# Double-$\beta$ Decay

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## Half-life Measurements and Limits for Double-$\beta$ Decay

In all cases of double-beta decay, (Z,A) $\rightarrow$ (Z+2,A) + $2e^-$ + (0 or 2)$\overline{\nu}_e$. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported. For $2\nu$ decay, which is well established, only measured half-lives are reported.

| $t_{1/2}(10^{21}$ yr) | CL% | ISOTOPE | TRANSITION | | METHOD | DOCUMENT ID | |
|---|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | | |
| $>15700$ | 90 | $^{76}$Ge | $0\nu$ | | Enriched HPGe | [1] AALSETH | 02B |
| $>$ 58 | 90 | $^{134}$Xe | $0\nu$ | | Liquid Xe Scint. | [2] BERNABEI | 02D |
| $>$ 1200 | 90 | $^{136}$Xe | $0\nu$ | | Liquid Xe Scint. | [3] BERNABEI | 02D |
| $15000\ ^{+168000}_{-\ \ 7500}$ | | $^{76}$Ge | $0\nu$ | | Enriched HPGe | [4] KLAPDOR-K... | 02D |
| $(7.2 \pm 0.9 \pm 1.8)$E-3 | | $^{100}$Mo | $2\nu$ | | Liq. Ar ioniz. | [5] ASHITKOV | 01 |
| $>$ 4.9 | 90 | $^{100}$Mo | $0\nu$ | | Liq. Ar ioniz. | [6] ASHITKOV | 01 |
| $>$ 1.3 | 90 | $^{160}$Gd | $0\nu$ | | $^{160}$Gd$_2$SiO$_5$:Ce | [7] DANEVICH | 01 |
| $>$ 1.3 | 90 | $^{160}$Gd | $0\nu$ | $0^+ \rightarrow 2^+$ | $^{160}$Gd$_2$SiO$_5$:Ce | [8] DANEVICH | 01 |
| $0.59^{+0.17}_{-0.11} \pm 0.06$ | | $^{100}$Mo | $0\nu$+$2\nu$ | $0^+ \rightarrow 0^+_1$ | Ge coinc. | [9] DEBRAECKEL... | 01 |
| $>$ 55 | 90 | $^{100}$Mo | $0\nu$,$\langle m_\nu \rangle$ | | ELEGANT V | [10] EJIRI | 01 |
| $>$ 42 | 90 | $^{100}$Mo | $0\nu$,$\langle \lambda \rangle$ | | ELEGANT V | [10] EJIRI | 01 |
| $>$ 49 | 90 | $^{100}$Mo | $0\nu$,$\langle \eta \rangle$ | | ELEGANT V | [10] EJIRI | 01 |
| $>19000$ | 90 | $^{76}$Ge | $0\nu$ | | Enriched HPGe | [11] KLAPDOR-K... | 01 |
| $1.55 \pm 0.001^{+0.19}_{-0.15}$ | 90 | $^{76}$Ge | $2\nu$ | | Enriched HPGe | [12] KLAPDOR-K... | 01 |
| $(9.4 \pm 3.2)$E-3 | 90 | $^{96}$Zr | $0\nu$+$2\nu$ | | Geochem | [13] WIESER | 01 |
| $>$ 144 | 90 | $^{130}$Te | $0\nu$ | | Cryog. det. | [14] ALESSAND... | 00 |
| $>$ 86 | 90 | $^{128}$Te | $0\nu$ | | Cryog. det. | [14] ALESSAND... | 00 |
| $0.042^{+0.033}_{-0.013}$ | | $^{48}$Ca | $2\nu$ | | Ge spectrometer | [15] BRUDANIN | 00 |
| $0.026 \pm 0.001^{+0.007}_{-0.004}$ | | $^{116}$Cd | $2\nu$ | | $^{116}$CdWO$_4$ scint. | [16] DANEVICH | 00 |
| $>$ 70 | 90 | $^{116}$Cd | $0\nu$ | | $^{116}$CdWO$_4$ scint. | [17] DANEVICH | 00 |
| $0.021^{+0.008}_{-0.004} \pm 0.002$ | | $^{96}$Zr | $2\nu$ | | NEMO-2 | [18] ARNOLD | 99 |
| $>$ 1.0 | 90 | $^{96}$Zr | $0\nu$ | | NEMO-2 | [18] ARNOLD | 99 |
| $(8.3 \pm 1.0 \pm 0.7)$E-2 | | $^{82}$Se | $2\nu$ | | NEMO-2 | [19] ARNOLD | 98 |
| $>$ 9.5 | 90 | $^{82}$Se | $0\nu$ | | NEMO-2 | [20] ARNOLD | 98 |
| $>$ 2.8 | 90 | $^{82}$Se | $0\nu$ | $0^+ \rightarrow 2^+$ | NEMO-2 | [21] ARNOLD | 98 |
| $(7.6^{+2.2}_{-1.4})$E-3 | | $^{100}$Mo | $2\nu$ | | Si(Li) | [22] ALSTON-... | 97 |
| $(6.82^{+0.38}_{-0.53} \pm 0.68)$E-3 | | $^{100}$Mo | $2\nu$ | | TPC | [23] DESILVA | 97 |
| $(6.75^{+0.37}_{-0.42} \pm 0.68)$E-3 | | $^{150}$Nd | $2\nu$ | | TPC | [24] DESILVA | 97 |
| $>$ 1.2 | 90 | $^{150}$Nd | $0\nu$ | | TPC | [25] DESILVA | 97 |
| $1.77 \pm 0.01^{+0.13}_{-0.11}$ | | $^{76}$Ge | $2\nu$ | | Enriched HPGe | [26] GUENTHER | 97 |
| $(3.75 \pm 0.35 \pm 0.21)$E-2 | | $^{116}$Cd | $2\nu$ | $0^+ \rightarrow 0^+$ | NEMO 2 | [27] ARNOLD | 96 |

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| $0.043^{+0.024}_{-0.011} \pm 0.014$ | | $^{48}$Ca | $2\nu$ | | TPC | [28] | BALYSH | 96 |
| $0.79 \pm 0.10$ | | $^{130}$Te | $0\nu$+$2\nu$ | | Geochem | [29] | TAKAOKA | 96 |
| $0.61^{+0.18}_{-0.11}$ | | $^{100}$Mo | $0\nu$+$2\nu$ | $0^+ \rightarrow 0^+_1$ | $\gamma$ in HPGe | [30] | BARABASH | 95 |
| $(9.5 \pm 0.4 \pm 0.9)$E-3 | | $^{100}$Mo | $2\nu$ | | NEMO 2 | | DASSIE | 95 |
| $>$ 0.6 | 90 | $^{100}$Mo | $0\nu$ | $0^+ \rightarrow 0^+_1$ | NEMO 2 | | DASSIE | 95 |
| $0.026^{+0.009}_{-0.005}$ | | $^{116}$Cd | $2\nu$ | $0^+ \rightarrow 0^+$ | ELEGANT IV | | EJIRI | 95 |
| $0.017^{+0.010}_{-0.005} \pm 0.0035$ | | $^{150}$Nd | $2\nu$ | $0^+ \rightarrow 0^+$ | TPC | | ARTEMEV | 93 |
| $0.039 \pm 0.009$ | | $^{96}$Zr | $0\nu$+$2\nu$ | | Geochem | | KAWASHIMA | 93 |
| $2.7 \pm 0.1$ | | $^{130}$Te | $0\nu$+$2\nu$ | | Geochem | | BERNATOW... | 92 |
| $7200 \pm 400$ | | $^{128}$Te | $0\nu$+$2\nu$ | | Geochem | [31] | BERNATOW... | 92 |
| $>$ 27 | 68 | $^{82}$Se | $0\nu$ | $0^+ \rightarrow 0^+$ | TPC | | ELLIOTT | 92 |
| $0.108^{+0.026}_{-0.006}$ | | $^{82}$Se | $2\nu$ | $0^+ \rightarrow 0^+$ | TPC | | ELLIOTT | 92 |
| $2.0 \pm 0.6$ | | $^{238}$U | $0\nu$+$2\nu$ | | Radiochem | [32] | TURKEVICH | 91 |
| $>$ 9.5 | 76 | $^{48}$Ca | $0\nu$ | | $CaF_2$ scint. | | YOU | 91 |
| $2.60 \pm 0.28$ | | $^{130}$Te | $0\nu$+$2\nu$ | | Geochem | [33] | KIRSTEN | 83 |

[1] AALSETH 02B limit is based on 117 mol·yr of data using enriched Ge detectors. Background reduction by means of pulse shape analysis is applied to part of the data set. Reported limit is slightly less restrictive than that in KLAPDOR-KLEINGROTHAUS 01 However, it excludes part of the allowed half-life range reported in KLAPDOR-KLEINGROTHAUS 01B for the same nuclide.

[2] BERNABEI 02D report a limit for the $0\nu$, $0^+ \rightarrow 0^+$ decay of $^{134}$Xe, present in the source at 17%, by considering the maximum number of events for this mode compatible with the fitted smooth background.

[3] BERNABEI 02D report a limit for the $0\nu$, $0^+ \rightarrow 0^+$ decay of $^{136}$Xe, by considering the maximum number of events for this mode compatible with the fitted smooth background. The quoted sensitivity is $450 \times 10^{21}$ yr. The Feldman and Cousins method is used to obtain the quoted limit.

[4] KLAPDOR-KLEINGROTHAUS 02D is an expanded version of KLAPDOR-KLEINGROTHAUS 01B. The authors re-evaluate the data collected by the Heidelberg-Moscow experiment (KLAPDOR-KLEINGROTHAUS 01) and present a more detailed description of their analysis of an excess of counts at the energy expected for neutrinoless double-beta decay. They interpret this excess, which has a significance of 2.2 to 3.1 $\sigma$ depending on the data analysis, as evidence for the observation of Lepton Number violation and violation of Baryon minus Lepton Number. The analysis has been criticized by AALSETH 02. The criticisms have been addressed in KLAPDOR-KLEINGROTHAUS 02. See also KLAPDOR-KLEINGROTHAUS 02B.

[5] ASHITKOV 01 result for $2\nu$ of $^{100}$Mo is in agreement with other determinations of that halflife.

[6] ASHITKOV 01 result for $0\nu$ of $^{100}$Mo is less stringent than EJIRI 01.

[7] DANEVICH 01 place limit on $0\nu$ decay of $^{160}$Gd using $Gd_2SiO_5$:Ce crystal scintillators. The limit is more stringent than KOBAYASHI 95.

[8] DANEVICH 01 place limits on $0\nu$ decay of $^{160}$Gd into excited $2^+$ state of daughter nucleus using $Gd_2SiO_5$:Ce crystal scintillators.

[9] DEBRAECKELEER 01 performed an inclusive measurement of the $\beta\beta$ decay into the second excited state of the daughter nucleus. A novel coincidence technique counting the de-excitation photons is employed. The result agrees with BARABASH 95.

[10] EJIRI 01 uses tracking calorimeter and isotopically enriched passive source. Efficiencies were calculated assuming $\langle m_\nu \rangle$, $\langle \lambda \rangle$, or $\langle \eta \rangle$ driven decay. This is a continuation of EJIRI 96 which it supersedes.

[11] KLAPDOR-KLEINGROTHAUS 01 is a continuation of the work published in BAUDIS 99. Isotopically enriched Ge detectors are used in calorimetric measurement. The most stringent bound is derived from the data set in which pulse-shape analysis has been used to

reduce background. Exposure time is 35.5 kg y. Supersedes BAUDIS 99 as most stringent result.

[12] KLAPDOR-KLEINGROTHAUS 01 is a measurement of the $\beta\beta 2\nu$-decay rate with higher statistics than GUENTHER 97. The reported value has a worse systematic error than their previous result.

[13] WIESER 01 reports an inclusive geochemical measurement of $^{96}$Zr $\beta\beta$ half life. Their result agress within $2\sigma$ with ARNOLD 99 but only marginally, within $3\sigma$, with KAWASHIMA 93.

[14] ALESSANDRELLO 00 limit is based on calorimetric measurement with an array of 20 $TeO_2$ cryogenic detectors. Uses enriched and natural Te crystals. Replaces ALESSANDRELLO 98.

[15] BRUDANIN 00 determine the $2\nu$ halflife of $^{48}$Ca. Their value is less accurate than BALYSH 96.

[16] DANEVICH 00 provides calorimetric measurement of $2\nu$ decay of $^{116}$Cd using enriched $CdWO_4$ scintillators. Agrees with EJIRI 95 and ARNOLD 96.

[17] DANEVICH 00 places limits on $0\nu$ decay of $^{116}$Cd using enriched $CdWO_4$ scintillators. Replaces GEORGADZE 95.

[18] ARNOLD 99 measure directly the $2\nu$ decay of Zr for the first time, using the NEMO-2 tracking detector and an isotopically enriched source. The lifetime is more accurate than the geochemical result of KAWASHIMA 93.

[19] ARNOLD 98 measure the $2\nu$ decay of $^{82}$Se by comparing the spectra in an enriched and natural selenium source using the NEMO-2 tracking detector. The measured half-life is in agreement, perhaps slightly shorter, than ELLIOTT 92.

[20] ARNOLD 98 determine the limit for $0\nu$ decay to the ground state of $^{82}$Se using the NEMO-2 tracking detector. The half-life limit is in agreement, but less stringent, than ELLIOTT 92.

[21] ARNOLD 98 determine the limit for $0\nu$ decay to the excited $2^+$ state of $^{82}$Se using the NEMO-2 tracking detector.

[22] ALSTON-GARNJOST 97 report evidence for $2\nu$ decay of $^{100}$Mo. This decay has been also observed by EJIRI 91, DASSIE 95, and DESILVA 97.

[23] DESILVA 97 result for $2\nu$ decay of $^{100}$Mo is in agreement with ALSTON-GARNJOST 97 and DASSIE 95. This measurement has the smallest errors.

[24] DESILVA 97 result for $2\nu$ decay of $^{150}$Nd is in marginal agreement with ARTEMEV 93. It has smaller errors.

[25] DESILVA 97 do not explain whether their efficiency for $0\nu$ decay of $^{150}$Nd was calculated under the assumption of a $\langle m_\nu \rangle$, $\langle \lambda \rangle$, or $\langle \eta \rangle$ driven decay.

[26] GUENTHER 97 half-life for the $2\nu$ decay of $^{76}$Ge is not in good agreement with the previous measurements of BALYSH 94, AVIGNONE 91, and MILEY 90.

[27] ARNOLD 96 measure the $2\nu$ decay of $^{116}$Cd. This result is in agreement with EJIRI 95, but has smaller errors. Supersedes ARNOLD 95.

[28] BALYSH 96 measure the $2\nu$ decay of $^{48}$Ca, using a passive source of enriched $^{48}$Ca in a TPC.

[29] TAKAOKA 96 measure the geochemical half-life of $^{130}$Te. Their value is in disagreemnt with the quoted values of BERNATOWICZ 92 and KIRSTEN 83; but agrees with several other unquoted determinations, e.g., MANUEL 91.

[30] BARABASH 95 cannot distinguish $0\nu$ and $2\nu$, but it is inferred indirectly that the $0\nu$ mode accounts for less than 0.026% of their event sample. They also note that their result disagrees with the previous experiment by the NEMO group (BLUM 92).

[31] BERNATOWICZ 92 finds $^{128}$Te/$^{130}$Te activity ratio from slope of $^{128}$Xe/$^{132}$Xe vs $^{130}$Xe/$^{132}$Xe ratios during extraction, and normalizes to lead-dated ages for the $^{130}$Te lifetime. The authors state that their results imply that "(a) the double beta decay of $^{128}$Te has been firmly established and its half-life has been determined . . . without any ambiguity due to trapped Xe interferences. . . (b) Theoretical calculations . . . underestimate the [long half-lives of $^{128}$Te $^{130}$Te] by 1 or 2 orders of magnitude, pointing to a real supression in the $2\nu$ decay rate of these isotopes. (c) Despite [this], most $\beta\beta$-models

predict a *ratio* of $2\nu$ decay widths ... in fair agreement with observation." Further details of the experiment are given in BERNATOWICZ 93. Our listed half-life has been revised downward from the published value by the authors, on the basis of reevaluated cosmic-ray $^{128}$Xe production corrections.

[32] TURKEVICH 91 observes activity in old U sample. The authors compare their results with theoretical calculations. They state "Using the phase-space factors of Boehm and Vogel (BOEHM 87) leads to matrix element values for the $^{238}$U transition in the same range as deduced for $^{130}$Te and $^{76}$Ge. On the other hand, the latest theoretical estimates (STAUDT 90) give an upper limit that is 10 times lower. This large discrepancy implies either a defect in the calculations or the presence of a faster path than the standard two-neutrino mode in this case." See BOEHM 87 and STAUDT 90.

[33] KIRSTEN 83 reports "$2\sigma$" error. References are given to earlier determinations of the $^{130}$Te lifetime.

## $\langle m_\nu \rangle$, The Effective Weighted Sum of Majorana Neutrino Masses Contributing to Neutrinoless Double-$\beta$ Decay

$\langle m_\nu \rangle = |\Sigma\, U^2_{1j} m_{\nu_j}|$, where the sum goes from 1 to $n$ and where $n$ = number of neutrino generations, and $\nu_j$ is a Majorana neutrino. Note that $U^2_{ej}$, not $|U_{ej}|^2$, occurs in the sum. The possibility of cancellations has been stressed. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

| *VALUE* (eV) | *CL%* | *ISOTOPE* | *TRANSITION* | *METHOD* | *DOCUMENT ID* | |
|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| < 0.33–1.35 | 90 | | | Enriched HPGe | [34] AALSETH | 02B |
| <2.9 | 90 | $^{136}$Xe | $0\nu$ | Liquid Xe Scint. | [35] BERNABEI | 02D |
| $0.39^{+0.17}_{-0.28}$ | | $^{76}$Ge | $0\nu$ | Enriched HPGe | [36] KLAPDOR-K... | 02D |
| < 2.1–4.8 | 90 | $^{100}$Mo | $0\nu$ | ELEGANT V | [37] EJIRI | 01 |
| < 0.35 | 90 | $^{76}$Ge | | Enriched HPGe | [38] KLAPDOR-K... | 01 |
| < 1.1–2.6 | 90 | $^{130}$Te | $0\nu$ | Cryog. det. | [39] ALESSAND... | 00 |
| < 2.4–2.6 | 90 | $^{116}$Cd | $0\nu$ | $^{116}CdWO_4$ scint | [40] DANEVICH | 00 |
| <23 | 90 | $^{96}$Zr | | NEMO-2 | [41] ARNOLD | 99 |
| < 1.1–1.5 | | $^{128}$Te | | Geochem | [42] BERNATOW... | 92 |
| <5 | 68 | $^{82}$Se | | TPC | [43] ELLIOTT | 92 |
| <8.3 | 76 | $^{48}$Ca | $0\nu$ | $CaF_2$ scint. | YOU | 91 |

[34] AALSETH 02B reported range of limits on $\langle m_\nu \rangle$ reflects the spread of theoretical nuclear matrix elements. Excludes part of allowed mass range reported in KLAPDOR-KLEINGROTHAUS 01B.

[35] BERNABEI 02D limit is based on the matrix elements of SIMKOVIC 02. The range of neutrino masses based on a variety of matrix elements is 1.1–2.9 eV.

[36] KLAPDOR-KLEINGROTHAUS 02D is a detailed description of the analysis of the data collected by the Heidelberg-Moscow experiment, previously presented in KLAPDOR-KLEINGROTHAUS 01B. Matrix elements in STAUDT 90 have been used. See the footnote in the preceding table for further details. See also KLAPDOR-KLEINGROTHAUS 02B.

[37] The range of the reported $\langle m_\nu \rangle$ values reffects the spread of the nuclear matrix elements. On axis value assuming $\langle \lambda \rangle = \langle \eta \rangle = 0$.

[38] KLAPDOR-KLEINGROTHAUS 01 uses the calculation by STAUDT 90. Using several other models in the literature could worsen the limit up to 1.2 eV. This is the most stringent experimental bound on $m_\nu$. It supersedes BAUDIS 99B.

[39] ALESSANDRELLO 00 spread in limit for $\langle m_\nu \rangle$ reflects the range found for theoretical matrix elements.

[40] DANEVICH 00 limit for $\langle m_\nu \rangle$ is based on the nuclear matrix elements of STAUDT 90 (2.6 eV) and ARNOLD 96 (2.4 eV).

[41] ARNOLD 99 limit based on the nuclear matrix elements of STAUDT 90.

[42] BERNATOWICZ 92 finds these majorona neutrino mass limits assuming that the measured geochemical decay width is a limit on the $0\nu$ decay width. The range is the range found using matrix elements from HAXTON 84, TOMODA 87, and SUHONEN 91. Further details of the experiment are given in BERNATOWICZ 93.

[43] ELLIOTT 92 uses the matrix elements of HAXTON 84.

## Limits on Lepton-Number Violating ($V+A$) Current Admixture

For reasons given in the discussion at the beginning of this section, we list only results from 1989 and later. $\langle \lambda \rangle = \lambda \sum U_{ej} V_{ej}$ and $\langle \eta \rangle = \eta \sum U_{ej} V_{ej}$, where the sum is over the number of neutrino generations. This sum vanishes for massless or unmixed neutrinos. In the following Listings, only best or comparable limits or lifetimes for each isotope are reported.

| $\langle \lambda \rangle$ ($10^{-6}$) | *CL%* | $\langle \eta \rangle$ ($10^{-8}$) | *CL%* | *ISOTOPE* | *METHOD* | *DOCUMENT ID* | |
|---|---|---|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | | |
| $< 3.2$–$4.7$ | 90 | $< 2.4$–$2.7$ | 90 | $^{100}$Mo | ELEGANT V | [44] EJIRI | 01 |
| $< 1.9$–$3.9$ | 90 | $< 1.2$–$6.4$ | 90 | $^{130}$Te | Cryog. det. | [45] ALESSAND... | 00 |
| $<3.4$ | 90 | $<3.9$ | 90 | $^{116}$Cd | $^{116}$CdWO$_4$ scint. | [46] DANEVICH | 00 |
| $<1.1$ | 90 | $<0.64$ | 90 | $^{76}$Ge | Enriched HPGe | [47] GUENTHER | 97 |
| $<4.4$ | 90 | $<2.3$ | 90 | $^{136}$Xe | TPC | [48] VUILLEUMIER | 93 |
| | | $<5.3$ | | $^{128}$Te | Geochem | [49] BERNATOW... | 92 |

[44] The range of the reported $\langle \lambda \rangle$ and $\langle \eta \rangle$ values reflects the spread of the nuclear matrix elements. On axis value assuming $\langle m_\nu \rangle$=0 and $\langle \lambda \rangle$=$\langle \eta \rangle$=0, respectively.

[45] ALESSANDRELLO 00 limits for $\langle \lambda \rangle$ and $\langle \eta \rangle$ use several nuclear matrix element calculations. Limits reported for $\langle m_\nu \rangle = \langle \eta \rangle = \langle \lambda \rangle = 0$.

[46] DANEVICH 00 limits for $\langle \lambda \rangle$ and $\langle \eta \rangle$ are based on nuclear matrix element of STAUDT 90. Replaces DANEVICH 95.

[47] GUENTHER 97 limits use the matrix elements of STAUDT 90. Supersedes BALYSH 95 and BALYSH 92.

[48] VUILLEUMIER 93 uses the matrix elements of MUTO 89. Based on a half-life limit $2.6 \times 10^{23}$ y at 90%CL.

[49] BERNATOWICZ 92 takes the measured geochemical decay width as a limit on the $0\nu$ width, and uses the SUHONEN 91 coefficients to obtain the least restrictive limit on $\eta$. Further details of the experiment are given in BERNATOWICZ 93.

## Double-$\beta$ Decay REFERENCES


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| MANUEL | 91 | JPG 17 S221 | O.K. Manuel | (MISSR) |
| SUHONEN | 91 | NP A535 509 | J. Suhonen, S.B. Khadkikar, A. Faessler | (JYV+) |
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| YOU | 91 | PL B265 53 | K. You *et al.* | (BHEP, CAST+) |
| MILEY | 90 | PRL 65 3092 | H.S. Miley *et al.* | (SCUC, PNL) |
| STAUDT | 90 | EPL 13 31 | A. Staudt, K. Muto, H.V. Klapdor-Kleingrothaus | |
| MUTO | 89 | ZPHY A334 187 | K. Muto, E. Bender, H.V. Klapdor | (TINT, MPIH) |
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| HAXTON | 84 | PPNP 12 409 | W.C. Haxton, G.J. Stevenson | |
| KIRSTEN | 83 | PRL 50 474 | T. Kirsten, H. Richter, E. Jessberger | (MPIH) |