoretical half-lives are given for $m_\nu = 1$ eV. In calculations of Ver83, the Majoron coupling constant is $g = 5 \times 10^{-3}$. The theoretical results of Eng88 are given for $\alpha'_1 = -390$ MeV $\cdot$ fm^3. The generalized seniority calculations of Eng89 are given without monopole proton–neutron interaction; we use the phase space factors of Eng88 to calculate the values of $T_{1/2}$.

A	Mass number
Z	Atomic number
El	Element symbol
ΔM_A	Mass difference between parent and daughter atoms (with error in parentheses), taken from Aud93; where a second mass difference is given, the reference source is given behind the value
δ	Abundance of parent nuclide (with error in parentheses), taken from Bar91
Type of result	
Exp.	Experimental values
Th.	Theoretical estimates
Decay channel	
$2\beta^-$	Double electron decay
$2\beta^+$	Double positron decay
$\epsilon\beta^+$	Electron capture and β^+ decay
Kβ^+	Electron capture from K shell and β^+ decay
2ϵ	Double electron capture
2K	Double electron capture from K shell
Transition	
g.s.–g.s.	Ground-state to ground-state 2β transition
g.s.–2_1^+, 0_1^+, $\cdots$	2β transitions to 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
0ν(rhc)	Neutrinoless decay due to right-handed currents
0νM	Neutrinoless mode with emission of Majoron
0νMM	Neutrinoless mode with double Majoron emission
Half-life, years	The 2β decay half-life in years
Confidence level	Confidence level of result
Reference and remark	The data source keyed to the list of References for Introduction and Tables, with a numerical superscript indicating that additional information is given as a footnote to the table

EXPLANATION OF TABLES continued

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 [Led78] which are absent in natural isotopic composition of elements because of short half-life decays through other channels.

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 parent nuclide, from Led78
α	Alpha decay
sf	Spontaneous fission
y, 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 error in parentheses), taken from Aud93 or Led78

EXPLANATION OF GRAPHS

GRAPH I. Atomic Mass Differences between 2β-Unstable Parents and Their Daughters

GRAPH II. Natural Abundances of 2β-Unstable Isotopes

GRAPH III. Limits on Half-Lives for Neutrinoless 2β Processes

GRAPH IV. Positive Results and Limits on Half-Lives for Two-Neutrino Processes

GRAPH V. Limits on Half-Lives for 2β Decay with Majoron Emission

GRAPH VI. Positive Results on Half-Lives Deduced from Indirect Experiments

The Graphs are plots of selected data from Table I.

In Graphs I–IV, the data in the top half (labeled a) are those for $2\beta^-$-unstable parents, and the data in the bottom half (labeled b) are those for $2\beta^+$-, $\epsilon\beta^+$-, and 2ϵ-unstable parents.

The positive values and limits on lifetimes shown in Graphs III–V are from direct 2β experiments for 0ν, 2ν, and $0\nu M$ transitions. Data are for transitions to daughter ground states only.

Lifetimes shown in Graph VI are obtained indirectly, from geochemical and radiochemical experiments.

For confidence levels of the limits presented, see Table I.

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

See page 64 for Explanation of Tables

^A_ZEl–$^A_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{36}_{18}$Ar–$^{36}_{16}$S	Exp.	2ε			–		
433.5(0.3) keV	Th.	2ε			–		
0.337(0.003)%							
$^{40}_{20}$Ca–$^{40}_{18}$Ar	Exp.	2ε			–		
193.78(0.29) keV	Th.	2ε	g.s.–g.s.		$> 1.2 \cdot 10^{33}$		Qin84
96.941(0.018)%							
$^{46}_{20}$Ca–$^{46}_{22}$Ti	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 6.9 \cdot 10^{11}$		Fre52[1]
990.4(2.4) keV	Th.	$2\beta^-$	g.s.–g.s.	2ν	$= 5.1 \cdot 10^{23}$		Hax84[2]
0.004(0.003)%							
$^{48}_{20}$Ca–$^{48}_{22}$Ti	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 2.0 \cdot 10^{21}$	80%	Bar70[3]
4272(4) keV					$> 9.5 \cdot 10^{21}$	76%	Key91
0.187(0.004)%				2ν	$> 3.6 \cdot 10^{19}$		Bar70
				0νM	$> 7.2 \cdot 10^{20}$	90%	Bar70[4]
			g.s.–2^+_1	0ν	$> 1.0 \cdot 10^{21}$	90%	Bar70[4]
			g.s.–0^+_1	0ν	$> 8.0 \cdot 10^{18}$	95%	Alb86
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 3.8 \cdot 10^{24}$		Doi83
					$= (6.4 - 7.8) \cdot 10^{24}$		Ret95
				2ν	$= 3.6 \cdot 10^{19}$		Doi83
					$= 2.7 \cdot 10^{20}$		Ver83
					$= 2.9 \cdot 10^{19}$		Hax84
					$= 5.5 \cdot 10^{19}$		Cau90[15]
			g.s.–2^+_1	2ν	$= 5.0 \cdot 10^{26}$		Hax84
			g.s.–2^+_2	2ν	$= 3.6 \cdot 10^{26}$		Hax84
$^{50}_{24}$Cr–$^{50}_{22}$Ti	Exp.	$\varepsilon\beta^+$	g.s.–g.s.	$0\nu + 2\nu$	$> 1.8 \cdot 10^{17}$	68%	Nor85
1171.3(1.2) keV	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
4.345(0.013)%							
$^{54}_{26}$Fe–$^{54}_{24}$Cr	Exp.	2ε			–		
680.1(0.6) keV	Th.	2ε			–		
5.8(0.1)%							
$^{58}_{28}$Ni–$^{58}_{26}$Fe	Exp.	$\varepsilon\beta^+$	g.s.–g.s.	$0\nu + 2\nu$	$> 7.0 \cdot 10^{20}$	68%	Vas93
1925.9(0.7) keV			g.s.–2^+_1	$0\nu + 2\nu$	$> 4.0 \cdot 10^{20}$	68%	Vas93
68.077(0.009)%		$\varepsilon\beta^+ + 2\varepsilon$	g.s.–2^+_1	$0\nu + 2\nu$	$> 4.0 \cdot 10^{19}$	90%	Bel82
			g.s.–2^+_2	$0\nu + 2\nu$	$> 4.0 \cdot 10^{19}$	90%	Bel82
		2ε	g.s.–g.s.+2^+_1	0ν	$> 2.1 \cdot 10^{19}$	68%	Nor84

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$^{A}_{Z}$El–$^{A}_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{58}_{28}$Ni *(continued)*	Th.	$\varepsilon\beta^+$	g.s.–g.s.	0ν	$= 5.1 \cdot 10^{28}$		Ver83
					$= 1.1 \cdot 10^{29}$		Bal89
				2ν	$= 1.9 \cdot 10^{24}$		Ver83
					$= 5.7 \cdot 10^{24}$		Suh93b
					$= 5.5 \cdot 10^{25}$		Hir94a
				0νM	$= 7.6 \cdot 10^{23}$		Ver83
		2ε		0ν	$= 1.8 \cdot 10^{38}$		Ver83
				2ν	$= 2.8 \cdot 10^{25}$		Ver83
					$= 3.9 \cdot 10^{23}$		Suh93b
					$= 3.9 \cdot 10^{24}$		Hir94a
				0νM	$= 2.4 \cdot 10^{24}$		Ver83
$^{64}_{30}$Zn–$^{64}_{28}$Ni	Exp.	$\varepsilon\beta^+$	g.s.–g.s.	$0\nu + 2\nu$	$> 2.3 \cdot 10^{18}$	68%	Nor85
1096.3(0.9) keV		2ε		$0\nu + 2\nu$	$> 8.0 \cdot 10^{15}$		Ber53
48.6(0.3)%	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
$^{70}_{30}$Zn–$^{70}_{32}$Ge	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 4.8 \cdot 10^{14}$		Fre52[1]
1001(3) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 9.8 \cdot 10^{25}$		Sta90
0.6(0.1)%				2ν	$= 4.5 \cdot 10^{21} - 3.6 \cdot 10^{24}$		Sta90
					$= 1.4 \cdot 10^{24}$		Hir94b
$^{76}_{32}$Ge–$^{76}_{34}$Se	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 1.9 \cdot 10^{24}$	90%	Kla93a
2038.7(0.5) keV				2ν	$= (9.0 \pm 1.0) \cdot 10^{20}$	68%	Vas90a
2038.58(0.31) keV [Hyk93]					$= 1.1^{+0.6}_{-0.3} \cdot 10^{21}$	95%	Mil90
7.44(0.02)%					$= 8.4^{+1.0}_{-0.8} \cdot 10^{20}$	95%	Bro93
					$= (1.4 \pm 0.1) \cdot 10^{21}$		Bal94
				0νM	$> 3.9 \cdot 10^{22}$	90%	Kla93a
			g.s.–2^+_1	0ν	$> 8.2 \cdot 10^{23}$	90%	Mai94
				$0\nu + 2\nu$	$> 3.7 \cdot 10^{20}$	90%	Bec92
					$> 3.0 \cdot 10^{21}$	90%	Bar92
			g.s.–0^+_1	0ν	$> 2.0 \cdot 10^{22}$	68%	Bus90
				$0\nu + 2\nu$	$> 3.7 \cdot 10^{20}$	90%	Bec92
					$> 4.1 \cdot 10^{21}$	90%	Bar92
			g.s.–2^+_2	$0\nu + 2\nu$	$> 2.4 \cdot 10^{20}$	90%	Bec92
					$> 3.3 \cdot 10^{21}$	90%	Bar92
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 9.4 \cdot 10^{24}$		Doi83
					$= 2.7 \cdot 10^{25}$		Eng88[5]
					$= 4.1 \cdot 10^{24}$		Eng89[6]
					$= 2.3 \cdot 10^{24}$		Sta90
					$= 2.2 \cdot 10^{24}$		Tom91
					$= 2.8 \cdot 10^{24}$		Hir94b

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$^{A}_{Z}$El–$^{A}_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{76}_{32}$Ge *(continued)*				2ν	$= 2.3 \cdot 10^{21}$		Doi83
					$= 5.0 \cdot 10^{20} - 6.3 \cdot 10^{21}$		Vog86
					$= 1.3 \cdot 10^{21}$		Eng88
					$= 7.0 \cdot 10^{19} - 3.0 \cdot 10^{21}$		Sta90
					$= 9.0 \cdot 10^{20}$		Civ94
					$= 2.6 \cdot 10^{20}$		Hir94b
					$= 1.3 \cdot 10^{21}$		Dhi94
			g.s.–2^+_1	2ν	$= 1.2 \cdot 10^{30}$		Hax84
					$= 5.8 \cdot 10^{23}$		Dhi94
					$= 5.0 \cdot 10^{26}$		Civ94
			g.s.–0^+_1	2ν	$= 4.0 \cdot 10^{22}$		Civ94
			g.s.–2^+_2	2ν	$= 1.0 \cdot 10^{29}$		Civ94
$^{74}_{34}$Se–$^{74}_{32}$Ge	Exp.	$\varepsilon\beta^+ + 2\varepsilon$			–		
1209.4(0.6) keV	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
1209.53(0.48) keV [Hyk93]							
0.89(0.02)%							
$^{80}_{34}$Se–$^{80}_{36}$Kr	Exp.	$2\beta^-$			–		
134(4) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 1.1 \cdot 10^{27}$		Sta90
49.61(0.10)%				2ν	$= 7.5 \cdot 10^{28} - 1.9 \cdot 10^{30}$		Sta90
					$= 2.7 \cdot 10^{29}$		Hir94b
$^{82}_{34}$Se–$^{82}_{36}$Kr	Exp.	$2\beta^-$	all modes		$= (1.4 \pm 0.2) \cdot 10^{20}$		Kir69[7]
2995.0(2.0) keV					$= (1.7 \pm 0.3) \cdot 10^{20}$		Kir69[7]
2995.8(1.5) keV [Nxu93]					$= (1.3 \pm 0.3) \cdot 10^{20}$		Kir69[7]
8.73(0.06)%					$= (1.4 \pm 0.7) \cdot 10^{20}$		Kir69[7]
					$= (1.3 \pm 0.4) \cdot 10^{20}$		Kir69[7]
					$= (2.8 \pm 0.9) \cdot 10^{20}$		Sri73[7]
					$= (1.5 \pm 0.2) \cdot 10^{20}$		Kir83b[7]
					$= (2.1 \pm 0.3) \cdot 10^{20}$		Kir83b[7]
					$= 9.7^{+3.6}_{-4.5} \cdot 10^{19}$		Mar85[7]
					$= (1.0 \pm 0.4) \cdot 10^{20}$		Man86[7*]
					$= (1.3 \pm 0.1) \cdot 10^{20}$		Kir86[7*]
					$< (1.7 \pm 0.2) \cdot 10^{20}$		Lin86[7]
					$= 1.0^{+0.3}_{-0.4} \cdot 10^{20}$		Mur87[7]
					$= (1.2 \pm 0.1) \cdot 10^{20}$		Lin88a[7]
					$= 1.0 \cdot 10^{20}$		Man91[7*]
			g.s.–g.s.	0ν	$> 2.7 \cdot 10^{22}$	68%	Ell92
				2ν	$= 1.1^{+0.3}_{-0.1} \cdot 10^{20}$	68%	Ell92
				0νM	$> 1.6 \cdot 10^{21}$	68%	Moe88

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^A_ZEl–$^{\ A}_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{82}_{34}$Se *(continued)*			g.s.–2^+_1	0ν	$> 3.4 \cdot 10^{21}$	68%	Moe88
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 3.2 \cdot 10^{24}$		Doi83
					$= 1.1 \cdot 10^{25}$		Eng88[5]
					$= 1.7 \cdot 10^{24}$		Eng89[6]
					$= 6.0 \cdot 10^{23}$		Sta90
					$= 6.0 \cdot 10^{23}$		Tom91
					$= 7.0 \cdot 10^{23}$		Hir94b
				2ν	$= 1.5 \cdot 10^{20}$		Doi83
					$= 5.5 \cdot 10^{19} - 6.3 \cdot 10^{20}$		Vog86
					$= 1.2 \cdot 10^{20}$		Eng88
					$= 2.9 \cdot 10^{18} - 5.9 \cdot 10^{21}$		Sta90
					$= 8.5 \cdot 10^{19}$		Hir94b
					$= 1.5 \cdot 10^{20}$		Dhi94
			g.s.–2^+_1	2ν	$= 5.5 \cdot 10^{21}$		Dhi94
$^{78}_{36}$Kr–$^{78}_{34}$Se	Exp.	$2\beta^+$	g.s.–g.s.	$0\nu + 2\nu$	$> 2.0 \cdot 10^{21}$	68%	Sae94
2867(7) keV		$K\beta^+$	g.s.–g.s.	0ν	$> 5.1 \cdot 10^{21}$	68%	Sae94
0.35(0.02)%				2ν	$> 1.1 \cdot 10^{20}$	68%	Sae94
	Th.	$2\beta^+$	g.s.–g.s.	0ν	$= 1.7 \cdot 10^{28}$		Bal89
					$= 1.6 \cdot 10^{27}$		Hir94a
				2ν	$= 3.7 \cdot 10^{25}$		Bal89
					$= 2.3 \cdot 10^{26}$		Hir94a
		$\varepsilon\beta^+$	g.s.–g.s.	0ν	$= 4.2 \cdot 10^{28}$		Bal89
					$= 6.5 \cdot 10^{26}$		Hir94a
				2ν	$= 2.2 \cdot 10^{23}$		Bal89
					$= 5.3 \cdot 10^{22}$		Hir94a
		2ε	g.s.–g.s.	2ν	$= 1.4 \cdot 10^{23}$		Bal89
					$= 3.7 \cdot 10^{22}$		Hir94a
$^{86}_{36}$Kr–$^{86}_{38}$Sr	Exp.	$2\beta^-$			–		
1258(5) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 2.8 \cdot 10^{25}$		Sta90
17.3(0.2)%				2ν	$= 1.6 \cdot 10^{22} - 2.2 \cdot 10^{24}$		Sta90
					$= 3.4 \cdot 10^{23}$		Hir94b
$^{84}_{38}$Sr–$^{84}_{36}$Kr	Exp.	$\varepsilon\beta^+$	g.s.–g.s.	0ν	$> 7.3 \cdot 10^{13}$		Fre52[1]
1787(4) keV	Th.	$K\beta^+$	g.s.–g.s.	0ν	$= 9.7 \cdot 10^{28}$		Bal89
0.56(0.01)%				2ν	$= 4.3 \cdot 10^{25}$		Bal89
		2K	g.s.–g.s.	2ν	$= 6.9 \cdot 10^{23}$		Bal89
$^{94}_{40}$Zr–$^{94}_{42}$Mo	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 1.5 \cdot 10^{16}$	68%	Bar90b
1143.6(2.0) keV				2ν	$> 6.0 \cdot 10^{15}$	68%	Bar90b

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$^{A}_{Z}\mathrm{El}-^{A}_{Z\pm2}\mathrm{El}$ ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{94}_{40}$**Zr** *(continued)*				$0\nu M$	$> 1.5 \cdot 10^{16}$	68%	Bar90b
17.38(0.04)%			g.s.–2_1^+	$0\nu + 2\nu$	$> 1.3 \cdot 10^{19}$	68%	Nor87
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 4.0 \cdot 10^{25}$		Sta90
				2ν	$= (1.7 - 7.4) \cdot 10^{22}$		Sta90
					$= 1.7 \cdot 10^{24}$		Hir94b
$^{96}_{40}\mathrm{Zr}-^{96}_{42}\mathrm{Mo}$	Exp.	$2\beta^-$	all modes		$= (3.9 \pm 0.9) \cdot 10^{19}$	68%	Kaw93[7,8]
3350.3(2.9) keV			g.s.–g.s.	0ν	$> 3.0 \cdot 10^{19}$	68%	Zde81
2.80(0.02)%				2ν	$> 1.0 \cdot 10^{17}$	68%	Bar90b
				$0\nu M$	$> 1.3 \cdot 10^{17}$	68%	Bar90b
			g.s.–2_1^+	$0\nu + 2\nu$	$> 4.1 \cdot 10^{19}$	90%	Arp94
			g.s.–0_1^+	$0\nu + 2\nu$	$> 3.3 \cdot 10^{19}$	90%	Arp94
			g.s.–2_2^+	$0\nu + 2\nu$	$> 2.4 \cdot 10^{19}$	90%	Arp94
			g.s.–2_3^+	$0\nu + 2\nu$	$> 3.1 \cdot 10^{19}$	90%	Arp94
			g.s.–4_1^+	$0\nu + 2\nu$	$> 1.8 \cdot 10^{18}$	68%	Nor87
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 7.8 \cdot 10^{24}$		Eng88
					$= 5.3 \cdot 10^{23}$		Sta90
				2ν	$= 3.2 \cdot 10^{17} - 8.5 \cdot 10^{18}$		Vog86
					$= 8.5 \cdot 10^{18}$		Eng88
					$= 1.9 \cdot 10^{18} - 1.9 \cdot 10^{19}$		Sta90
					$= 2.0 \cdot 10^{20}$		Hir94b
$^{92}_{42}\mathrm{Mo}-^{92}_{40}\mathrm{Zr}$	Exp.	$\epsilon\beta^+$	g.s.–g.s.	0ν	$> 2.7 \cdot 10^{18}$	68%	Ell87b
1650(4) keV				$0\nu + 2\nu$	$> 3.0 \cdot 10^{17}$	68%	Nor85
14.84(0.04)%		$\epsilon\beta^+ + 2\epsilon$	g.s.–2_1^+	$0\nu + 2\nu$	$> 3.0 \cdot 10^{18}$	90%	Bel82
			g.s.–0_1^+	$0\nu + 2\nu$	$> 4.0 \cdot 10^{18}$	90%	Bel82
			g.s.–4_1^+	$0\nu + 2\nu$	$> 6.0 \cdot 10^{18}$	90%	Bel82
	Th.	$\epsilon\beta^+$	g.s.–g.s.	0ν	$= 4.1 \cdot 10^{30}$		Ver83
					$= 1.3 \cdot 10^{28}$		Bal89
				2ν	$= 1.4 \cdot 10^{25}$		Ver83
					$= 6.5 \cdot 10^{26}$		Bal89
				$0\nu M$	$= 9.6 \cdot 10^{25}$		Ver83
		2ϵ		0ν	$= 2.5 \cdot 10^{39}$		Ver83
				2ν	$= 5.7 \cdot 10^{24}$		Ver83
					$= 2.8 \cdot 10^{24}$		Bal89
				$0\nu M$	$= 9.2 \cdot 10^{24}$		Ver83
$^{98}_{42}\mathrm{Mo}-^{98}_{44}\mathrm{Ru}$	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 1.0 \cdot 10^{14}$		Fre52[1]
112(6) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 1.1 \cdot 10^{27}$		Sta90
24.13(0.07)%				2ν	$= 3.4 \cdot 10^{29} - 3.6 \cdot 10^{30}$		Sta90
					$= 6.2 \cdot 10^{30}$		Hir94b

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${}^{A}_{Z}$El–${}^{A}_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
${}^{100}_{42}$Mo–${}^{100}_{44}$Ru	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 4.4 \cdot 10^{22}$	68%	Als93
3034(6) keV				2ν	$= 3.3^{+2.0}_{-1.0} \cdot 10^{18}$	90%	Vas90b
9.63(0.03)%					$= 1.2^{+0.5}_{-0.3} \cdot 10^{19}$	90%	Eji91
					$= 1.2^{+0.3}_{-0.1} \cdot 10^{19}$	68%	Ell91
					$= (9.5 \pm 1.0) \cdot 10^{18}$		Das94
				0νM	$> 7.9 \cdot 10^{20}$	68%	Tan93
				0νMM	$> 5.3 \cdot 10^{19}$	68%	Tan93
			g.s.–2^+_1	$0\nu + 2\nu$	$> 2.3 \cdot 10^{21}$	90%	Bar93
			g.s.–0^+_1	$0\nu + 2\nu$	$> 1.2 \cdot 10^{21}$	90%	Blu92
					$= 6.3^{+2.1}_{-1.2} \cdot 10^{20}$		Avi94
			g.s.–4^+_1	0ν	$> 6.3 \cdot 10^{20}$		Kud92
				2ν	$> 5.1 \cdot 10^{19}$		Kud92
			g.s.–2^+_2	$0\nu + 2\nu$	$> 2.5 \cdot 10^{21}$	90%	Bar93
			g.s.–0^+_2	$0\nu + 2\nu$	$> 1.5 \cdot 10^{21}$	90%	Bar93
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 1.9 \cdot 10^{24}$		Eng88
					$= 1.3 \cdot 10^{24}$		Sta90
					$= 2.6 \cdot 10^{23}$		Tom91
				2ν	$= 8.0 \cdot 10^{17} - 3.7 \cdot 10^{19}$		Vog86
					$= 6.0 \cdot 10^{18}$		Eng88
					$= 1.3 \cdot 10^{17} - 1.1 \cdot 10^{20}$		Sta90
					$= 3.6 \cdot 10^{19}$		Hir94b
					$= (2.9 - 7.7) \cdot 10^{18}$		Suh94
			g.s.–2^+_1	2ν	$= (5.3 - 7.5) \cdot 10^{20}$		Suh94
			g.s.–0^+_1	2ν	$= (6.7 - 7.0) \cdot 10^{19}$		Suh94
			g.s.–2^+_2	2ν	$= (1.9 - 2.1) \cdot 10^{23}$		Suh94
${}^{96}_{44}$Ru–${}^{96}_{42}$Mo	Exp.	$2\beta^+$	g.s.–g.s.	$0\nu + 2\nu$	$> 3.1 \cdot 10^{16}$	68%	Nor85
2725(8) keV		$\epsilon\beta^+$	g.s.–g.s.	$0\nu + 2\nu$	$> 6.7 \cdot 10^{16}$	68%	Nor85
5.52(0.06)%			g.s.–2^+_1	$0\nu + 2\nu$	$> 6.0 \cdot 10^{16}$	68%	Nor85
			g.s.–0^+_1	$0\nu + 2\nu$	$> 4.5 \cdot 10^{16}$	68%	Nor85
			g.s.–2^+_2	$0\nu + 2\nu$	$> 5.5 \cdot 10^{16}$	68%	Nor85
			g.s.–2^+_3	$0\nu + 2\nu$	$> 5.3 \cdot 10^{16}$	68%	Nor85
			g.s.–4^+_1	$0\nu + 2\nu$	$> 5.3 \cdot 10^{16}$	68%	Nor85
	Th.	$2\beta^+$	g.s.–g.s.	0ν	$= 5.1 \cdot 10^{29}$		Ver83
					$= 8.7 \cdot 10^{27}$		Hir94a
				2ν	$= 1.6 \cdot 10^{28}$		Ver83
					$= 5.8 \cdot 10^{26}$		Hir94a
				0νM	$= 1.1 \cdot 10^{26}$		Ver83
		$\epsilon\beta^+$	g.s.–g.s.	0ν	$= 2.3 \cdot 10^{29}$		Ver83
					$= 7.5 \cdot 10^{26}$		Hir94a
				2ν	$= 2.6 \cdot 10^{24}$		Ver83

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$^{A}_{Z}$El–$^{A}_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{96}_{44}$**Ru** *(continued)*					$= 7.8 \cdot 10^{21} - 1.7 \cdot 10^{22}$		Suh93b
					$= 1.2 \cdot 10^{22}$		Hir94a
				0νM	$= 6.0 \cdot 10^{24}$		Ver83
			g.s.–0^+_1	0ν	$= 2.0 \cdot 10^{30}$		Ver83
				2ν	$= 3.8 \cdot 10^{29}$		Ver83
				0νM	$= 9.2 \cdot 10^{25}$		Ver83
		2ε	g.s.–g.s.	0ν	$= 2.8 \cdot 10^{34}$		Ver83
				2ν	$= 6.5 \cdot 10^{24}$		Ver83
					$= (1.3 - 2.8) \cdot 10^{21}$		Suh93b
					$= 2.1 \cdot 10^{21}$		Hir94a
				0νM	$= 3.2 \cdot 10^{24}$		Ver83
			g.s.–0^+_1	2ν	$= 5.2 \cdot 10^{27}$		Ver83
				0νM	$= 4.5 \cdot 10^{24}$		Ver83
$^{104}_{44}$**Ru**–$^{104}_{46}$**Pd**	Exp.	$2\beta^-$			–		
1300(4) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 4.2 \cdot 10^{24}$		Sta90
18.7(0.2)%				2ν	$= 3.2 \cdot 10^{20} - \infty$		Sta90
					$= 3.1 \cdot 10^{22}$		Hir94b
$^{102}_{46}$**Pd**–$^{102}_{44}$**Ru**	Exp.	$\varepsilon\beta^+ + 2\varepsilon$			–		
1172.1(2.6) keV	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
1.02(0.01)%							
$^{110}_{46}$**Pd**–$^{110}_{48}$**Cd**	Exp.	$2\beta^-$	all modes		$> 6.0 \cdot 10^{17}$		Win52
2000(11) keV			g.s.–g.s.	2ν	$> 6.0 \cdot 10^{16}$		Win52[9]
11.72(0.09)%				0νM	$> 6.0 \cdot 10^{16}$		Win52[9]
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 2.0 \cdot 10^{24}$		Sta90
				2ν	$= 8.5 \cdot 10^{18} - \infty$		Sta90
					$= 1.2 \cdot 10^{21}$		Hir94b
$^{106}_{48}$**Cd**–$^{106}_{46}$**Pd**	Exp.	$2\beta^+$	g.s.–g.s.	0ν	$> 1.4 \cdot 10^{18}$	90%	Dan95
2771(8) keV				0ν + 2ν	$> 2.6 \cdot 10^{17}$	68%	Nor84
1.25(0.04)%			g.s.–2^+_1	0ν	$> 5.1 \cdot 10^{17}$	90%	Dan95
				0ν + 2ν	$> 2.2 \cdot 10^{17}$	68%	Nor84
		$\varepsilon\beta^+$	g.s.–g.s.	0ν	$> 1.1 \cdot 10^{19}$	90%	Dan95
				0ν + 2ν	$> 5.7 \cdot 10^{17}$	68%	Nor84
			g.s.–2^+_1	0ν	$> 4.0 \cdot 10^{18}$	90%	Dan95
				0ν + 2ν	$> 4.9 \cdot 10^{17}$	68%	Nor84
			g.s.–2^+_2	0ν	$> 3.0 \cdot 10^{18}$	90%	Dan95
		2ε	g.s.–g.s.+2^+_1	0ν	$> 1.5 \cdot 10^{17}$	68%	Nor84
		2K	g.s.–g.s.	2ν	$> 5.8 \cdot 10^{17}$	90%	Dan95

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$^A_Z\mathrm{El}-{}^{\;A}_{Z\pm2}\mathrm{El}$ ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{106}_{48}$Cd *(continued)*	Th.	$2\beta^+$	g.s.–g.s.	0ν	$= 3.9 \cdot 10^{28}$		Bal89
					$= 4.8 \cdot 10^{27}$		Hir94a
				2ν	$= 6.1 \cdot 10^{26}$		Bal89
					$= 4.2 \cdot 10^{26}$		Hir94a
		$\varepsilon\beta^+$	g.s.–g.s.	0ν	$= 2.2 \cdot 10^{28}$		Bal89
					$= 3.4 \cdot 10^{26}$		Hir94a
				2ν	$= 5.2 \cdot 10^{23}$		Bal89
					$= (1.2 - 2.1) \cdot 10^{21}$		Suh93b
					$= 4.1 \cdot 10^{21}$		Hir94a
		2ε	g.s.–g.s.	2ν	$= 7.5 \cdot 10^{22}$		Bal89
					$= (1.5 - 2.6) \cdot 10^{20}$		Suh93b
					$= 8.7 \cdot 10^{20}$		Hir94a
$^{108}_{48}$Cd–$^{108}_{46}$Pd	Exp.	2ε	g.s.–g.s.	0ν	$> 3.3 \cdot 10^{16}$	90%	Dan95
269(6) keV		2K	g.s.–g.s.	2ν	$> 4.1 \cdot 10^{17}$	90%	Dan95
0.89(0.02)%	Th.	2ε			–		
$^{114}_{48}$Cd–$^{114}_{50}$Sn	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 2.0 \cdot 10^{20}$	90%	Dan95
536(3) keV				2ν	$> 9.2 \cdot 10^{16}$	99%	Dan95
28.73(0.28)%	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 5.1 \cdot 10^{25}$		Sta90
				2ν	$= 7.3 \cdot 10^{23} - 1.8 \cdot 10^{24}$		Sta90
					$= 9.8 \cdot 10^{24}$		Hir94b
$^{116}_{48}$Cd–$^{116}_{50}$Sn	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 2.9 \cdot 10^{22}$	90%	Dan95
2804(4) keV				2ν	$> 1.8 \cdot 10^{19}$	99%	Dan95
7.49(0.12)%					$= 2.6^{+0.9}_{-0.5} \cdot 10^{19}$	68%	Kum94
					$= 2.7^{+1.0}_{-0.7} \cdot 10^{19}$	68%	Dan95
					$= 3.6^{+0.7}_{-0.6} \cdot 10^{19}$		Das95
				0νM	$> 1.0 \cdot 10^{21}$	90%	Dan95
			g.s.–2^+_1	0ν	$> 4.4 \cdot 10^{21}$	90%	Dan95
				$0\nu + 2\nu$	$> 2.4 \cdot 10^{21}$	90%	Pie94
			g.s.–0^+_1	$0\nu + 2\nu$	$> 2.1 \cdot 10^{21}$	90%	Pie94
			g.s.–0^+_2	$0\nu + 2\nu$	$> 2.1 \cdot 10^{21}$	90%	Pie94
			g.s.–2^+_2	$0\nu + 2\nu$	$> 1.7 \cdot 10^{20}$	68%	Bar90a
			g.s.–2^+_3	$0\nu + 2\nu$	$> 1.0 \cdot 10^{20}$	68%	Bar90a
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 4.9 \cdot 10^{23}$		Sta90
					$= 5.8 \cdot 10^{23}$		Hir94b
				2ν	$= 7.5 \cdot 10^{19} - 1.9 \cdot 10^{21}$		Vog86
					$= 2.9 \cdot 10^{18} - 1.2 \cdot 10^{20}$		Sta90
					$= 1.5 \cdot 10^{20}$		Hir94b
					$= 1.2 \cdot 10^{19}$		Pie94

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β processes ($2\beta^-$; $2\beta^+$; $\epsilon\beta^+$; 2ϵ)
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$^{A}_{Z}$El–$^{A}_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{116}_{48}$Cd *(continued)*			g.s.–2_1^+	2ν	$= 2.0 \cdot 10^{23}$		Pie94
			g.s.–0_2^+	2ν	$= 1.6 \cdot 10^{22}$		Pie94
$^{112}_{50}$Sn–$^{112}_{48}$Cd	Exp.	$\varepsilon\beta^+$	g.s.–g.s.	0ν	$> 6.1 \cdot 10^{13}$		Fre52[1]
1923(4) keV	Th.	$K\beta^+$	g.s.–g.s.	0ν	$= 1.7 \cdot 10^{29}$		Bal89
0.97(0.01)%				2ν	$= 1.2 \cdot 10^{26}$		Bal89
		2K	g.s.–g.s.	2ν	$= 1.0 \cdot 10^{25}$		Ber83
					$= 1.2 \cdot 10^{24}$		Bal89
			g.s.–0_3^+	0ν	$> 1.0 \cdot 10^{25}$		Ber83
$^{122}_{50}$Sn–$^{122}_{52}$Te	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 5.8 \cdot 10^{13}$		Fre52[1]
359(3) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 1.3 \cdot 10^{26}$		Sta90
4.63(0.03)%				2ν	$= 4.9 \cdot 10^{25} - 1.6 \cdot 10^{28}$		Sta90
					$= 1.3 \cdot 10^{26}$		Hir94b
$^{124}_{50}$Sn–$^{124}_{52}$Te	Exp.	$2\beta^-$		0ν	$> 2.4 \cdot 10^{17}$	95%	Kal52
2287.5(1.5) keV			g.s.–g.s.	2ν	$> 1.0 \cdot 10^{17}$		Kal52[11]
5.79(0.05)%				0νM	$> 1.0 \cdot 10^{17}$		Kal52[11]
			g.s.–2_1^+	$0\nu + 2\nu$	$> 4.1 \cdot 10^{19}$	95%	Smo85
			g.s.–2_2^+	$0\nu + 2\nu$	$> 2.0 \cdot 10^{18}$	68%	Nor87
			g.s.–0_1^+	$0\nu + 2\nu$	$> 2.2 \cdot 10^{18}$	68%	Nor87
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 1.4 \cdot 10^{24}$		Sta90
				2ν	$= 3.6 \cdot 10^{19} - 1.6 \cdot 10^{22}$		Sta90
					$= 1.5 \cdot 10^{21}$		Hir94b
$^{120}_{52}$Te–$^{120}_{50}$Sn	Exp.	$\varepsilon\beta^+$	g.s.–g.s.	0ν	$> 4.2 \cdot 10^{12}$		Fre52[1]
1703(11) keV	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
0.096(0.002)%							
$^{128}_{52}$Te–$^{128}_{54}$Xe	Exp.	$2\beta^-$	all modes		$= (1.5 \pm 0.2) \cdot 10^{24}$		Hen75[7]
867.2(1.5) keV					$> 8.0 \cdot 10^{24}$	95%	Kir83a[7]
867.2(1.0) keV [Dyc90]					$= (1.4 \pm 0.4) \cdot 10^{24}$		Man86[7*]
					$> 5.0 \cdot 10^{24}$		Kir86[7*]
31.69(0.01)%					$= (1.8 \pm 0.7) \cdot 10^{24}$		Lin88b[7]
					$= 2.0 \cdot 10^{24}$		Man91[7*]
					$= (7.7 \pm 0.4) \cdot 10^{24}$	68%	Ber92[7]
			g.s.–g.s.	0ν	$> 1.3 \cdot 10^{19}$	90%	Mit88
			g.s.–2_1^+	$0\nu + 2\nu$	$> 4.7 \cdot 10^{21}$	68%	Bel87
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 6.0 \cdot 10^{26}$		Doi83
					$= 2.5 \cdot 10^{25}$		Eng88[5]
					$= 9.1 \cdot 10^{24}$		Eng89[6]

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$^{A}_{Z}$El–$^{A}_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{128}_{52}$Te *(continued)*					$= 7.8 \cdot 10^{24}$		Sta90
					$= 9.5 \cdot 10^{24}$		Tom91
					$= 1.3 \cdot 10^{25}$		Hir94b
				2ν	$= 1.3 \cdot 10^{25}$		Doi83
					$= (1.0 - 8.2) \cdot 10^{23}$		Vog86
					$= 5.5 \cdot 10^{23}$		Eng88
					$= 2.0 \cdot 10^{22} - 3.4 \cdot 10^{27}$		Sta90
					$= 2.1 \cdot 10^{23}$		Hir94b
$^{130}_{52}$Te–$^{130}_{54}$Xe	Exp.	$2\beta^-$	all modes		$= 1.4 \cdot 10^{21}$		Ing50^{7}
2528.1(2.1) keV					$= (8.2 \pm 0.6) \cdot 10^{20}$		Tak66^{7}
2528.8(1.3) keV [Dyc90]					$= 6.2 \cdot 10^{20}$		Kir67^{7}
33.80(0.01)%					$= (3.0 \pm 0.4) \cdot 10^{20}$		Ger68^{7}
					$= (2.2 \pm 0.7) \cdot 10^{21}$		Kir68^{7}
					$= (2.0 \pm 0.3) \cdot 10^{21}$		Ale69^{7}
					$= (2.8 \pm 0.3) \cdot 10^{21}$		Sri72a^{7}
					$= (4.1 \pm 0.4) \cdot 10^{21}$		Sri72a^{7}
					$= (2.1 \pm 0.3) \cdot 10^{21}$		Sri72b^{7}
					$= (2.2 \pm 0.3) \cdot 10^{21}$		Sri72b^{7}
					$= (3.1 \pm 0.4) \cdot 10^{21}$		Sri72b^{7}
					$= (2.7 \pm 0.3) \cdot 10^{21}$		Sri72b^{7}
					$= (1.1 \pm 0.1) \cdot 10^{21}$		Hen75^{7}
					$= (8.9 \pm 1.1) \cdot 10^{20}$		Hen75^{7}
					$= (2.6 \pm 0.3) \cdot 10^{21}$		Kir83a^{7}
					$= (2.6 \pm 0.1) \cdot 10^{21}$		Kir83b^{7*}
					$= (7.0 \pm 2.0) \cdot 10^{20}$		Man86^{7*}
					$= (1.5 - 2.8) \cdot 10^{21}$		Kir86^{7*}
					$= (1.0 \pm 0.3) \cdot 10^{21}$		Ric86^{7}
					$= (2.0 \pm 0.3) \cdot 10^{21}$		Ric86^{7}
					$= (1.9 \pm 0.3) \cdot 10^{21}$		Ric86^{7}
					$= (1.2 \pm 0.2) \cdot 10^{21}$		Ric86^{7}
					$= (2.3 \pm 0.1) \cdot 10^{21}$		Ric86^{7}
					$= (1.0 \pm 0.3) \cdot 10^{21}$		Ric86^{7*}
					$< (1.3 \pm 0.1) \cdot 10^{21}$		Lin86^{7}
					$= (7.5 \pm 0.3) \cdot 10^{20}$		Lin88a^{7}
					$= 8.0 \cdot 10^{20}$		Man91^{7*}
					$= (2.7 \pm 0.1) \cdot 10^{21}$	68%	Ber92^{7}
			g.s.–g.s.	0ν	$> 1.8 \cdot 10^{22}$	90%	Ale94b
				2ν	$> 1.0 \cdot 10^{16}$		Zde80b^{12}
				0νM	$> 1.0 \cdot 10^{16}$		Zde80b^{12}
			g.s.–2^+_1	$0\nu + 2\nu$	$> 4.5 \cdot 10^{21}$	68%	Bel87

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

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^A_ZEl–$^A_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{130}_{52}$Te *(continued)*	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 2.5 \cdot 10^{25}$		Doi83
					$= 1.3 \cdot 10^{24}$		Eng88[5]
					$= 4.5 \cdot 10^{23}$		Eng89[6]
					$= 4.9 \cdot 10^{23}$		Sta90
					$= 5.2 \cdot 10^{23}$		Tom91
					$= 7.2 \cdot 10^{23}$		Hir94b
				2ν	$= 2.6 \cdot 10^{21}$		Doi83
					$= 4.4 \cdot 10^{19} - 2.5 \cdot 10^{20}$		Vog86
					$= 2.2 \cdot 10^{20}$		Eng88
					$= 6.9 \cdot 10^{18} - 1.7 \cdot 10^{24}$		Sta90
					$= 7.9 \cdot 10^{19}$		Hir94b
$^{124}_{54}$Xe–$^{124}_{52}$Te	Exp.	$2\beta^+$	g.s.–g.s.	0ν	$> 4.2 \cdot 10^{17}$	68%	Bar89b
2865.9(2.2) keV				2ν	$> 2.0 \cdot 10^{14}$		Bar89b
0.10(0.01)%		$K\beta^+$	g.s.–g.s.	0ν	$> 1.2 \cdot 10^{18}$	68%	Bar89b
				2ν	$> 4.8 \cdot 10^{16}$	68%	Bar89b
		$K\beta^+$	g.s.–2^+_1	0ν	$> 4.2 \cdot 10^{17}$	68%	Bar89b
	Th.	$2\beta^+$	g.s.–g.s.	0ν	$= 2.7 \cdot 10^{28}$		Bal89
					$= 3.0 \cdot 10^{27}$		Hir94a
				2ν	$= 1.6 \cdot 10^{25}$		Bal89
					$= 1.4 \cdot 10^{27}$		Hir94a
		$\epsilon\beta^+$	g.s.–g.s.	0ν	$= 1.8 \cdot 10^{28}$		Bal89
					$= 1.6 \cdot 10^{26}$		Hir94a
				2ν	$= 4.3 \cdot 10^{22}$		Bal89
					$= 3.0 \cdot 10^{22}$		Hir94a
		2ε	g.s.–g.s.	2ν	$= 6.4 \cdot 10^{21}$		Bal89
					$= 2.9 \cdot 10^{21}$		Hir94a
$^{126}_{54}$Xe–$^{126}_{52}$Te	Exp.	2ε			–		
897(6) keV	Th.	2ε			–		
0.09(0.01)%							
$^{134}_{54}$Xe–$^{134}_{56}$Ba	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 8.2 \cdot 10^{19}$	68%	Bar89b
830(3) keV				2ν	$> 1.1 \cdot 10^{16}$		Bar89b
10.4(0.2)%	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 1.7 \cdot 10^{25}$		Sta90
				2ν	$= 5.4 \cdot 10^{22} - 1.9 \cdot 10^{25}$		Sta90
					$= 2.7 \cdot 10^{23}$		Hir94b
$^{136}_{54}$Xe–$^{136}_{56}$Ba	Exp.	$2\beta^-$	g.s.–g.s.	$0\nu(m_\nu)$	$> 3.4 \cdot 10^{23}$	90%	Vui93
2467(7) keV				0ν(rhc)	$> 2.6 \cdot 10^{23}$	90%	Vui93
8.9(0.1)%				2ν	$> 2.1 \cdot 10^{20}$	90%	Vui93

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives
for Various 2β processes ($2\beta^-$; $2\beta^+$; $\epsilon\beta^+$; 2ϵ)
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$^{A}_{Z}\mathrm{El}-{}^{A}_{Z\pm2}\mathrm{El}$ ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{136}_{54}\mathrm{Xe}$ *(continued)*				0νM	$> 4.9 \cdot 10^{21}$	90%	Vui93
			g.s.–2^+_1	0ν	$> 6.5 \cdot 10^{21}$	90%	Bel91
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 6.3 \cdot 10^{24}$		Eng88[5]
					$= 2.2 \cdot 10^{24}$		Sta90
					$= 1.5 \cdot 10^{24}$		Tom91
					$= 4.3 \cdot 10^{24}$		Hir94b
				2ν	$= 1.5 \cdot 10^{20} - 1.5 \cdot 10^{21}$		Vog86
					$= 8.2 \cdot 10^{20}$		Eng88
					$= 1.5 \cdot 10^{19} - 2.1 \cdot 10^{22}$		Sta90
					$= 1.0 \cdot 10^{21}$		Hir94b
			g.s.–2^+_1	2ν	$= 4.0 \cdot 10^{23}$		Civ94
			g.s.–2^+_2	2ν	$= 1.0 \cdot 10^{26}$		Civ94
			g.s.–0^+_1	2ν	$= 3.0 \cdot 10^{21}$		Civ94
$^{130}_{56}\mathrm{Ba}-{}^{130}_{54}\mathrm{Xe}$	Exp.	$2\beta^+$	g.s.–g.s.	0ν	$> 2.7 \cdot 10^{11}$		Fre52[1]
2610(7) keV		$\epsilon\beta^+$	g.s.–g.s.	0ν	$> 1.5 \cdot 10^{12}$		Fre52[1]
0.106(0.002)%	Th.	$2\beta^+$	g.s.–g.s.	0ν	$= 3.3 \cdot 10^{28}$		Bal89
					$= 1.6 \cdot 10^{28}$		Hir94a
				2ν	$= 1.2 \cdot 10^{27}$		Bal89
					$= 1.7 \cdot 10^{29}$		Hir94a
		$\epsilon\beta^+$	g.s.–g.s.	0ν	$= 5.0 \cdot 10^{27}$		Bal89
					$= 1.7 \cdot 10^{26}$		Hir94a
				2ν	$= 8.9 \cdot 10^{22}$		Bal89
					$= 1.0 \cdot 10^{23}$		Hir94a
		2ϵ	g.s.–g.s.	2ν	$= 4.0 \cdot 10^{21}$		Bal89
					$= 4.2 \cdot 10^{21}$		Hir94a
$^{132}_{56}\mathrm{Ba}-{}^{132}_{54}\mathrm{Xe}$	Exp.	2ϵ			–		
840(3) keV	Th.	2ϵ			–		
0.101(0.002)%							
$^{136}_{58}\mathrm{Ce}-{}^{136}_{56}\mathrm{Ba}$	Exp.	$2\beta^+ + \epsilon\beta^+ + 2\epsilon$			–		
2400(50) keV	Th.	$2\beta^+$	g.s.–g.s.	0ν	$= 5.9 \cdot 10^{28}$		Bal89
0.19(0.01)%					$= 2.4 \cdot 10^{29}$		Hir94a
				2ν	$= 5.9 \cdot 10^{27}$		Bal89
					$= 5.2 \cdot 10^{31}$		Hir94a
		$\epsilon\beta^+$	g.s.–g.s.	0ν	$= 5.3 \cdot 10^{27}$		Bal89
					$= 4.7 \cdot 10^{26}$		Hir94a
				2ν	$= 1.2 \cdot 10^{23}$		Bal89
					$= 1.7 \cdot 10^{20} - 4.0 \cdot 10^{21}$		Suh93b
					$= 9.2 \cdot 10^{23}$		Hir94a

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β processes ($2\beta^-$; $2\beta^+$; $\epsilon\beta^+$; 2ϵ)
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$^{A}_{Z}$El–$^{A}_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{136}_{58}$Ce *(continued)*		2ε	g.s.–g.s.	2ν	$= 3.5 \cdot 10^{21}$		Bal89
					$= 2.8 \cdot 10^{18} - 6.4 \cdot 10^{19}$		Suh93b
					$= 1.7 \cdot 10^{22}$		Hir94a
$^{138}_{58}$Ce–$^{138}_{56}$Ba	Exp.	2ε			–		
693(11) keV	Th.	2ε			–		
0.25(0.01)%							
$^{142}_{58}$Ce–$^{142}_{60}$Nd	Exp.	$2\beta^-$			–		[13]
1417.1(2.1) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 2.8 \cdot 10^{24}$		Sta90
11.08(0.10)%				2ν	$= 2.2 \cdot 10^{20} - 4.2 \cdot 10^{21}$		Sta90
					$= 3.3 \cdot 10^{22}$		Hir94b
$^{146}_{60}$Nd–$^{146}_{62}$Sm	Exp.	$2\beta^-$			–		[13]
70.0(2.9) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 4.4 \cdot 10^{26}$		Sta90
17.19(0.09)%					$= 1.2 \cdot 10^{28}$		Hir95
				2ν	$= 1.1 \cdot 10^{30} - \infty$		Sta90
					$= 7.3 \cdot 10^{30}$		Hir94b
					$\geq 2.1 \cdot 10^{31}$		Cas94
$^{148}_{60}$Nd–$^{148}_{62}$Sm	Exp.	$2\beta^-$	g.s.–2^+_1	$0\nu + 2\nu$	$> 3.0 \cdot 10^{18}$	90%	Bel82[13]
1928.8(1.9) keV			g.s.–2^+_2	$0\nu + 2\nu$	$> 2.7 \cdot 10^{18}$	90%	Bel82
5.76(0.03)%	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 1.4 \cdot 10^{24}$		Sta90
					$= 6.8 \cdot 10^{24}$		Hir95
				2ν	$= 1.1 \cdot 10^{19} - \infty$		Sta90
					$= 1.2 \cdot 10^{21}$		Hir94b
					$\geq 6.0 \cdot 10^{20}$		Cas94
$^{150}_{60}$Nd–$^{150}_{62}$Sm	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 2.1 \cdot 10^{21}$	90%	Moe94a
3367.5(2.2) keV				$0\nu(m_\nu)$	$> 1.7 \cdot 10^{21}$	95%	Kli86
5.64(0.03)%				0ν(rhc)	$> 1.1 \cdot 10^{21}$	95%	Kli86
				2ν	$> 1.8 \cdot 10^{19}$	95%	Kli86
					$= 1.7^{+1.1}_{-0.6} \cdot 10^{19}$		Art93
					$= 1.0 \cdot 10^{19}$		Ell93[10]
				0νM	$> 5.3 \cdot 10^{20}$	90%	Moe94a
			g.s.–2^+_1	$0\nu + 2\nu$	$> 8.0 \cdot 10^{18}$	90%	Arp94
			g.s.–0^+_1	$0\nu + 2\nu$	$> 8.8 \cdot 10^{18}$	90%	Arp94
			g.s.–4^+_1	$0\nu + 2\nu$	$> 2.0 \cdot 10^{19}$	90%	Arp94
			g.s.–2^+_2	$0\nu + 2\nu$	$> 1.3 \cdot 10^{19}$	90%	Arp94
			g.s.–2^+_3	$0\nu + 2\nu$	$> 2.7 \cdot 10^{18}$	90%	Bel82
			g.s.–0^+_2	$0\nu + 2\nu$	$> 2.1 \cdot 10^{18}$	90%	Bel82

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$^{A}_{Z}$El–$^{A}_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{150}_{60}$Nd *(continued)*	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 3.4 \cdot 10^{24}$		Doi83
					$= 3.4 \cdot 10^{22}$		Sta90
					$= 4.5 \cdot 10^{22}$		Tom91
					$= 5.6 \cdot 10^{22}$		Hir94b
					$= 1.1 \cdot 10^{24}$		Hir95
				2ν	$= 3.9 \cdot 10^{19}$		Doi83
					$= 6.1 \cdot 10^{16} - 3.9 \cdot 10^{20}$		Sta90
					$= 1.7 \cdot 10^{19}$		Hir94b
					$\geq 6.0 \cdot 10^{18}$		Cas94
$^{144}_{62}$Sm–$^{144}_{60}$Nd	Exp.	$\varepsilon\beta^+ + 2\varepsilon$			–		13
1781.6(1.9) keV	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
3.1(0.1)%							
$^{154}_{62}$Sm–$^{154}_{64}$Gd	Exp.	$2\beta^-$			–		
1251.4(1.3) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 1.4 \cdot 10^{24}$		Sta90
22.7(0.2)%				2ν	$= 2.7 \cdot 10^{20} - 2.5 \cdot 10^{21}$		Sta90
					$= 1.5 \cdot 10^{22}$		Hir94b
					$= \infty$		Cas94
$^{152}_{64}$Gd–$^{152}_{62}$Sm	Exp.	2ε			–		13
56.0(1.2) keV	Th.	2ε			–		
0.20(0.01)%							
$^{160}_{64}$Gd–$^{160}_{66}$Dy	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 1.4 \cdot 10^{19}$	90%	Bur93b
1729.7(1.3) keV				2ν	$> 1.3 \cdot 10^{17}$	99%	Bur93b
21.86(0.04)%				0νM	$> 2.7 \cdot 10^{17}$	99%	Bur93b
			g.s.–2^+_1	0ν	$> 1.3 \cdot 10^{19}$	90%	Bur93b
				2ν	$> 1.2 \cdot 10^{17}$	99%	Bur93b
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 8.6 \cdot 10^{23}$		Sta90
				2ν	$= 4.9 \cdot 10^{18} - 9.9 \cdot 10^{20}$		Sta90
					$= 2.8 \cdot 10^{21}$		Hir94b
					$= \infty$		Cas94
$^{156}_{66}$Dy–$^{156}_{64}$Gd	Exp.	$\varepsilon\beta^+ + 2\varepsilon$			–		13
2011(6) keV	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
0.06(0.01)%							
$^{158}_{66}$Dy–$^{158}_{64}$Gd	Exp.	2ε			–		13
283.2(2.4) keV	Th.	2ε			–		
0.10(0.01)%							

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives
for Various 2β processes ($2\beta^-$; $2\beta^+$; $\epsilon\beta^+$; 2ϵ)
See page 64 for Explanation of Tables

${}^{A}_{Z}$El–${}^{A}_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
${}^{162}_{68}$Er–${}^{162}_{66}$Dy	Exp.	$\varepsilon\beta^+ + 2\varepsilon$			–		[13]
1844.7(2.8) keV	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
0.14(0.01)%							
${}^{164}_{68}$Er–${}^{164}_{66}$Dy	Exp.	2ε			–		[13]
24.3(2.5) keV	Th.	2ε			–		
1.61(0.02)%							
${}^{170}_{68}$Er–${}^{170}_{70}$Yb	Exp.	$2\beta^-$			–		[13]
653.7(1.7) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 1.4 \cdot 10^{25}$		Sta90
14.9(0.2)%				2ν	$= 1.7 \cdot 10^{23} - 1.6 \cdot 10^{26}$		Sta90
					$= 2.5 \cdot 10^{23}$		Hir94b
${}^{168}_{70}$Yb–${}^{168}_{68}$Er	Exp.	$\varepsilon\beta^+ + 2\varepsilon$			–		[13]
1422(4) keV	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
0.13(0.01)%							
${}^{176}_{70}$Yb–${}^{176}_{72}$Hf	Exp.	$2\beta^-$			–		[13]
1085.5(2.1) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 1.4 \cdot 10^{24}$		Sta90
12.7(0.2)%				2ν	$= 1.3 \cdot 10^{20} - 3.7 \cdot 10^{24}$		Sta90
					$= 4.9 \cdot 10^{21}$		Hir94b
					$= \infty$		Cas94
${}^{174}_{72}$Hf–${}^{174}_{70}$Yb	Exp.	$\varepsilon\beta^+ + 2\varepsilon$			–		[13]
1102.1(2.5) keV	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
0.162(0.003)%							
${}^{180}_{74}$W–${}^{180}_{72}$Hf	Exp.	2ε	g.s.–g.s.	0ν	$> 5.0 \cdot 10^{16}$	90%	Dan95[13]
146(5) keV	Th.	2ε			–		
0.13(0.04)%							
${}^{186}_{74}$W–${}^{186}_{76}$Os	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 2.7 \cdot 10^{20}$	90%	Dan95[13]
487.9(1.7) keV				2ν	$> 5.9 \cdot 10^{17}$	90%	Dan95
28.6(0.2)%			g.s.–2^+_1	0ν	$> 2.4 \cdot 10^{20}$	90%	Dan95
	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 6.4 \cdot 10^{24}$		Sta90
					$= 5.1 \cdot 10^{25}$		Hir95
				2ν	$= 7.1 \cdot 10^{23} - 1.2 \cdot 10^{25}$		Sta90
					$= 1.3 \cdot 10^{24}$		Hir94b
					$\geq 6.1 \cdot 10^{24}$		Cas94

TABLE I. Experimental Values (or Limits) and Theoretical Estimates of Half-Lives for Various 2β processes ($2\beta^-$; $2\beta^+$; $\epsilon\beta^+$; 2ϵ)
See page 64 for Explanation of Tables

$^{A}_{Z}$El–$^{A}_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
$^{184}_{76}$**Os**–$^{184}_{74}$**W**	Exp.	$\varepsilon\beta^+$	g.s.–g.s.	0ν	$> 9.9 \cdot 10^{9}$		Fre52[1,13]
1451.5(1.4) keV	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
0.02(0.01)%							
$^{192}_{76}$**Os**–$^{192}_{78}$**Pt**	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 9.8 \cdot 10^{12}$		Fre52[1,13]
413.5(3.0) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 4.1 \cdot 10^{24}$		Sta90
41.0(0.8)%					$= 3.3 \cdot 10^{26}$		Hir95
				2ν	$= 1.3 \cdot 10^{24} - 2.0 \cdot 10^{25}$		Sta90
					$= 2.4 \cdot 10^{24}$		Hir94b
					$\geq 9.0 \cdot 10^{25}$		Cas94
$^{190}_{78}$**Pt**–$^{190}_{76}$**Os**	Exp.	$\varepsilon\beta^+$	g.s.–g.s.	0ν	$> 3.1 \cdot 10^{11}$		Fre52[1,13]
1383(6) keV	Th.	$\varepsilon\beta^+ + 2\varepsilon$			–		
0.01(0.01)%							
$^{198}_{78}$**Pt**–$^{198}_{80}$**Hg**	Exp.	$2\beta^-$	g.s.–g.s.	0ν	$> 3.2 \cdot 10^{14}$		Fre52[1,13]
1047(3) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 4.7 \cdot 10^{23}$		Sta90
7.2(0.2)%				2ν	$= 4.8 \cdot 10^{21} - 4.8 \cdot 10^{23}$		Sta90
					$= 1.1 \cdot 10^{22}$		Hir94b
$^{196}_{80}$**Hg**–$^{196}_{78}$**Pt**	Exp.	2ε	g.s.–g.s.+2^+_1	$0\nu + 2\nu$	$> 2.5 \cdot 10^{18}$	68%	Buc90[13]
819.9(3.0) keV	Th.	2ε			–		
0.15(0.01)%							
$^{204}_{80}$**Hg**–$^{204}_{82}$**Pb**	Exp.	$2\beta^-$			–		
416.4(1.5) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 8.2 \cdot 10^{24}$		Sta90
6.87(0.04)%				2ν	$= 3.1 \cdot 10^{25} - 2.5 \cdot 10^{27}$		Sta90
					$= 1.8 \cdot 10^{25}$		Hir94b
$^{232}_{90}$**Th**–$^{232}_{92}$**U**	Exp.	$2\beta^-$			–		[13]
841.7(2.6) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 3.1 \cdot 10^{23}$		Sta90
100%				2ν	$= 4.2 \cdot 10^{21} - 1.8 \cdot 10^{23}$		Sta90
					$= 4.0 \cdot 10^{21}$		Hir94b
					$= \infty$		Cas94
$^{238}_{92}$**U**–$^{238}_{94}$**Pu**	Exp.	$2\beta^-$	all modes		$= (2.0 \pm 0.6) \cdot 10^{21}$	68%	Tur91[14,13]
1146.7(1.4) keV	Th.	$2\beta^-$	g.s.–g.s.	0ν	$= 2.6 \cdot 10^{23}$		Sta90
99.2745(0.0060)%					$= 1.0 \cdot 10^{24}$		Hir95
				2ν	$= 9.7 \cdot 10^{20} - 3.8 \cdot 10^{23}$		Sta90

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

See page 64 for Explanation of Tables

${}^A_Z$El–${}^A_{Z\pm2}$El ΔM_A δ	Type of result	Decay channel	Transition	Decay mode	Half-life, years	Confidence level	Reference and remark
${}^{238}_{92}$U *(continued)*					$= 9.1 \cdot 10^{20}$		Hir94b
					$\geq 1.4 \cdot 10^{21}$		Cas94

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[1] From results of Fre52 with corrections on the decay energy and the natural abundance of the isotope.

[2] The phase space estimate.

[3] An ordinary β^- decay ^{48}Ca(0^+)–^{48}Sc(6^+, 5^+, 4^+) is possible (Q_β = 278(5) keV [Aud93]). The calculated half-life of the most probable of them is $T_{1/2}$(^{48}Ca(0^+)–^{48}Sc(5^+)) = 7.6 × 10^{20} y [War85]. The experimental limit is $T_{1/2}$(^{48}Ca, β^-) > 6.0 × 10^{18} y with 95% CL [Alb85].

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

[5] The recalculations in Moe94b of the results from Eng88 for g_A = 1.25 give the following values of $T^{0\nu}_{1/2} \cdot \langle m_\nu \rangle^2$ in y·eV^2: ^{76}Ge, 1.4 × 10^{25}; ^{82}Se, 5.6 × 10^{24}; ^{128}Te, 1.5 × 10^{25}; ^{130}Te, 6.6 × 10^{23}; ^{136}Xe, 3.3 × 10^{24}.

[6] The recalculations in Moe94b of the results from Eng89 for g_A = 1.25 give the following values of $T^{0\nu}_{1/2} \cdot \langle m_\nu \rangle^2$ in y·eV^2: ^{76}Ge, 2.3 × 10^{24}; ^{82}Se, 9.2 × 10^{23}; ^{128}Te, 4.5 × 10^{24}; ^{130}Te, 2.4 × 10^{23}.

[7] Result of geochemical experiment.

[7*] Recommended value based on latest geochemical experiments.

[8] An ordinary β^- decay ^{96}Zr(0^+)–^{96}Nb(6^+) is possible (Q_β = 164(4) keV [Aud93]). The experimental limit is $T_{1/2}$(^{96}Zr, β^-) > 3.8 × 10^{19} y with 90% CL [Arp94].

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

[10] Preliminary result.

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

[12] This result was obtained in Bar87 using the experimental data of Zde80b.

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

See page 64 for Explanation of Tables

[13] Parent 2β isotope is (potentially) α radioactive. The corresponding Q_α values and half-lives are as follows:

	Q_α, keV	$T^{\alpha,exp}_{1/2}$, y		$T^{\alpha,calc}_{1/2}$, y	
	[Aud93]			[Poe86]	[Alb88]
${}^{142}_{58}$Ce	1299(4)	$> 5 \cdot 10^{16}$	[Mac61]	–	$3.8 \cdot 10^{27}$
${}^{146}_{60}$Nd	1182.0(2.2)	–	–	–	–
${}^{148}_{60}$Nd	599(3)	–	–	–	–
${}^{144}_{62}$Sm	77(19)	–	–	–	–
${}^{152}_{64}$Gd	2205.0(1.5)	$= 1.1 \cdot 10^{14}$	[Led78]	$1.0 \cdot 10^{14}$	–
${}^{156}_{66}$Dy	1757(6)	$> 1 \cdot 10^{18}$	[Rie58]	$5.0 \cdot 10^{24}$	$4.3 \cdot 10^{24}$
${}^{158}_{66}$Dy	874.7(2.4)	–	–	–	–
${}^{162}_{68}$Er	1646(3)	$> 1.4 \cdot 10^{14}$	[Por56]	$4.0 \cdot 10^{29}$	$2.2 \cdot 10^{29}$
${}^{164}_{68}$Er	1304.3(2.5)	–	–	–	$9.2 \cdot 10^{39}$
${}^{170}_{68}$Er	50.4(2.4)	–	–	–	–
${}^{168}_{70}$Yb	1951(4)	$> 1.3 \cdot 10^{14}$	[Por56]	$5.0 \cdot 10^{24}$	$1.9 \cdot 10^{24}$
${}^{176}_{70}$Yb	571(4)	–	–	$2.5 \cdot 10^{96}$	–
${}^{174}_{72}$Hf	2495.8(2.6)	$= 2.0 \cdot 10^{15}$	[Led78]	$6.3 \cdot 10^{16}$	–
${}^{180}_{74}$W	2514(5)	$> 1 \cdot 10^{15}$	[Bea60]	$2.5 \cdot 10^{18}$	$7.5 \cdot 10^{17}$
${}^{186}_{74}$W	1123(7)	$> 2 \cdot 10^{17}$	[Bea60]	$2.5 \cdot 10^{57}$	–
${}^{184}_{76}$Os	2964(4)	$> 5.6 \cdot 10^{13}$ 95% CL	[Spe76]	$5.0 \cdot 10^{13}$	$2.1 \cdot 10^{13}$
${}^{192}_{76}$Os	362(4)	–	–	$1.3 \cdot 10^{154}$	–
${}^{190}_{78}$Pt	3249(6)	$= 6 \cdot 10^{11}$	[Led78]	$6.3 \cdot 10^{11}$	–
${}^{198}_{78}$Pt	87(4)	–	–	$6.3 \cdot 10^{391}$	–
${}^{196}_{80}$Hg	2027(4)	$> 1 \cdot 10^{14}$	[Mac61]	$1.3 \cdot 10^{33}$	$1.0 \cdot 10^{32}$
${}^{232}_{90}$Th	4082.7(1.4)	$= 1.41 \cdot 10^{10}$	[Led78]	$2.0 \cdot 10^{10}$	–
${}^{238}_{92}$U	4269.8(2.9)	$= 4.468 \cdot 10^{9}$	[Led78]	$6.3 \cdot 10^{9}$	–

For the following six daughter isotopes α radioactivity was observed experimentally:

	Q_α, keV	$T^{\alpha,exp}_{1/2}$, y
	[Aud93]	[Led78]
${}^{144}_{60}$Nd	1905.1(1.8)	$2.1 \cdot 10^{15}$
${}^{146}_{62}$Sm	2529.0(2.9)	$1.03 \cdot 10^{8}$
${}^{148}_{62}$Sm	1985.8(1.2)	$8 \cdot 10^{15}$
${}^{186}_{76}$Os	2822.0(1.7)	$2 \cdot 10^{15}$
${}^{232}_{92}$U	5413.55(0.14)	72
${}^{238}_{94}$Pu	5593.20(0.19)	87.74

[14] Result of radiochemical experiment.

[15] This value was corrected later to 3.7×10^{19} y [Cau94].

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

See page 64 for Explanation of Tables

	Parent nuclide	Main channel of decay and $T_{1/2}$ [Led78]		Potential 2β transition and daughter nuclide		ΔM_A, keV [Aud93, Led78]
1	${}^{148}_{64}\mathrm{Gd}^1$	α	98 y	$2\beta^+ + \varepsilon\beta^+ + 2\varepsilon$	${}^{148}_{62}\mathrm{Sm}$	3066.9(2.0)
2	${}^{150}_{64}\mathrm{Gd}$	α	$1.8 \cdot 10^6$ y	$\varepsilon\beta^+ + 2\varepsilon$	${}^{150}_{62}\mathrm{Sm}$	1289(6)
3	${}^{154}_{66}\mathrm{Dy}$	α	$\approx 1 \cdot 10^7$ y	$2\beta^+ + \varepsilon\beta^+ + 2\varepsilon$	${}^{154}_{64}\mathrm{Gd}$	3316(8)
4	${}^{216}_{84}\mathrm{Po}$	α	0.15 s	$2\beta^-$	${}^{216}_{86}\mathrm{Rn}$	1534(8)
5	${}^{212}_{86}\mathrm{Rn}$	α	23 m	$\varepsilon\beta^+ + 2\varepsilon$	${}^{212}_{84}\mathrm{Po}$	1711.1(3.0)
6	${}^{214}_{86}\mathrm{Rn}$	α	0.27 μs	2ε	${}^{214}_{84}\mathrm{Po}$	149(9)
7	${}^{220}_{86}\mathrm{Rn}$	α	55.6 s	$2\beta^-$	${}^{220}_{88}\mathrm{Ra}$	344(10)
8	${}^{218}_{88}\mathrm{Ra}$	α	14 μs	$\varepsilon\beta^+ + 2\varepsilon$	${}^{218}_{86}\mathrm{Rn}$	1432(11)
9	${}^{226}_{88}\mathrm{Ra}$	α	$1.60 \cdot 10^3$ y	$2\beta^-$	${}^{226}_{90}\mathrm{Th}$	476(5)
10	${}^{224}_{90}\mathrm{Th}$	α	1.04 s	$\varepsilon\beta^+ + 2\varepsilon$	${}^{224}_{88}\mathrm{Ra}$	1171(12)
11	${}^{230}_{92}\mathrm{U}$	α	20.8 d	2ε	${}^{230}_{90}\mathrm{Th}$	747(5)
12	${}^{236}_{94}\mathrm{Pu}$	α	2.85 y	2ε	${}^{236}_{92}\mathrm{U}$	453.4(2.1)
13	${}^{244}_{94}\mathrm{Pu}^2$	α	$8.1 \cdot 10^7$ y	$2\beta^-$	${}^{244}_{96}\mathrm{Cm}$	1352(5)
14	${}^{242}_{96}\mathrm{Cm}$	α	162.8 d	2ε	${}^{242}_{94}\mathrm{Pu}$	86.2(0.9)
15	${}^{248}_{96}\mathrm{Cm}$	α+sf	$3.5 \cdot 10^5$ y	$2\beta^-$	${}^{248}_{98}\mathrm{Cf}$	153(7)
16	${}^{254}_{98}\mathrm{Cf}$	α+sf	60.5 d	$2\beta^-$	${}^{254}_{100}\mathrm{Fm}$	436(12)
17	${}^{256}_{98}\mathrm{Cf}$	sf	12 m	$2\beta^-$	${}^{256}_{100}\mathrm{Fm}$	≈ 0.9 MeV
18	${}^{252}_{100}\mathrm{Fm}$	α	25.4 h	2ε	${}^{252}_{98}\mathrm{Cf}$	783(7)
19	${}^{258}_{102}\mathrm{No}$	sf	1.2 ms	$\varepsilon\beta^+ + 2\varepsilon$	${}^{258}_{100}\mathrm{Fm}$	1060(280)

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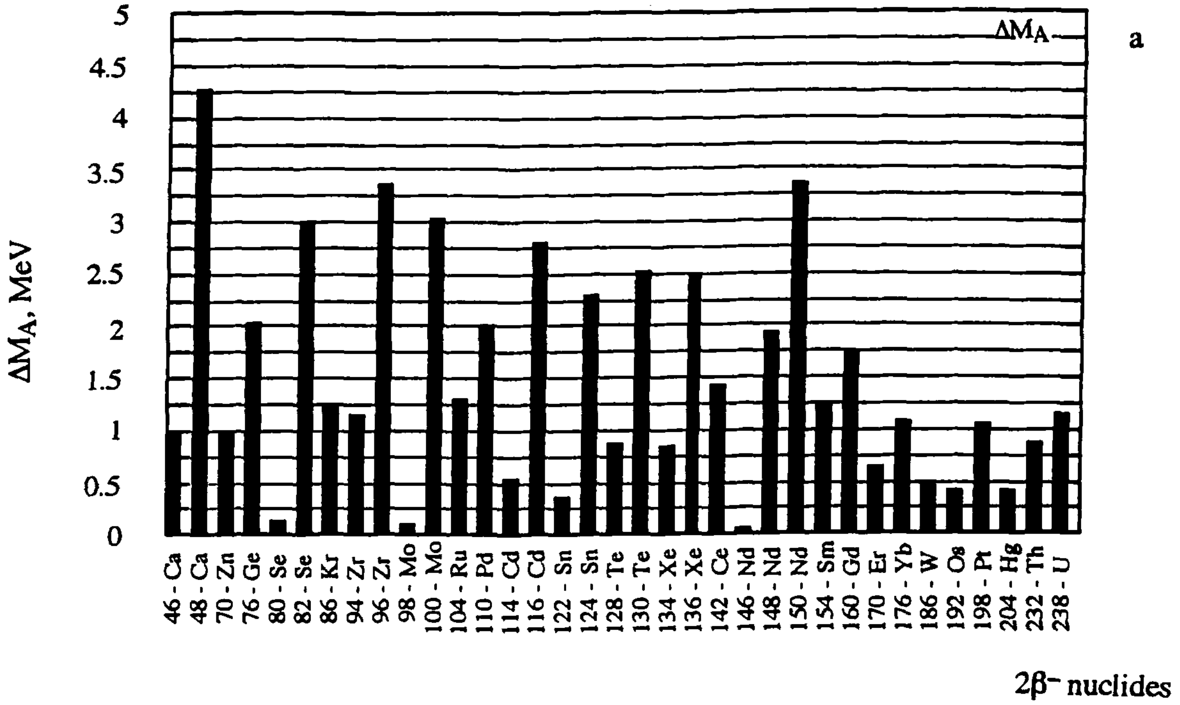
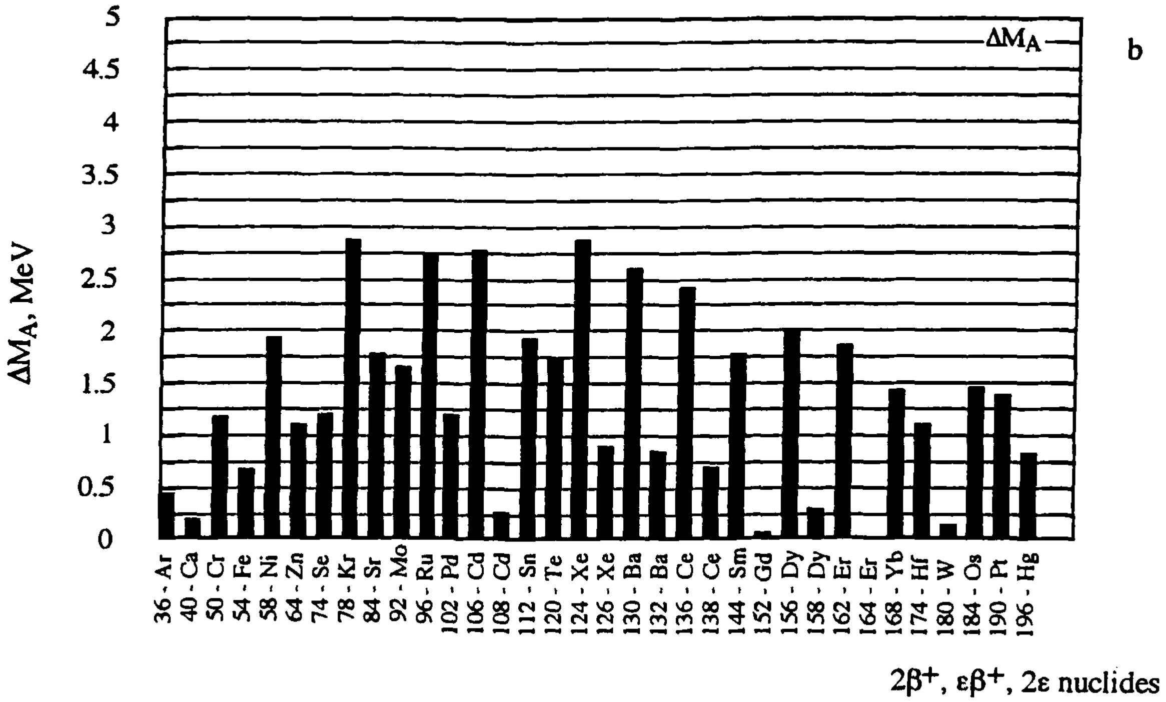
[1] Theoretical calculations [Sta91]: $T^{0\nu}_{1/2} \cdot \langle m_\nu \rangle^2 = 1.6 \times 10^{28}$ y·eV^2, $T^{2\nu}_{1/2} \geqslant 2.2 \times 10^{26}$ y.

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

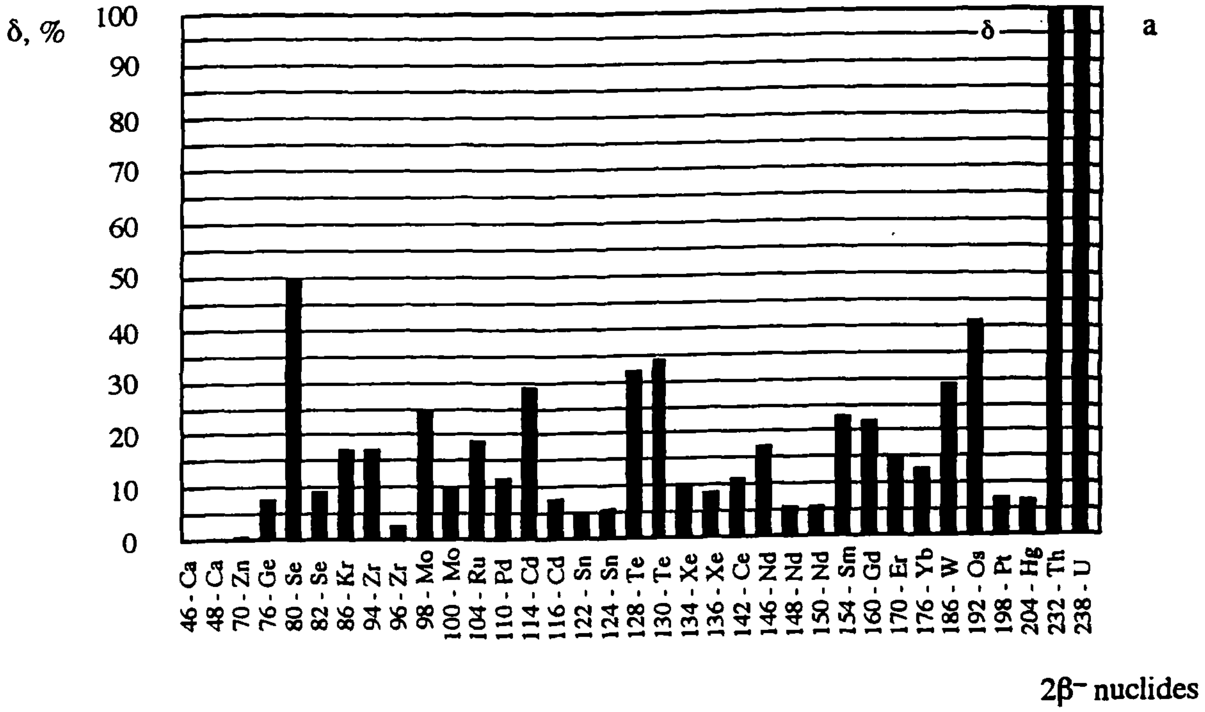
GRAPH I. Atomic Mass Differences between 2β-Unstable Parents and Their Daughters
See page 66 for Explanation of Graphs

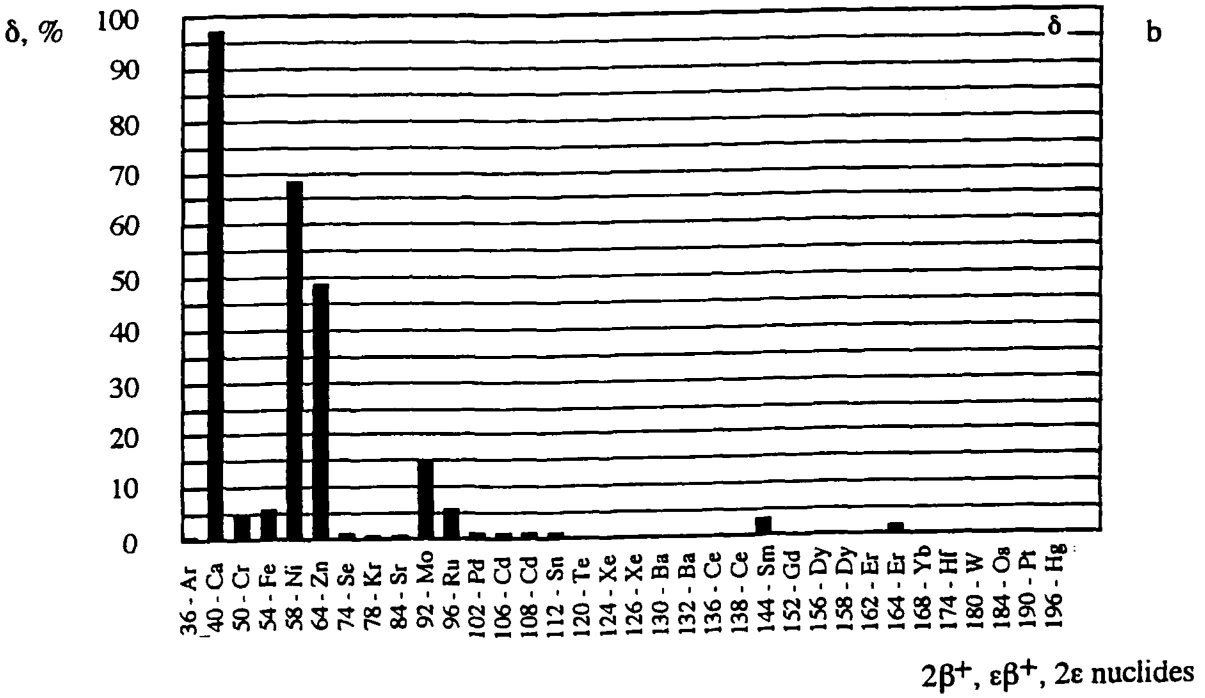




Note. (a) Parents 2β^- unstable and (b) parents 2β^+, $\epsilon\beta^+$, 2ϵ unstable.

GRAPH II. Natural Abundances of 2β-Unstable Isotopes
See page 66 for Explanation of Graphs

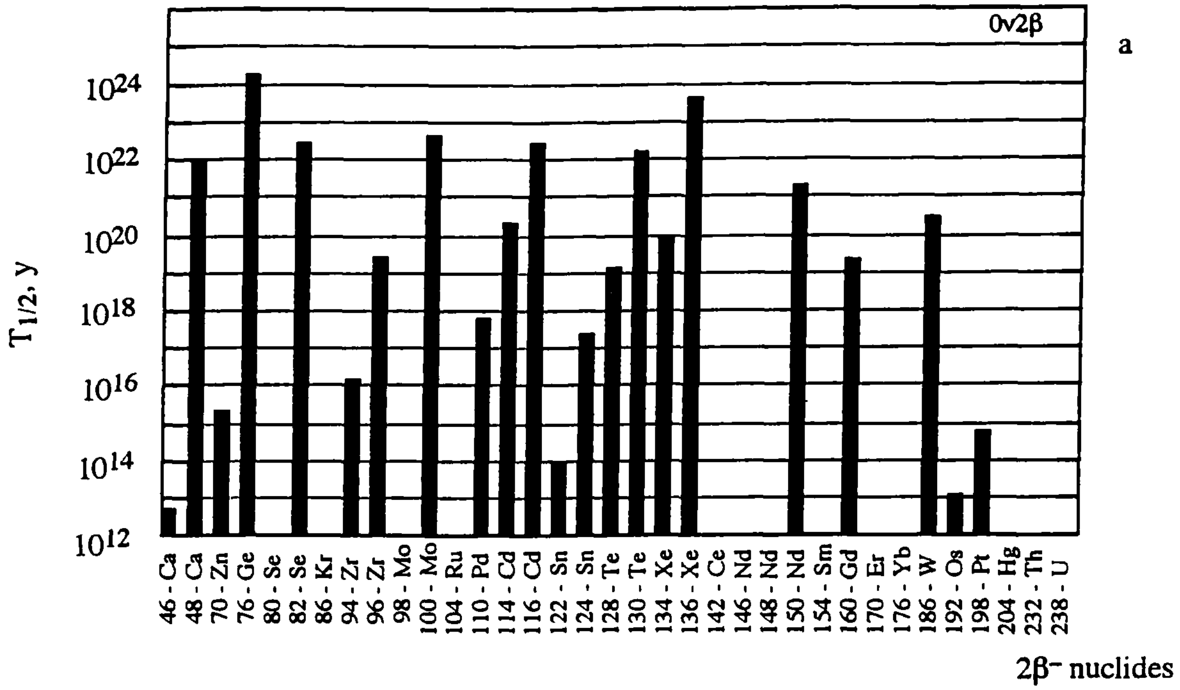


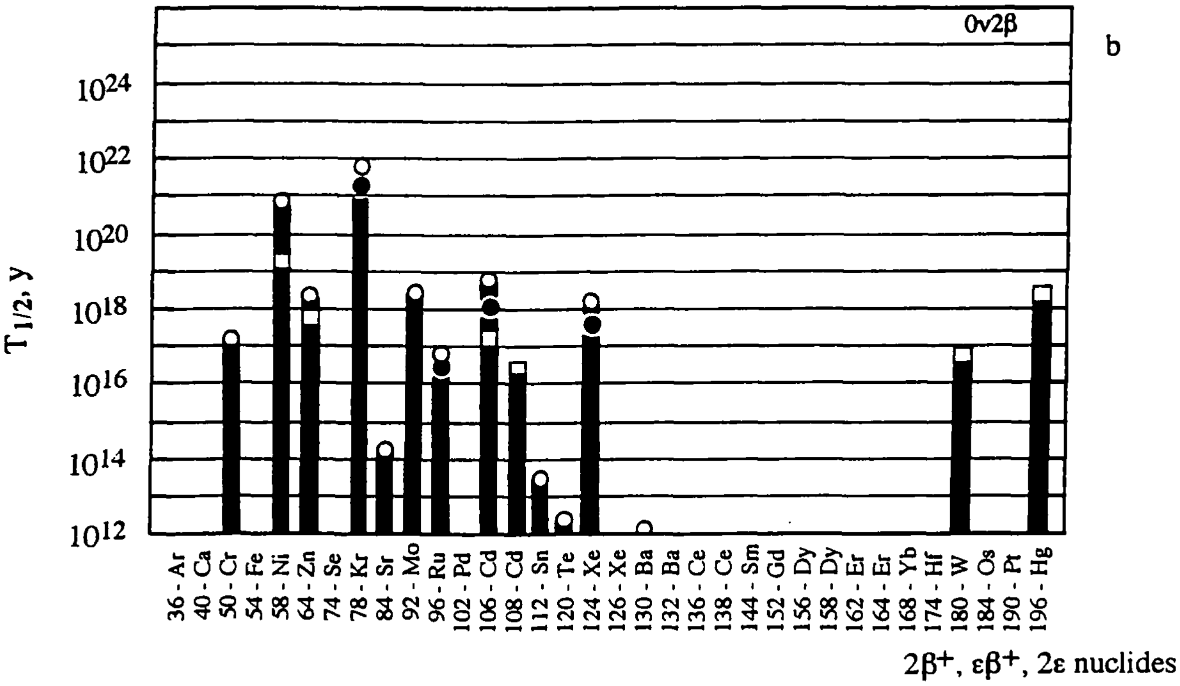


Note. (a) Parents $2\beta^-$ unstable and (b) parents $2\beta^+$, $\epsilon\beta^+$, 2ϵ unstable.

GRAPH III. Limits on Half-Lives for Neutrinoless 2β Processes

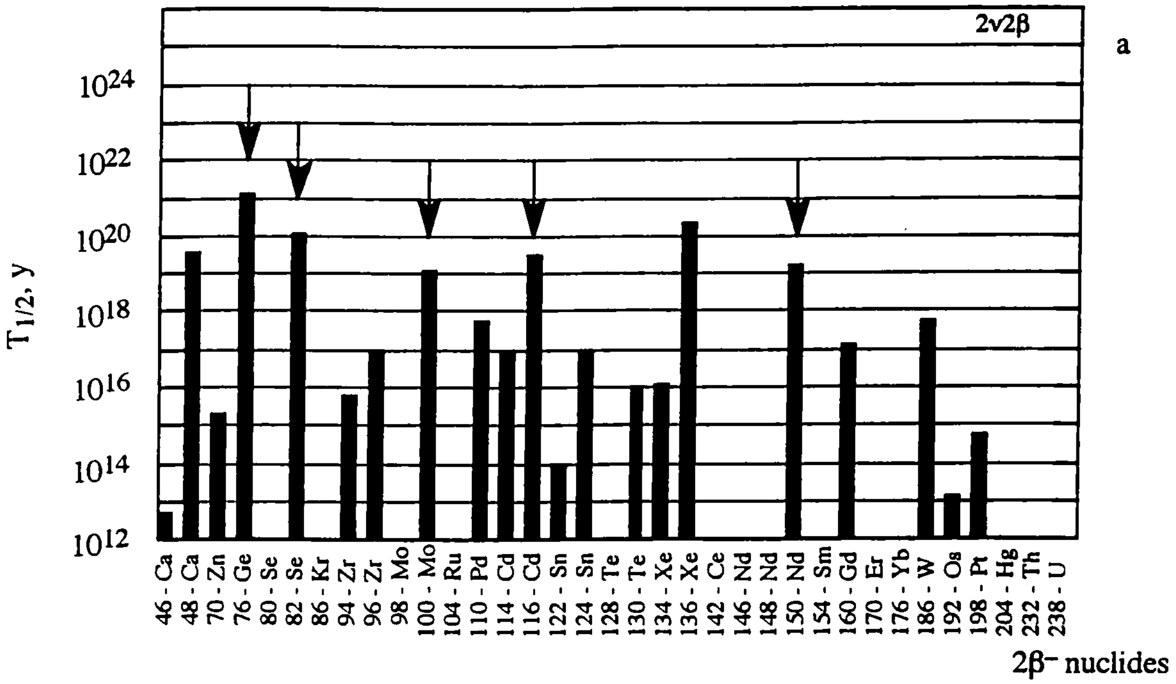
See page 66 for Explanation of Graphs

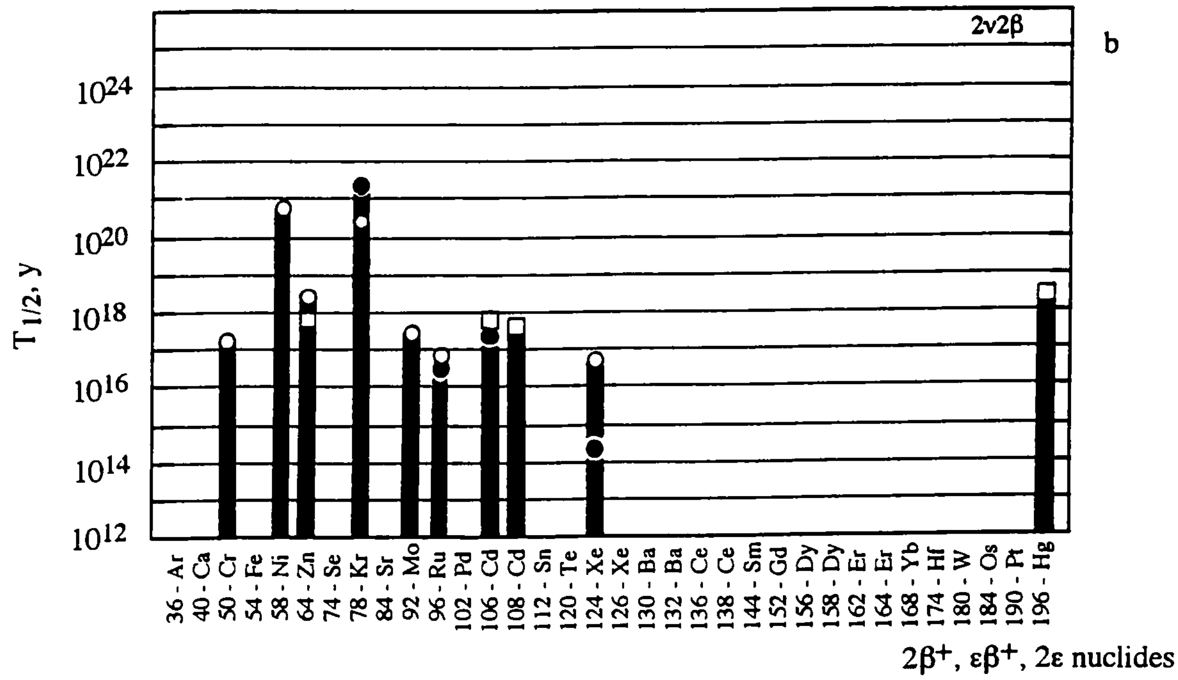




Note. Limits on half-lives are for neutrinoless 2β processes (g.s.–g.s. transitions) measured in direct experiments. (a) Parents $2\beta^-$ unstable and (b) parents $2\beta^+$ (filled circles), $\epsilon\beta^+$ (empty circles), 2ϵ (empty squares) unstable.

GRAPH IV. Positive Results and Limits on Half-Lives for Two-Neutrino Processes
See page 66 for Explanation of Graphs

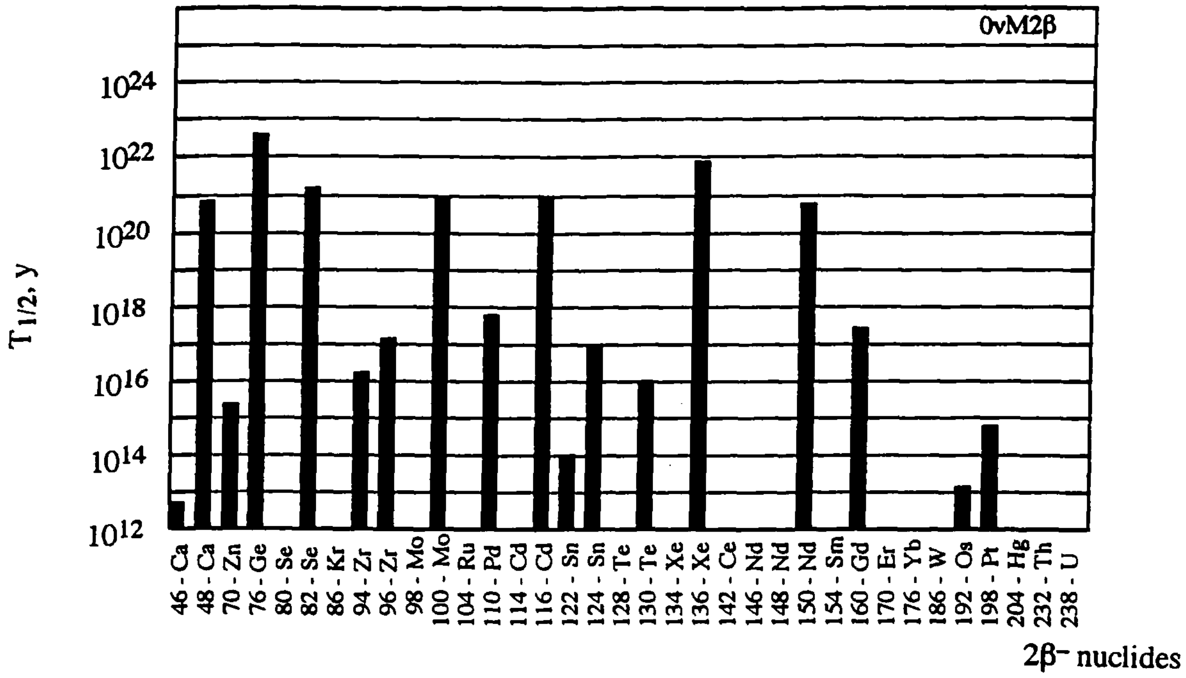




Note. Positive results and limits on half-lives are for two-neutrino processes (g.s.–g.s. transitions) measured in direct experiments. (a) Parents $2\beta^-$ unstable and (b) parents $2\beta^+$ (filled circles), $\epsilon\beta^+$ (empty circles), 2ϵ (empty squares) unstable. Positive results are marked by arrows.

GRAPH V. Limits on Half-Lives for 2β Decay with Majoron Emission

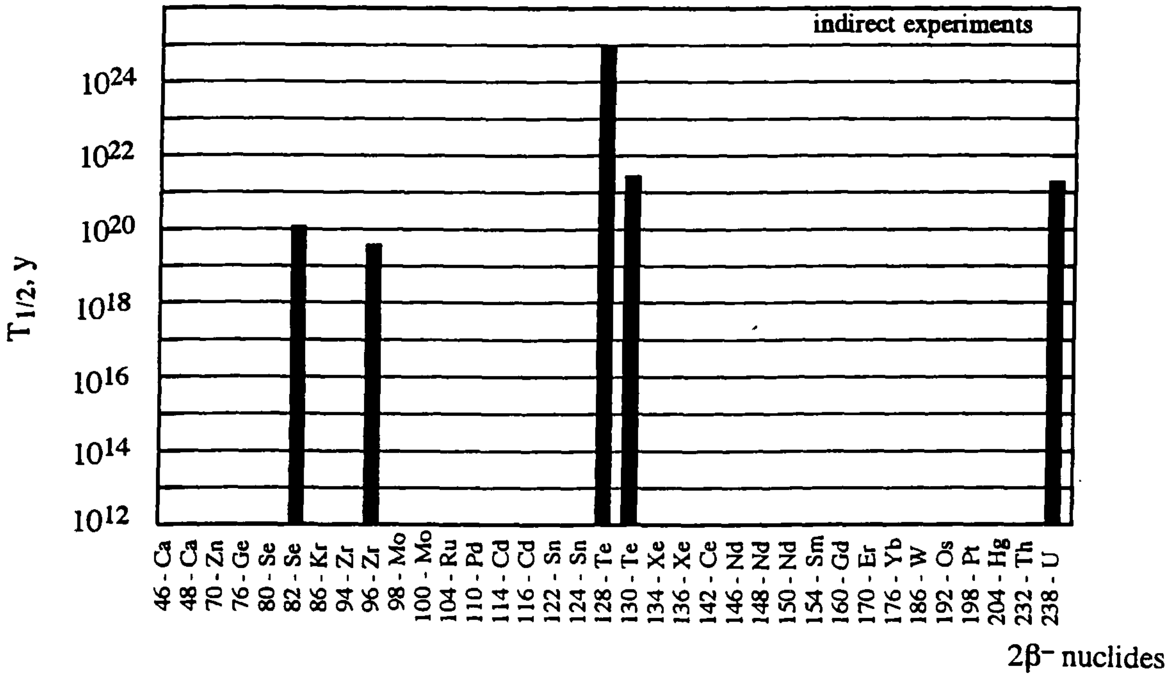
See page 66 for Explanation of Graphs



Note. Limits on half-lives are for 2β decay with Majoron emission (g.s.–g.s. transitions) measured in direct experiments.

GRAPH VI. Positive Results for Half-Lives Deduced from Indirect Experiments

See page 66 for Explanation of Graphs



Note. Indirect refers to geochemical and radiochemical experiments.