# n

$I(J^P) = \frac{1}{2}(\frac{1}{2}^+)$ Status: ∗∗∗∗

We have omitted some results that have been superseded by later experiments. See our earlier editions.

Anyone interested in the neutron should look at these two new review articles: D. Dubbers and M.G. Schmidt, "The neutron and its role in cosmology and particle physics," Reviews of Modern Physics **83** 1111 (2011); and F.E. Wietfeldt and G.L. Greene, "The neutron lifetime," Reviews of Modern Physics **83** 1173 (2011).

## *n* MASS (atomic mass units u)

The mass is known much more precisely in u (atomic mass units) than in MeV. See the next data block.

| *VALUE* (u) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **1.00866491588±0.00000000049** | MOHR | 16 | RVUE | 2014 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 1.00866491600±0.00000000043 | MOHR | 12 | RVUE | 2010 CODATA value |
| 1.00866491597±0.00000000043 | MOHR | 08 | RVUE | 2006 CODATA value |
| 1.00866491560±0.00000000055 | MOHR | 05 | RVUE | 2002 CODATA value |
| 1.00866491578±0.00000000055 | MOHR | 99 | RVUE | 1998 CODATA value |
| 1.008665904 ±0.000000014 | COHEN | 87 | RVUE | 1986 CODATA value |

## *n* MASS (MeV)

The mass is known much more precisely in u (atomic mass units) than in MeV. The conversion from u to MeV, 1 u = 931.494 0054(57)) MeV/$c^2$ (MOHR 16, the 2014 CODATA value), involves the relatively poorly known electronic charge.

| *VALUE* (MeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **939.5654133±0.0000058** | MOHR | 16 | RVUE | 2014 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 939.565379 ±0.000021 | MOHR | 12 | RVUE | 2010 CODATA value |
| 939.565346 ±0.000023 | MOHR | 08 | RVUE | 2006 CODATA value |
| 939.565360 ±0.000081 | MOHR | 05 | RVUE | 2002 CODATA value |
| 939.565331 ±0.000037 | [1] KESSLER | 99 | SPEC | $n p \rightarrow d \gamma$ |
| 939.565330 ±0.000038 | MOHR | 99 | RVUE | 1998 CODATA value |
| 939.56565 ±0.00028 | [2,3] DIFILIPPO | 94 | TRAP | Penning trap |
| 939.56563 ±0.00028 | COHEN | 87 | RVUE | 1986 CODATA value |
| 939.56564 ±0.00028 | [3,4] GREENE | 86 | SPEC | $n p \rightarrow d \gamma$ |
| 939.5731 ±0.0027 | [3] COHEN | 73 | RVUE | 1973 CODATA value |

[1] We use the 1998 CODATA u-to-MeV conversion factor (see the heading above) to get this mass in MeV from the much more precisely measured KESSLER 99 value of 1.00866491637 ± 0.00000000082 u.

[2] The mass is known much more precisely in u: $m = 1.0086649235 \pm 0.0000000023$ u. We use the 1986 CODATA conversion factor to get the mass in MeV.

[3] These determinations are not independent of the $m_n - m_p$ measurements below.

[4] The mass is known much more precisely in u: $m = 1.008664919 \pm 0.000000014$ u.

## $\overline{n}$ MASS

| *VALUE* (MeV) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **939.485±0.051** | 59 | [1] CRESTI | 86 | HBC | $\overline{p}p \rightarrow \overline{n}n$ |

[1] This is a corrected result (see the erratum). The error is statistical. The maximum systematic error is 0.029 MeV.

## $(m_n - m_{\overline{n}})/\ m_n$

A test of *CPT* invariance. Calculated from the *n* and $\overline{n}$ masses, above.

| *VALUE* | *DOCUMENT ID* |
|---|---|
| **(9±6) × $10^{-5}$ OUR EVALUATION** | |

## $m_n - m_p$

| *VALUE* (MeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **1.29333205±0.00000051** | [1] MOHR | 16 | RVUE | 2014 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 1.29333217±0.00000042 | [2] MOHR | 12 | RVUE | 2010 CODATA value |
| 1.29333214±0.00000043 | [3] MOHR | 08 | RVUE | 2006 CODATA value |
| 1.2933317 ±0.0000005 | [4] MOHR | 05 | RVUE | 2002 CODATA value |
| 1.2933318 ±0.0000005 | [5] MOHR | 99 | RVUE | 1998 CODATA value |
| 1.293318 ±0.000009 | [6] COHEN | 87 | RVUE | 1986 CODATA value |
| 1.2933328 ±0.0000072 | GREENE | 86 | SPEC | $np \rightarrow d\gamma$ |
| 1.293429 ±0.000036 | COHEN | 73 | RVUE | 1973 CODATA value |

[1] The 2014 CODATA mass difference in *u* is $m_n - m_p = 1.001\,388\,449\,00(51) \times 10^{-3} u$.

[2] The 2010 CODATA mass difference in *u* is $m_n - m_p = 1.388\,449\,19(45) \times 10^{-3} u$.

[3] Calculated by us from the MOHR 08 ratio $m_n/m_p = 1.00137841918(46)$. In u, $m_n - m_p = 1.38844920(46) \times 10^{-3}$ u.

[4] Calculated by us from the MOHR 05 ratio $m_n/m_p = 1.00137841870 \pm 0.00000000058$. In u, $m_n - m_p = (1.3884487 \pm 0.0000006) \times 10^{-3}$ u.

[5] Calculated by us from the MOHR 99 ratio $m_n/m_p = 1.00137841887 \pm 0.00000000058$. In u, $m_n - m_p = (1.3884489 \pm 0.0000006) \times 10^{-3}$ u.

[6] Calculated by us from the COHEN 87 ratio $m_n/m_p = 1.001378404 \pm 0.000000009$. In u, $m_n - m_p = 0.001388434 \pm 0.000000009$ u.

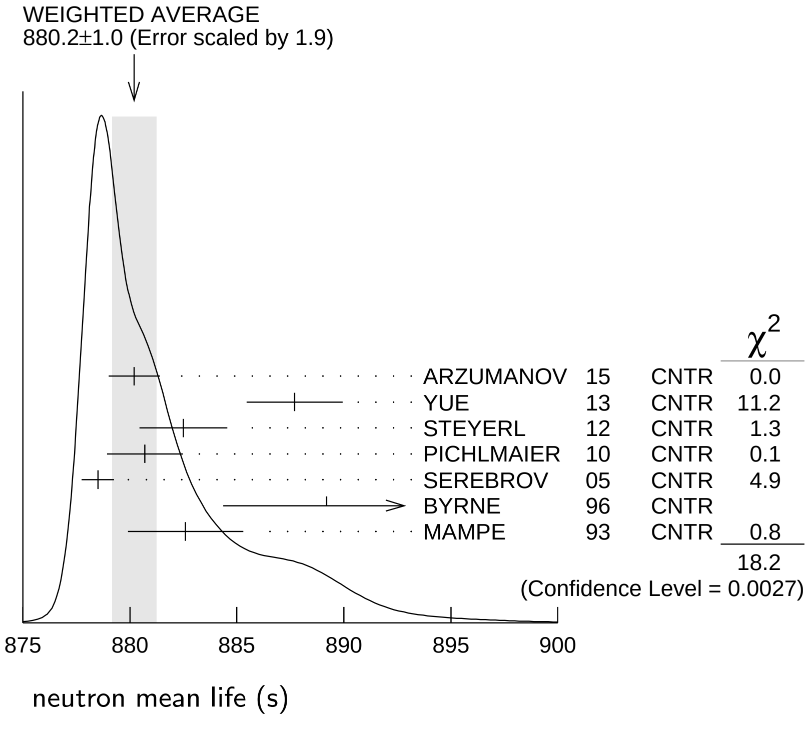
## *n* MEAN LIFE

Limits on lifetimes for *bound* neutrons are given in the section "p PARTIAL MEAN LIVES."

We average the best seven measurements. The result, 880.2 ± 1.0 s (including a scale factor of 1.9), is 5.5 seconds lower than the value we gave in 2010—a drop of 6.9 old and 5.5 new standard deviations.

For a full review of all matters concerning the neutron lifetime, see F.E. Wietfeldt and G.L. Greene, "The neutron lifetime," Reviews of Modern Physics **83** 1173 (2011). In particular, there is a full discussion of the experimental methods and results; and an average lifetime is obtained making several different selections of the results then available.

| *VALUE* (s) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **880.2± 1.0 OUR AVERAGE** | Error includes scale factor of 1.9. See the ideogram below. | | | |
| 880.2± 1.2 | [1] ARZUMANOV | 15 | CNTR | UCN double bottle |
| 887.7± 1.2± 1.9 | [2] YUE | 13 | CNTR | In-beam *n*, trapped *p* |
| 882.5± 1.4± 1.5 | [3] STEYERL | 12 | CNTR | UCN material bottle |
| 880.7± 1.3± 1.2 | PICHLMAIER | 10 | CNTR | UCN material bottle |
| 878.5± 0.7± 0.3 | SEREBROV | 05 | CNTR | UCN gravitational trap |
| 889.2± 3.0± 3.8 | BYRNE | 96 | CNTR | Penning trap |
| 882.6± 2.7 | [4] MAMPE | 93 | CNTR | UCN material bottle |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 881.6± 0.8± 1.9 | [5] ARZUMANOV | 12 | CNTR | See ARZUMANOV 15 |
| 886.3± 1.2± 3.2 | NICO | 05 | CNTR | See YUE 13 |
| 886.8± 1.2± 3.2 | DEWEY | 03 | CNTR | See NICO 05 |
| 885.4± 0.9± 0.4 | ARZUMANOV | 00 | CNTR | See ARZUMANOV 12 |
| 888.4± 3.1± 1.1 | [6] NESVIZHEV... | 92 | CNTR | UCN material bottle |
| 888.4± 2.9 | ALFIMENKOV | 90 | CNTR | See NESVIZHEVSKII 92 |
| 893.6± 3.8± 3.7 | BYRNE | 90 | CNTR | See BYRNE 96 |
| 878 ±27 ±14 | KOSSAKOW... | 89 | TPC | Pulsed beam |
| 887.6± 3.0 | MAMPE | 89 | CNTR | See STEYERL 12 |
| 877 ±10 | PAUL | 89 | CNTR | Magnetic storage ring |
| 876 ±10 ±19 | LAST | 88 | SPEC | Pulsed beam |
| 891 ± 9 | SPIVAK | 88 | CNTR | Beam |
| 903 ±13 | KOSVINTSEV | 86 | CNTR | UCN material bottle |
| 937 ±18 | [7] BYRNE | 80 | CNTR | |
| 875 ±95 | KOSVINTSEV | 80 | CNTR | |
| 881 ± 8 | BONDAREN... | 78 | CNTR | See SPIVAK 88 |
| 918 ±14 | CHRISTENSEN | 72 | CNTR | |



[1] ARZUMANOV 15 is a reanalysis of their 2008–2010 dataset, with improved systematic corrections of of ARZUMANOV 00 and ARZUMANOV 12.

[2] YUE 13 differs from NICO 05 in that a different and better method was used to measure the neutron density in the fiducial volume. This shifted the lifetime by +1.4 seconds and reduced the previously largest source of systematic uncertainty by a factor of five.

[3] STEYERL 12 is a detailed reanalysis of neutron storage loss corrections to the raw data of MAMPE 89, and it replaces that value.

[4] IGNATOVICH 95 calls into question some of the corrections and averaging procedures used by MAMPE 93. The response, BONDARENKO 96, denies the validity of the criticisms.

[5] ARZUMANOV 12 reanalyzes its systematic corrections in ARZUMANOV 00 and obtains this corrected value.

[6] The NESVIZHEVSKII 92 measurement has been withdrawn by A. Serebrov.

[7] The BYRNE 80 measurement has been withdrawn (J. Byrne, private communication, 1990).

## *n* MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the $\Lambda$ Listings.

| *VALUE* ($\mu_N$) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **−1.91304273±0.00000045** | MOHR | 16 | RVUE | 2014 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| −1.91304272±0.00000045 | MOHR | 12 | RVUE | 2010 CODATA value |
| −1.91304273±0.00000045 | MOHR | 08 | RVUE | 2006 CODATA value |
| −1.91304273±0.00000045 | MOHR | 05 | RVUE | 2002 CODATA value |
| −1.91304272±0.00000045 | MOHR | 99 | RVUE | 1998 CODATA value |
| −1.91304275±0.00000045 | COHEN | 87 | RVUE | 1986 CODATA value |
| −1.91304277±0.00000048 | [1] GREENE | 82 | MRS | |

[1] GREENE 82 measures the moment to be (1.04187564 ± 0.00000026) × $10^{-3}$ Bohr magnetons. The value above is obtained by multiplying this by $m_p/m_e = 1836.152701 \pm 0.000037$ (the 1986 CODATA value from COHEN 87).

## *n* ELECTRIC DIPOLE MOMENT

A nonzero value is forbidden by both $T$ invariance and $P$ invariance. A number of early results have been omitted. See RAMSEY 90, GOLUB 94, and LAMOREAUX 09 for reviews.

The results are upper limits on $|d_n|$.

| *VALUE* ($10^{-25}$ *e*cm) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **< 0.30** | 90 | PENDLEBURY | 15 | MRS | $d = (-0.21 \pm 1.82) \times 10^{-26}$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 0.22 | | [1] SAHOO | 17 | | Theory + $^{199}$Hg atom EDM |
| < 0.55 | 90 | SEREBROV | 15 | MRS | UCN's, $h\nu = 2\mu_n B \pm 2d_n E$ |
| < 0.55 | 90 | [2] SEREBROV | 14 | MRS | See SEREBROV 15 |
| < 0.29 | 90 | [3] BAKER | 06 | MRS | See PENDLEBURY 15 |
| < 0.63 | 90 | [4] HARRIS | 99 | MRS | $d = (-0.1 \pm 0.36) \times 10^{-25}$ |
| < 0.97 | 90 | ALTAREV | 96 | MRS | See SEREBROV 14 |

| | | | | | |
|---|---|---|---|---|---|
| $< 1.1$ | 95 | ALTAREV | 92 | MRS | See ALTAREV 96 |
| $< 1.2$ | 95 | SMITH | 90 | MRS | See HARRIS 99 |
| $< 2.6$ | 95 | ALTAREV | 86 | MRS | $d = (-1.4 \pm 0.6) \times 10^{-25}$ |
| $0.3 \pm 4.8$ | | PENDLEBURY | 84 | MRS | Ultracold neutrons |
| $< 6$ | 90 | ALTAREV | 81 | MRS | $d = (2.1 \pm 2.4) \times 10^{-25}$ |
| $<16$ | 90 | ALTAREV | 79 | MRS | $d = (4.0 \pm 7.5) \times 10^{-25}$ |

[1] SAHOO 17 is not a direct measurement of the neutron electric dipole moment. It uses theory to calculate this limit from the limit on the electric dipole moment of the $^{199}$Hg atom.

[2] SEREBROV 14 includes the data of ALTAREV 96.

[3] LAMOREAUX 07 faults BAKER 06 for not including in the estimate of systematic error an effect due to the Earth's rotation. BAKER 07 replies (1) that the effect was included implicitly in the analysis and (2) that further analysis confirms that the BAKER 06 limit is correct as is. See also SILENKO 07.

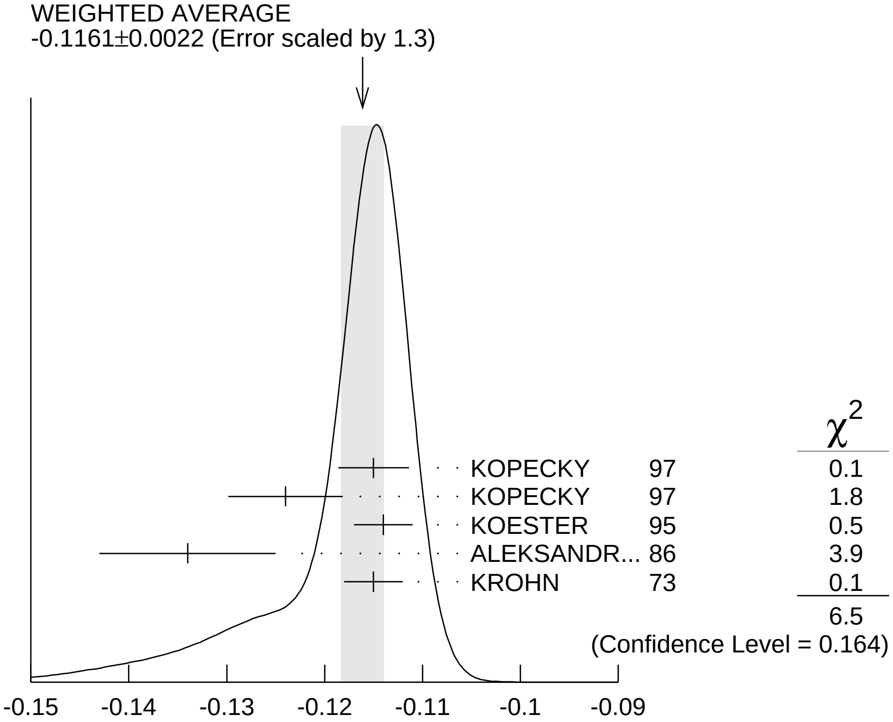
[4] This HARRIS 99 result includes the result of SMITH 90. However, the averaging of the results of these two experiments has been criticized by LAMOREAUX 00.

## *n* MEAN-SQUARE CHARGE RADIUS

The mean-square charge radius of the neutron, $\langle r_n^2 \rangle$, is related to the neutron-electron scattering length $b_{ne}$ by $\langle r_n^2 \rangle = 3(m_e a_0/m_n) b_{ne}$, where $m_e$ and $m_n$ are the masses of the electron and neutron, and $a_0$ is the Bohr radius. Numerically, $\langle r_n^2 \rangle = 86.34\ b_{ne}$, if we use $a_0$ for a nucleus with infinite mass.

| *VALUE* (fm$^2$) | *DOCUMENT ID* | | *COMMENT* |
|---|---|---|---|
| **−0.1161±0.0022 OUR AVERAGE** | Error includes scale factor of 1.3. See the ideogram below. | | |
| $-0.115 \pm 0.002 \pm 0.003$ | KOPECKY | 97 | *ne* scattering (Pb) |
| $-0.124 \pm 0.003 \pm 0.005$ | KOPECKY | 97 | *ne* scattering (Bi) |
| $-0.114 \pm 0.003$ | KOESTER | 95 | *ne* scattering (Pb, Bi) |
| $-0.134 \pm 0.009$ | ALEKSANDR... | 86 | *ne* scattering (Bi) |
| $-0.115 \pm 0.003$ | [1] KROHN | 73 | *ne* scattering (Ne, Ar, Kr, Xe) |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | |
| $-0.117^{+0.007}_{-0.011}$ | BELUSHKIN | 07 | Dispersion analysis |
| $-0.113 \pm 0.003 \pm 0.004$ | KOPECKY | 95 | *ne* scattering (Pb) |
| $-0.114 \pm 0.003$ | KOESTER | 86 | *ne* scattering (Pb, Bi) |
| $-0.118 \pm 0.002$ | KOESTER | 76 | *ne* scattering (Pb) |
| $-0.120 \pm 0.002$ | KOESTER | 76 | *ne* scattering (Bi) |
| $-0.116 \pm 0.003$ | KROHN | 66 | *ne* scattering (Ne, Ar, Kr, Xe) |

[1] This value is as corrected by KOESTER 76.



*n* mean-square charge radius

## *n* MAGNETIC RADIUS

This is the rms magnetic radius, $\sqrt{\langle r^2_M \rangle}$.

| *VALUE* (fm) | *DOCUMENT ID* | | *COMMENT* |
|---|---|---|---|
| **$0.864^{+0.009}_{-0.008}$ OUR AVERAGE** | | | |
| 0.89 ±0.03 | EPSTEIN | 14 | Using $e p$, $e n$, $\pi\pi$ data |
| $0.862^{+0.009}_{-0.008}$ | BELUSHKIN | 07 | Dispersion analysis |

## *n* ELECTRIC POLARIZABILITY $\alpha_n$

Following is the electric polarizability $\alpha_n$ defined in terms of the induced electric dipole moment by $\mathbf{D} = 4\pi\epsilon_0\alpha_n\mathbf{E}$. For a review, see SCHMIEDMAYER 89.

For very complete reviews of the polarizability of the nucleon and Compton scattering, see SCHUMACHER 05 and GRIESSHAMMER 12.

| *VALUE* ($10^{-4}$ fm$^3$) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **11.8 ± 1.1 OUR AVERAGE** | | | | |
| 11.55± 1.25±0.8 | MYERS | 14 | CNTR | $\gamma d \rightarrow \gamma d$ |
| 12.5 ± 1.8 $^{+1.6}_{-1.3}$ | [1] KOSSERT | 03 | CNTR | $\gamma d \rightarrow \gamma p n$ |
| 12.0 ± 1.5 ±2.0 | SCHMIEDM... | 91 | CNTR | *n* Pb transmission |
| 10.7 $^{+\ 3.3}_{-10.7}$ | ROSE | 90B | CNTR | $\gamma d \rightarrow \gamma n p$ |

| | | | | |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $8.8 \pm 2.4 \pm 3.0$ | [2] LUNDIN | 03 | CNTR | $\gamma d \to \gamma d$ |
| 13.6 | [3] KOLB | 00 | CNTR | $\gamma d \to \gamma n p$ |
| $0.0 \pm 5.0$ | [4] KOESTER | 95 | CNTR | *n* Pb, *n* Bi transmission |
| $11.7^{+4.3}_{-11.7}$ | ROSE | 90 | CNTR | See ROSE 90B |
| $8 \pm 10$ | KOESTER | 88 | CNTR | *n* Pb, *n* Bi transmission |
| $12 \pm 10$ | SCHMIEDM... | 88 | CNTR | *n* Pb, *n* C transmission |

[1] KOSSERT 03 gets $\alpha_n - \beta_n = (9.8 \pm 3.6^{+2.1}_{-1.1} \pm 2.2) \times 10^{-4}$ fm$^3$, and uses $\alpha_n + \beta_n = (15.2 \pm 0.5) \times 10^{-4}$ fm$^3$ from LEVCHUK 00. Thus the errors on $\alpha_n$ and $\beta_n$ are anti-correlated.

[2] LUNDIN 03 measures $\alpha_N - \beta_N = (6.4 \pm 2.4) \times 10^{-4}$ fm$^3$ and uses accurate values for $\alpha_p$ and $\alpha_p$ and a precise sum-rule result for $\alpha_n + \beta_n$. The second error is a model uncertainty, and errors on $\alpha_n$ and $\beta_n$ are anticorrelated. The data from this paper aer included in the analysis of MYERS 14.

[3] KOLB 00 obtains this value with a lower limit of $7.6 \times 10^{-4}$ fm$^3$ but no upper limit from this experiment alone. Combined with results of ROSE 90, the 1-$\sigma$ range is (7.6–14.0) $\times$ $10^{-4}$ fm$^3$.

[4] KOESTER 95 uses natural Pb and the isotopes 208, 207, and 206. See this paper for a discussion of methods used by various groups to extract $\alpha_n$ from data.

## *n* MAGNETIC POLARIZABILITY $\beta_n$

| *VALUE* ($10^{-4}$ fm$^3$) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **3.7 ±1.2 OUR AVERAGE** | | | | |
| $3.65 \pm 1.25 \pm 0.8$ | MYERS | 14 | CNTR | $\gamma d \to \gamma d$ |
| $2.7 \pm 1.8 ^{+1.3}_{-1.6}$ | [1] KOSSERT | 03 | CNTR | $\gamma d \to \gamma p n$ |
| $6.5 \pm 2.4 \pm 3.0$ | [2] LUNDIN | 03 | CNTR | $\gamma d \to \gamma d$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 1.6 | [3] KOLB | 00 | CNTR | $\gamma d \to \gamma n p$ |

[1] KOSSERT 03 gets $\alpha_n - \beta_n = (9.8 \pm 3.6^{+2.1}_{-1.1} \pm 2.2) \times 10^{-4}$ fm$^3$, and uses $\alpha_n + \beta_n = (15.2 \pm 0.5) \times 10^{-4}$ fm$^3$ from LEVCHUK 00. Thus the errors on $\alpha_n$ and $\beta_n$ are anti-correlated.

[2] LUNDIN 03 measures $\alpha_N - \beta_N = (6.4 \pm 2.4) \times 10^{-4}$ fm$^3$ and uses accurate values for $\alpha_p$ and $\alpha_p$ and a precise sum-rule result for $\alpha_n + \beta_n$. The second error is a model uncertainty, and errors on $\alpha_n$ and $\beta_n$ are anticorrelated.

[3] KOLB 00 obtains this value with an upper limit of $7.6 \times 10^{-4}$ fm$^3$ but no lower limit from this experiment alone. Combined with results of ROSE 90, the 1-$\sigma$ range is (1.2–7.6) $\times$ $10^{-4}$ fm$^3$.

## *n* CHARGE

See also "$|q_p + q_e|/e$" in the proton Listings.

| *VALUE* ($10^{-21}$ *e*) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **$-$ 0.2± 0.8 OUR AVERAGE** | | | | |
| $-0.1 \pm 1.1$ | [1] BRESSI | 11 | | Neutrality of $SF_6$ |
| $-0.4 \pm 1.1$ | [2] BAUMANN | 88 | | Cold *n* deflection |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $-15 \pm 22$ | [3] GAEHLER | 82 | CNTR | Cold *n* deflection |

[1] As a limit, this BRESSI 11 value is $< 1 \times 10^{-21}$ *e*.
[2] The BAUMANN 88 error ±1.1 gives the 68% CL limits about the the value −0.4.
[3] The GAEHLER 82 error ±22 gives the 90% CL limits about the the value −15.

## LIMIT ON $n\overline{n}$ OSCILLATIONS

### Mean Time for $n\overline{n}$ Transition in Vacuum

A test of ΔB=2 baryon number nonconservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for $n\overline{n}$ oscillations. DOVER 83 and DOVER 85 give phenomenological analyses. The best limits come from looking for the decay of neutrons bound in nuclei. However, these analyses require model-dependent corrections for nuclear effects. See KABIR 83, DOVER 89, ALBERICO 91, and GAL 00 for discussions. Direct searches for $n \rightarrow \overline{n}$ transitions using reactor neutrons are cleaner but give somewhat poorer limits. We include limits for both free and bound neutrons in the Summary Table. See MOHAPATRA 09 for a recent review.

| *VALUE* (s) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **$>2.7 \times 10^{8}$** | 90 | ABE | 15C | CNTR | *n* bound in oxygen |
| **$>8.6 \times 10^{7}$** | 90 | BALDO-... | 94 | CNTR | Reactor (free) neutrons |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $>1.3 \times 10^{8}$ | 90 | CHUNG | 02B | SOU2 | *n* bound in iron |
| $>1 \times 10^{7}$ | 90 | BALDO-... | 90 | CNTR | See BALDO-CEOLIN 94 |
| $>1.2 \times 10^{8}$ | 90 | BERGER | 90 | FREJ | *n* bound in iron |
| $>4.9 \times 10^{5}$ | 90 | BRESSI | 90 | CNTR | Reactor neutrons |
| $>4.7 \times 10^{5}$ | 90 | BRESSI | 89 | CNTR | See BRESSI 90 |
| $>1.2 \times 10^{8}$ | 90 | TAKITA | 86 | CNTR | *n* bound in oxygen |
| $>1 \times 10^{6}$ | 90 | FIDECARO | 85 | CNTR | Reactor neutrons |
| $>8.8 \times 10^{7}$ | 90 | PARK | 85B | CNTR | |
| $>3 \times 10^{7}$ | | BATTISTONI | 84 | NUSX | |
| $>$ 0.27–$1.1 \times 10^{8}$ | | JONES | 84 | CNTR | |
| $>2 \times 10^{7}$ | | CHERRY | 83 | CNTR | |

## LIMIT ON $n n'$ OSCILLATIONS

Lee and Yang (LEE 56) proposed the existence of mirror world in an attempt to restore global parity symmetry. See BEREZHIANI 06 for a recent discussion.

| *VALUE* (s) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **>414** | 90 | SEREBROV | 08 | CNTR | UCN, B field on & off |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| > 12 | 95 | [1] ALTAREV | 09A | CNTR | UCN, scan $0 \leq B \leq 12.5\ \mu$T |
| >103 | 95 | BAN | 07 | CNTR | UCN, B field on & off |

[1] Losses of neutrons due to oscillations to mirror neutrons would be maximal when the magnetic fields $B$ and $B'$ in the two worlds were equal. Hence the scan over $B$ by ALTAREV 09A: the limit applies for any $B'$ over the given range. At $B' = 0$, the limit is 141 s (95% CL).

## *n* DECAY MODES

| | Mode | | Fraction ($\Gamma_i/\Gamma$) | Confidence level |
|---|---|---|---|---|
| $\Gamma_1$ | $pe^-\overline{\nu}_e$ | | 100 % | |
| $\Gamma_2$ | $pe^-\overline{\nu}_e\gamma$ | [a] | $(9.2\pm0.7)\times10^{-3}$ | |
| $\Gamma_3$ | hydrogen-atom $\overline{\nu}_e$ | | | |

### Charge conservation ($Q$) violating mode

| | Mode | | Fraction ($\Gamma_i/\Gamma$) | Confidence level |
|---|---|---|---|---|
| $\Gamma_4$ | $p\nu_e\overline{\nu}_e$ | $Q$ | $< 8\times10^{-27}$ | 68% |

[a] This limit is for $\gamma$ energies between 0.4 and 782 keV.

## *n* BRANCHING RATIOS

### $\Gamma(pe^-\overline{\nu}_e\gamma)/\Gamma_{\text{total}}$ $\qquad\Gamma_2/\Gamma$

| *VALUE* (units $10^{-3}$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **9.17±0.24±0.64** | | [1] BALES | 16 | RDK2 | Two different set-ups |

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* (units $10^{-3}$) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| 3.09±0.11±0.30 | | [2] COOPER | 10 | CNTR | See BALES 16 |
| 3.13±0.11±0.33 | | NICO | 06 | CNTR | See COOPER 10 |
| <6.9 | 90 | [3] BECK | 02 | CNTR | $\gamma$, $p$, $e^-$ coincidence |

[1] BALES 16 gets a branching fraction of $(5.82\pm0.23\pm0.62)\times10^{-3}$ for a photon energy range 0.4 to 14.0 keV, and with a different detector array, $(3.35\pm0.05\pm0.15)\times10^{-3}$ for 14.1 to 782 keV. Our result above is the sum; the error on the sum is completely dominated by the error on the lower range.

[2] This COOPER 10 result is for $\gamma$ energies between 15 and 340 keV.

[3] This BECK 02 limit is for $\gamma$ energies between 35 and 100 keV.

### $\Gamma(\text{hydrogen-atom }\overline{\nu}_e)/\Gamma_{\text{total}}$ $\qquad\Gamma_3/\Gamma$

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|
| $<3\times10^{-2}$ | 95 | [1] GREEN | 90 | RVUE |

[1] GREEN 90 infers that $\tau(\text{hydrogen-atom}\overline{\nu}_e) > 3\times10^4$ s by comparing neutron lifetime measurements made in storage experiments with those made in $\beta$-decay experiments. However, the result depends sensitively on the lifetime measurements, and does not of course take into account more recent measurements of same.

### $\Gamma(p\nu_e\overline{\nu}_e)/\Gamma_{\text{total}}$ $\qquad\Gamma_4/\Gamma$

Forbidden by charge conservation.

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **$<8\times10^{-27}$** | 68 | [1] NORMAN | 96 | RVUE | ${}^{71}$Ga → ${}^{71}$Ge neutrals |

• • • We do not use the following data for averages, fits, limits, etc. • • •

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| $<9.7\times10^{-18}$ | 90 | ROY | 83 | CNTR | ${}^{113}$Cd → ${}^{113m}$In neut. |
| $<7.9\times10^{-21}$ | | VAIDYA | 83 | CNTR | ${}^{87}$Rb → ${}^{87m}$Sr neut. |
| $<9\times10^{-24}$ | 90 | BARABANOV | 80 | CNTR | ${}^{71}$Ga → ${}^{71}$GeX |
| $<3\times10^{-19}$ | | NORMAN | 79 | CNTR | ${}^{87}$Rb → ${}^{87m}$Sr neut. |

[1] NORMAN 96 gets this limit by attributing SAGE and GALLEX counting rates to the charge-nonconserving transition $^{71}$Ga → $^{71}$Ge+neutrals rather than to solar-neutrino reactions.

---

# A REVIEW GOES HERE – Check our WWW List of Reviews

---

## $n \to pe^- \overline{\nu}_e$ DECAY PARAMETERS

See the above "Note on Baryon Decay Parameters." For discussions of recent results, see the references cited at the beginning of the section on the neutron mean life. For discussions of the values of the weak coupling constants $g_A$ and $g_V$ obtained using the neutron lifetime and asymmetry parameter $A$, comparisons with other methods of obtaining these constants, and implications for particle physics and for astrophysics, see DUBBERS 91 and WOOLCOCK 91. For tests of the $V-A$ theory of neutron decay, see EROZOLIMSKII 91B, MOSTOVOI 96, NICO 05, SEVERIJNS 06, and ABELE 08.

### $\lambda \equiv g_A / g_V$

| *VALUE* | | | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|---|
| **−1.2723** | **±0.0023** | **OUR AVERAGE** | | | | Error includes scale factor of 2.2. See the ideogram below. |
| −1.2755 | ±0.0030 | | [1] MENDENHALL | 13 | UCNA | Ultracold *n*, polarized |
| −1.2748 | ±0.0008 | $^{+0.0010}_{-0.0011}$ | [2] MUND | 13 | SPEC | Cold *n*, polarized |
| −1.275 | ±0.006 | ±0.015 | SCHUMANN | 08 | CNTR | Cold *n*, polarized |
| −1.2686 | ±0.0046 | ±0.0007 | [3] MOSTOVOI | 01 | CNTR | *A* and *B* × polarizations |
| −1.266 | ±0.004 | | LIAUD | 97 | TPC | Cold *n*, polarized, *A* |
| −1.2594 | ±0.0038 | | [4] YEROZLIM... | 97 | CNTR | Cold *n*, polarized, *A* |
| −1.262 | ±0.005 | | BOPP | 86 | SPEC | Cold *n*, polarized, *A* |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | | |
| −1.27590 | ±0.00239 | $^{+0.00331}_{-0.00377}$ | [5] PLASTER | 12 | UCNA | See MENDENHALL 13 |
| −1.27590 | $^{+0.00409}_{-0.00445}$ | | LIU | 10 | UCNA | See PLASTER 12 |
| −1.2739 | ±0.0019 | | [6] ABELE | 02 | SPEC | See MUND 13 |
| −1.274 | ±0.003 | | ABELE | 97D | SPEC | Cold *n*, polarized, *A* |
| −1.266 | ±0.004 | | SCHRECK... | 95 | TPC | See LIAUD 97 |
| −1.2544 | ±0.0036 | | EROZOLIM... | 91 | CNTR | See YEROZOLIMSKY 97 |
| −1.226 | ±0.042 | | MOSTOVOY | 83 | RVUE | |
| −1.261 | ±0.012 | | EROZOLIM... | 79 | CNTR | Cold *n*, polarized, *A* |
| −1.259 | ±0.017 | | [7] STRATOWA | 78 | CNTR | *p* recoil spectrum, *a* |
| −1.263 | ±0.015 | | EROZOLIM... | 77 | CNTR | See EROZOLIMSKII 79 |
| −1.250 | ±0.036 | | [7] DOBROZE... | 75 | CNTR | See STRATOWA 78 |
| −1.258 | ±0.015 | | [8] KROHN | 75 | CNTR | Cold *n*, polarized, *A* |
| −1.263 | ±0.016 | | [9] KROPF | 74 | RVUE | *n* decay alone |
| −1.250 | ±0.009 | | [9] KROPF | 74 | RVUE | *n* decay + nuclear ft |

[1] MENDENHALL 13 gets $A = -0.11954 \pm 0.00055 \pm 0.00098$ and $\lambda = -1.2756 \pm 0.0030$. We quote the nearly identical values that include the earlier UCNA measurement (PLASTER 12), with a correction to that result.

[2] This MUND 13 value includes earlier PERKEO II measurements (ABELE 02 and ABELE 97D).

[3] MOSTOVOI 01 measures the two *P*-odd correlations *A* and *B*, or rather *SA* and *SB*, where *S* is the *n* polarization, in free neutron decay.

[4] YEROZOLIMSKY 97 makes a correction to the EROZOLIMSKII 91 value.

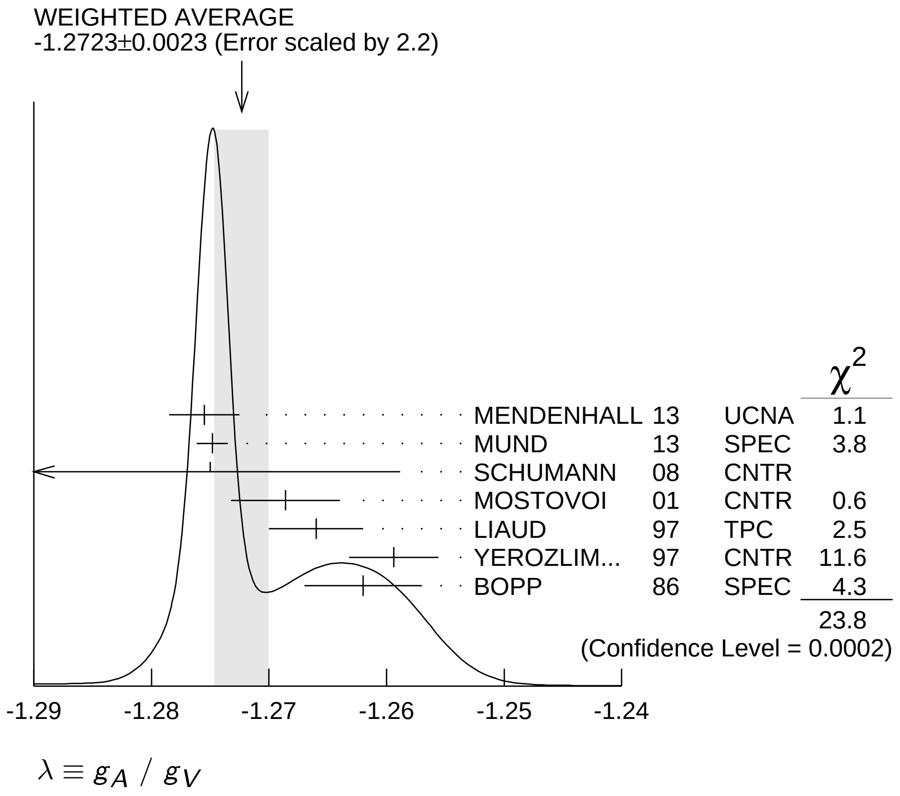
[5] This PLASTER 12 value is identical with that given in LIU 10, but the experiment is now described in detail.

[6] This is the combined result of ABELE 02 and ABELE 97D.

[7] These experiments measure the absolute value of $g_A/g_V$ only.

[8] KROHN 75 includes events of CHRISTENSEN 70.

[9] KROPF 74 reviews all data through 1972.



## $e^-$ ASYMMETRY PARAMETER *A*

This is the neutron-spin electron-momentum correlation coefficient. Unless otherwise noted, the values are corrected for radiative effects and weak magnetism. In the Standard Model, *A* is related to $\lambda \equiv g_A/g_V$ by $A = -2\,\lambda\,(\lambda + 1)\,/\,(1 + 3\lambda^2)$; this assumes that $g_A$ and $g_V$ are real.

| *VALUE* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **$-0.1184 \pm 0.0010$ OUR AVERAGE** | Error includes scale factor of 2.4. See the ideogram below. | | | |
| $-0.11952 \pm 0.00110$ | [1] MENDENHALL | 13 | UCNA | Ultracold *n*, polarized |
| $-0.11926 \pm 0.00031 {}^{+0.00036}_{-0.00042}$ | [2] MUND | 13 | SPEC | Cold *n*, polarized |
| $-0.1160 \pm 0.0009 \pm 0.0012$ | LIAUD | 97 | TPC | Cold *n*, polarized |
| $-0.1135 \pm 0.0014$ | [3] YEROZLIM... | 97 | CNTR | Cold *n*, polarized |
| $-0.1146 \pm 0.0019$ | BOPP | 86 | SPEC | Cold *n*, polarized |

• • • We do not use the following data for averages, fits, limits, etc. • • •

| | | | | |
|---|---|---|---|---|
| $-0.11966 \pm 0.00089 ^{+0.00123}_{-0.00140}$ | [4] PLASTER | 12 | UCNA | See MENDENHALL 13 |
| $-0.11966 \pm 0.00089 ^{+0.00123}_{-0.00140}$ | LIU | 10 | UCNA | See PLASTER 12 |
| $-0.1138 \pm 0.0046 \pm 0.0021$ | PATTIE | 09 | SPEC | Ultracold $n$, polarized |
| $-0.1189 \pm 0.0007$ | [5] ABELE | 02 | SPEC | See MUND 13 |
| $-0.1168 \pm 0.0017$ | [6] MOSTOVOI | 01 | CNTR | Inferred |
| $-0.1189 \pm 0.0012$ | ABELE | 97D | SPEC | Cold $n$, polarized |
| $-0.1160 \pm 0.0009 \pm 0.0011$ | SCHRECK... | 95 | TPC | See LIAUD 97 |
| $-0.1116 \pm 0.0014$ | EROZOLIM... | 91 | CNTR | See YEROZOLIMSKY 97 |
| $-0.114 \pm 0.005$ | [7] EROZOLIM... | 79 | CNTR | Cold $n$, polarized |
| $-0.113 \pm 0.006$ | [7] KROHN | 75 | CNTR | Cold $n$, polarized |

[1] MENDENHALL 13 gets $A = -0.11954 \pm 0.00055 \pm 0.00098$ and $\lambda = -1.2756 \pm 0.0030$. We quote the nearly identical values that include the earlier UCNA measurement (PLASTER 12), with a correction to that result.

[2] This MUND 13 value includes earlier PERKEO II measurements (ABELE 02 and ABELE 97D), with a correction to those results.

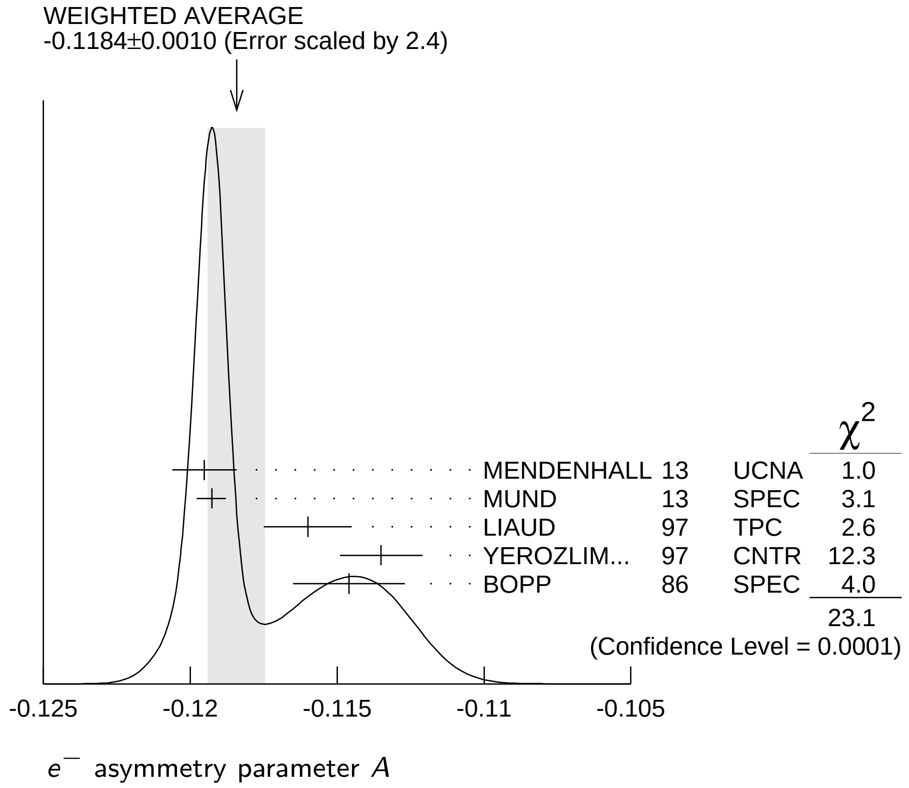
[3] YEROZOLIMSKY 97 makes a correction to the EROZOLIMSKII 91 value.

[4] This PLASTER 12 value is identical with that given in LIU 10, but the experiment is now described in detail.

[5] This is the combined result of ABELE 02 and ABELE 97D.

[6] MOSTOVOI 01 calculates this from its measurement of $\lambda = g_A/g_V$ above.

[7] These results are not corrected for radiative effects and weak magnetism, but the corrections are small compared to the errors.



## $\overline{\nu}_e$ ASYMMETRY PARAMETER *B*

This is the neutron-spin antineutrino-momentum correlation coefficient. In the Standard Model, *B* is related to $\lambda \equiv g_A/g_V$ by $B = 2\lambda(\lambda - 1) / (1 + 3\lambda^2)$; this assumes that $g_A$ and $g_V$ are real.

| *VALUE* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **0.9807±0.0030 OUR AVERAGE** | | | | |
| 0.9802±0.0034±0.0036 | SCHUMANN | 07 | CNTR | Cold *n*, polarized |
| 0.967 ±0.006 ±0.010 | KREUZ | 05 | CNTR | Cold *n*, polarized |
| 0.9801±0.0046 | SEREBROV | 98 | CNTR | Cold *n*, polarized |
| 0.9894±0.0083 | KUZNETSOV | 95 | CNTR | Cold *n*, polarized |
| 1.00 ±0.05 | CHRISTENSEN | 70 | CNTR | Cold *n*, polarized |
| 0.995 ±0.034 | EROZOLIM... | 70C | CNTR | Cold *n*, polarized |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 0.9876±0.0004 | [1] MOSTOVOI | 01 | CNTR | Inferred |

[1] MOSTOVOI 01 calculates this from its measurement of $\lambda = g_A/g_V$ above.

## PROTON ASYMMETRY PARAMETER *C*

Describes the correlation between the neutron spin and the proton momentum. In the Standard Model, *C* is related to $\lambda \equiv g_A/g_V$ by $C = -x_c\ (A + B) = x_c\ 4\lambda/(1 + 3\lambda^2)$, where $x_c = 0.27484$ is a kinematic factor; this assumes that $g_A$ and $g_V$ are real.

| *VALUE* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **−0.2377±0.0010±0.0024** | SCHUMANN | 08 | CNTR | Cold *n*, polarized |

## $e$-$\overline{\nu}_e$ ANGULAR CORRELATION COEFFICIENT *a*

For a review of past experiments and plans for future measurements of the *a* parameter, see WIETFELDT 05. In the Standard Model, *a* is related to $\lambda \equiv g_A/g_V$ by $a = (1 - \lambda^2) / (1 + 3\lambda^2)$; this assumes that $g_A$ and $g_V$ are real.

| *VALUE* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **−0.103 ±0.004 OUR AVERAGE** | | | | |
| −0.1054±0.0055 | BYRNE | 02 | SPEC | Proton recoil spectrum |
| −0.1017±0.0051 | STRATOWA | 78 | CNTR | Proton recoil spectrum |
| −0.091 ±0.039 | GRIGOREV | 68 | SPEC | Proton recoil spectrum |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| −0.1045±0.0014 | [1] MOSTOVOI | 01 | CNTR | Inferred |

[1] MOSTOVOI 01 calculates this from its measurement of $\lambda = g_A/g_V$ above.

## $\phi_{AV}$, PHASE OF $g_A$ RELATIVE TO $g_V$

Time reversal invariance requires this to be 0 or 180°. This is related to *D* given in the next data block and $\lambda \equiv g_A/g_V$ by $\sin(\phi_{AV}) \equiv D(1+3\lambda^2)/2|\lambda|$; this assumes that $g_A$ and $g_V$ are real.

| *VALUE* (°) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **180.017±0.026 OUR AVERAGE** | | | | | |
| 180.012±0.028 | 68 | CHUPP | 12 | CNTR | Cold *n*, polarized > 91% |
| 180.04 ±0.09 | | SOLDNER | 04 | CNTR | Cold *n*, polarized |
| 180.08 ±0.13 | | LISING | 00 | CNTR | Polarized > 93% |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| 180.013±0.028 | | MUMM | 11 | CNTR | See CHUPP 12 |
| 179.71 ±0.39 | | EROZOLIM... | 78 | CNTR | Cold *n*, polarized |
| 180.35 ±0.43 | | EROZOLIM... | 74 | CNTR | Cold *n*, polarized |
| 181.1 ±1.3 | | [1] KROPF | 74 | RVUE | *n* decay |
| 180.14 ±0.22 | | STEINBERG | 74 | CNTR | Cold *n*, polarized |

[1] KROPF 74 reviews all data through 1972.

## TRIPLE CORRELATION COEFFICIENT *D*

These are measurements of the component of *n* spin perpendicular to the decay plane in $\beta$ decay. Should be zero if *T* invariance is not violated.

| *VALUE* (units $10^{-4}$) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **$-$ 1.2 $\pm$ 2.0 OUR AVERAGE** | | | | |
| $-0.94 \pm 1.89 \pm 0.97$ | CHUPP | 12 | CNTR | Cold *n*, polarized $> 91\%$ |
| $-2.8 \pm 6.4 \pm 3.0$ | SOLDNER | 04 | CNTR | Cold *n*, polarized |
| $-6 \pm 12 \pm 5$ | LISING | 00 | CNTR | Polarized $> 93\%$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $-0.96 \pm 1.89 \pm 1.01$ | MUMM | 11 | CNTR | See CHUPP 12 |
| $+22 \pm 30$ | EROZOLIM... | 78 | CNTR | Cold *n*, polarized |
| $-27 \pm 50$ | [1] EROZOLIM... | 74 | CNTR | Cold *n*, polarized |
| $-11 \pm 17$ | STEINBERG | 74 | CNTR | Cold *n*, polarized |

[1] EROZOLIMSKII 78 says asymmetric proton losses and nonuniform beam polarization may give a systematic error up to $30 \times 10^{-4}$, thus increasing the EROZOLIMSKII 74 error to $50 \times 10^{-4}$. STEINBERG 74 and STEINBERG 76 estimate these systematic errors to be insignificant in their experiment.

## TRIPLE CORRELATION COEFFICIENT *R*

Another test of time-reversal invariance. *R* measures the polarization of the electron in the direction perpendicular to the plane defined by the neutron spin and the electron momentum. $R = 0$ for T invariance.

| *VALUE* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **$+0.004 \pm 0.012 \pm 0.005$** | [1] KOZELA | 12 | CNTR | Mott polarimeter |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $+0.008 \pm 0.015 \pm 0.005$ | KOZELA | 09 | CNTR | See KOZELA 12 |

[1] KOZELA 12 also measures the polarization of the electron along the direction of the neutron spin. This is nonzero in the Standard Model; the correlation coefficient is $N = +0.067 \pm 0.011 \pm 0.004$.

---

## *n* REFERENCES

We have omitted some papers that have been superseded by later experiments. See our earlier editions.

| | | | | |
|---|---|---|---|---|
| SAHOO | 17 | PR D95 013002 | B.K. Sahoo | (AHMEB) |
| BALES | 16 | PRL 116 242501 | M.J. Bales *et al.* | (RDK II Collab.) |
| MOHR | 16 | PMP 88 035009 | P.J. Mohr, D.B. Newell, B.N. Taylor | (NIST) |
| ABE | 15C | PR D91 072006 | K. Abe *et al.* | (Super-Kamiokande Collab.) |
| ARZUMANOV | 15 | PL B745 79 | S. Arzumanov *et al.* | (ILLG, KIAE) |
| PENDLEBURY | 15 | PR D92 092003 | J.M. Pendlebury *et al.* | (ETHZ, PSI, SUSS) |
| SEREBROV | 15 | PR C92 055501 | A.P. Serebrov *et al.* | (PNPI, ILLG, IOFF) |
| EPSTEIN | 14 | PR D90 074027 | Z. Epstein, G. Paz, J. Roy | (UMD, WAYN) |
| MYERS | 14 | PRL 113 262506 | L.S. Myers *et al.* | (COMPTON/MAX-lab Collab.) |
| SEREBROV | 14 | JETPL 99 4 | A.P. Serebrov *et al.* | (PNPI, ILL, IOFF) |
| MENDENHALL | 13 | PR C87 032501 | M.P. Mendenhall *et al.* | (UCNA Collab.) |
| MUND | 13 | PRL 110 172502 | D. Mund *et al.* | (HEID, ILLG) |
| YUE | 13 | PRL 111 222501 | A.T. Yue *et al.* | (UMD, NIST, TENN, ORNL+) |
| ARZUMANOV | 12 | JETPL 95 224<br>Translated from ZETFP 95 248. | S.S. Arzumanov *et al.* | (KIAE) |
| CHUPP | 12 | PR C86 035505 | T.E. Chupp *et al.* | (MICH, UCB, WASH+) |
| GRIESSHAM... | 12 | PPNP 67 841 | H.W. Griesshammer *et al.* | (GWU, MCHS+) |
| KOZELA | 12 | PR C85 045501 | A. Kozela *et al.* | (nTRV Collab.) |
| MOHR | 12 | RMP 84 1527 | P.J. Mohr, B.N. Taylor, D.B. Newell | (NIST) |
| PLASTER | 12 | PR C86 055501 | B. Plaster *et al.* | (UCNA Collab.) |

| | | | | |
|---|---|---|---|---|
| STEYERL | 12 | PR C85 065503 | A. Steyerl *et al.* | (URI, SUSS) |
| BRESSI | 11 | PR A83 052101 | G. Bressi *et al.* | (LEGN, PAVII, PADO, TRST+) |
| DUBBERS | 11 | RMP 83 1111 | D. Dubbers, M.G. Schmidt | (HEID) |
| MUMM | 11 | PRL 107 102301 | H.P. Mumm *et al.* | (NIST, WASH, MICH, LBL+) |
| WIETFELDT | 11 | RMP 83 1173 | F.E. Wietfeldt, G.L. Greene | (TULA, TENN) |
| COOPER | 10 | PR C81 035503 | R.L. Cooper *et al.* | (MICH, NIST, TULA+) |
| LIU | 10 | PRL 105 181803 | J. Liu *et al.* | (UCNA Collab.) |
| Also | | PRL 105 219903 (errat.) | J. Liu *et al.* | (UCNA Collab.) |
| PICHLMAIER | 10 | PL B693 221 | A. Pichlmaier *et al.* | (MUNT, PNPI, ILLG) |
| ALTAREV | 09A | PR D80 032003 | I. Altarev *et al.* | (MUNT, RAL, CAEN+) |
| KOZELA | 09 | PRL 102 172301 | A. Kozela *et al.* | (JAGL, CRAC, PSI, CAEN+) |
| LAMOREAUX | 09 | JP G36 104002 | S.K. Lamoreaux, R. Golub | (YALE, NCSU) |
| MOHAPATRA | 09 | JP G36 104006 | R.N. Mohapatra | (UMD) |
| PATTIE | 09 | PRL 102 012301 | R.W. Pattie Jr. *et al.* | (Los Alamos UCNA Collab.) |
| ABELE | 08 | PPNP 60 1 | H. Abele | (HEID) |
| MOHR | 08 | RMP 80 633 | P.J. Mohr, B.N. Taylor, D.B. Newell | (NIST) |
| SCHUMANN | 08 | PRL 100 151801 | M. Schumann *et al.* | (HEID, ILLG, KARL+) |
| SEREBROV | 08 | PL B663 181 | A.P. Serebrov *et al.* | (PNPI, IOFF, ILLG+) |
| BAKER | 07 | PRL 98 149102 | C.A. Baker *et al.* | (RAL, SUSS, ILLG) |
| BAN | 07 | PRL 99 161603 | G. Ban *et al.* | (CAEN, JAGL, PSI, JINR+) |
| BELUSHKIN | 07 | PR C75 035202 | M.A. Belushkin, H.W. Hammer, U.-G. Meissner | (BONN+) |
| LAMOREAUX | 07 | PRL 98 149101 | S.K. Lamoreaux, R. Golub | (YALE, NCSU) |
| SCHUMANN | 07 | PRL 99 191803 | M. Schumann *et al.* | (HEID, ILLG, KARL+) |
| SILENKO | 07 | PPNL 4 468 | A.Ya. Silenko | (Belarussian U.) |
| | | Translated from PFECAY 6 784. | | |
| BAKER | 06 | PRL 97 131801 | C.A. Baker *et al.* | (RAL, SUSS, ILLG) |
| BEREZHIANI | 06 | PRL 96 081801 | Z. Berezhiani, L. Bento | (Aguila U., LISB) |
| NICO | 06 | NAT 444 1059 | J.S. Nico *et al.* | (NIST, TULN, MICH, UMD+) |
| SEVERIJNS | 06 | RMP 78 991 | N. Severijns, M. Beck, O. Naviliat-Cuncic | (LEUV+) |
| KREUZ | 05 | PL B619 263 | M. Kreuz *et al.* | (HEID, ILLG, MANZ, KARL+) |
| MOHR | 05 | RMP 77 1 | P.J. Mohr, B.N. Taylor | (NIST) |
| NICO | 05 | PR C71 055502 | J.S. Nico *et al.* | (NIST, TULN, IND, TENN+) |
| SCHUMACHER | 05 | PPNP 55 567 | M. Schumacher | (GOET) |
| SEREBROV | 05 | PL B605 72 | A. Serebrov *et al.* | (PNPI, JINR, ILLG) |
| Also | | SPU 48 867 | A.P. Serebrov *et al.* | (PPNI, JINR, ILLG) |
| | | Translated from UFN 175 905. | | |
| WIETFELDT | 05 | MPL A20 1783 | F.E. Wietfeldt | (TULN) |
| SOLDNER | 04 | PL B581 49 | T. Soldner *et al.* | (ILLG, MUNT) |
| DEWEY | 03 | PRL 91 152302 | M.S. Dewey *et al.* | (NIST, TULN, IND+) |
| KOSSERT | 03 | EPJ A16 259 | K. Kossert *et al.* | (Mainz MAMI Collab.) |
| Also | | PRL 88 162301 | K. Kossert *et al.* | (Mainz MAMI Collab.) |
| LUNDIN | 03 | PRL 90 192501 | M. Lundin *et al.* | |
| ABELE | 02 | PRL 88 211801 | H. Abele *et al.* | (PERKEO-II Collab.) |
| BECK | 02 | JETPL 76 332 | M. Beck *et al.* | (LEUV, SUSS, KIAE, PNPI) |
| | | Translated from ZETFP 76 392. | | |
| BYRNE | 02 | JP G28 1325 | J. Byrne *et al.* | |
| CHUNG | 02B | PR D66 032004 | J. Chung *et al.* | (SOUDAN-2 Collab.) |
| MOSTOVOI | 01 | PAN 64 1955 | Yu.A. Mostovoi *et al.* | |
| | | Translated from YAF 64 2040. | | |
| ARZUMANOV | 00 | PL B483 15 | S. Arzumanov *et al.* | |
| GAL | 00 | PR C61 028201 | A. Gal | |
| KOLB | 00 | PRL 85 1388 | N.R. Kolb *et al.* | |
| LAMOREAUX | 00 | PR D61 051301 | S.K. Lamoreaux, R. Golub | |
| LEVCHUK | 00 | NP A674 449 | M.I. Levchuk, A.I. L'vov | (BELA, LEBD) |
| LISING | 00 | PR C62 055501 | L.J. Lising *et al.* | (NIST emiT Collab.) |
| HARRIS | 99 | PRL 82 904 | P.G. Harris *et al.* | |
| KESSLER | 99 | PL A255 221 | E.G. Kessler Jr *et al.* | |
| MOHR | 99 | JPCRD 28 1713 | P.J. Mohr, B.N. Taylor | (NIST) |
| Also | | RMP 72 351 | P.J. Mohr, B.N. Taylor | (NIST) |
| SEREBROV | 98 | JETP 86 1074 | A.P. Serebrov *et al.* | |
| | | Translated from ZETF 113 1963. | | |
| ABELE | 97D | PL B407 212 | H. Abele *et al.* | (HEIDP, ILLG) |
| KOPECKY | 97 | PR C56 2229 | S. Kopecky *et al.* | |
| LIAUD | 97 | NP A612 53 | P. Liaud *et al.* | (ILLG, LAPP) |
| YEROZLIM... | 97 | PL B412 240 | B.G. Erozolimsky *et al.* | (HARV, PNPI, KIAE) |
| ALTAREV | 96 | PAN 59 1152 | I.S. Altarev *et al.* | (PNPI) |
| | | Translated from YAF 59 1204. | | |
| BONDAREN... | 96 | JETPL 64 416 | L.N. Bondarenko *et al.* | (KIAE) |
| | | Translated from ZETFP 64 382. | | |
| BYRNE | 96 | EPL 33 187 | J. Byrne *et al.* | (SUSS, ILLG) |
| MOSTOVOI | 96 | PAN 59 968 | Y.A. Mostovoy | (KIAE) |
| | | Translated from YAF 59 1013. | | |

NORMAN 96 PR D53 4086 E.B. Norman, J.N. Bahcall, M. Goldhaber (LBL+)
IGNATOVICH 95 JETPL 62 1 V.K. Ignatovich (JINR)
Translated from ZETFP 62 3.
KOESTER 95 PR C51 3363 L. Koester *et al.* (MUNT, JINR, LATV)
KOPECKY 95 PRL 74 2427 S. Kopecky *et al.*
KUZNETSOV 95 PRL 75 794 I.A. Kuznetsov *et al.* (PNPI, KIAE, HARV+)
SCHRECK... 95 PL B349 427 K. Schreckenbach *et al.* (MUNT, ILLG, LAPP)
BALDO-... 94 ZPHY C63 409 M. Baldo-Ceolin *et al.* (HEID, ILLG, PADO+)
DIFILIPPO 94 PRL 73 1481 F. DiFilippo *et al.* (MIT)
Also PRL 71 1998 V. Natarajan *et al.* (MIT)
GOLUB 94 PRPL 237C 1 R. Golub, K. Lamoreaux (HAHN, WASH)
MAMPE 93 JETPL 57 82 B. Mampe *et al.* (KIAE)
Translated from ZETFP 57 77.
ALTAREV 92 PL B276 242 I.S. Altarev *et al.* (PNPI)
NESVIZHEV... 92 JETP 75 405 V.V. Nesvizhevsky *et al.* (PNPI, JINR)
Translated from ZETF 102 740.
ALBERICO 91 NP A523 488 W.M. Alberico, A. de Pace, M. Pignone (TORI)
DUBBERS 91 NP A527 239c D. Dubbers (ILLG)
Also EPL 11 195 D. Dubbers, W. Mampe, J. Dohner (ILLG, HEID)
EROZOLIM... 91 PL B263 33 B.G. Erozolimsky *et al.* (PNPI, KIAE)
Also SJNP 52 999 B.G. Erozolimsky *et al.* (PNPI, KIAE)
Translated from YAF 52 1583.
EROZOLIM... 91B SJNP 53 260 B.G. Erozolimsky, Y.A. Mostovoy (KIAE)
Translated from YAF 53 418.
SCHMIEDM... 91 PRL 66 1015 J. Schmiedmayer *et al.* (TUW, ORNL)
WOOLCOCK 91 MPL A6 2579 W.S. Woolcock (CANB)
ALFIMENKOV 90 JETPL 52 373 V.P. Alfimenkov *et al.* (PNPI, JINR)
Translated from ZETFP 52 984.
BALDO-... 90 PL B236 95 M. Baldo-Ceolin *et al.* (PADO, PAVI, HEIDP+)
BERGER 90 PL B240 237 C. Berger *et al.* (FREJUS Collab.)
BRESSI 90 NC 103A 731 G. Bressi *et al.* (PAVI, ROMA, MILA)
BYRNE 90 PRL 65 289 J. Byrne *et al.* (SUSS, NBS, SCOT, CBNM)
GREEN 90 JP G16 L75 K. Green, D. Thompson (RAL)
RAMSEY 90 ARNPS 40 1 N.F. Ramsey (HARV)
ROSE 90 PL B234 460 K.W. Rose *et al.* (GOET, MPCM, MANZ)
ROSE 90B NP A514 621 K.W. Rose *et al.* (GOET, MPCM)
SMITH 90 PL B234 191 K.F. Smith *et al.* (SUSS, RAL, HARV+)
BRESSI 89 ZPHY C43 175 G. Bressi *et al.* (INFN, MILA, PAVI, ROMA)
DOVER 89 NIM A284 13 C.B. Dover, A. Gal, J.M. Richard (BNL, HEBR+)
KOSSAKOW... 89 NP A503 473 R. Kossakowski *et al.* (LAPP, SAVO, ISNG+)
MAMPE 89 PRL 63 593 W. Mampe *et al.* (ILLG, RISL, SUSS, URI)
MOHAPATRA 89 NIM A284 1 R.N. Mohapatra (UMD)
PAUL 89 ZPHY C45 25 W. Paul *et al.* (BONN, WUPP, MPIH, ILLG)
SCHMIEDM... 89 NIM A284 137 J. Schmiedmayer, H. Rauch, P. Riehs (WIEN)
BAUMANN 88 PR D37 3107 J. Baumann *et al.* (BAYR, MUNI, ILLG)
KOESTER 88 ZPHY A329 229 L. Koester, W. Waschkowski, J. Meier (MUNI, MUNT)
LAST 88 PRL 60 995 I. Last *et al.* (HEIDP, ILLG, ANL)
SCHMIEDM... 88 PRL 61 1065 J. Schmiedmayer, H. Rauch, P. Riehs (TUW)
Also PRL 61 2509 (erratum) J. Schmiedmayer, H. Rauch, P. Riehs (TUW)
SPIVAK 88 JETP 67 1735 P.E. Spivak (KIAE)
Translated from ZETF 94 1.
COHEN 87 RMP 59 1121 E.R. Cohen, B.N. Taylor (RISC, NBS)
ALEKSANDR... 86 SJNP 44 900 Yu.A. Aleksandrov *et al.*
Translated from YAF 44 1384.
ALTAREV 86 JETPL 44 460 I.S. Altarev *et al.* (PNPI)
Translated from ZETFP 44 360.
BOPP 86 PRL 56 919 P. Bopp *et al.* (HEIDP, ANL, ILLG)
Also ZPHY C37 179 E. Klempt *et al.* (HEIDP, ANL, ILLG)
CRESTI 86 PL B177 206 M. Cresti *et al.* (PADO)
Also PL B200 587 (erratum) M. Cresti *et al.* (PADO)
GREENE 86 PRL 56 819 G.L. Greene *et al.* (NBS, ILLG)
KOESTER 86 Physica B137 282 L. Koester *et al.*
KOSVINTSEV 86 JETPL 44 571 Y.Y. Kosvintsev, V.I. Morozov, G.I. Terekhov (KIAE)
Translated from ZETFP 44 444.
TAKITA 86 PR D34 902 M. Takita *et al.* (KEK, TOKY+)
DOVER 85 PR C31 1423 C.B. Dover, A. Gal, J.M. Richard (BNL)
FIDECARO 85 PL 156B 122 G. Fidecaro *et al.* (CERN, ILLG, PADO+)
PARK 85B NP B252 261 H.S. Park *et al.* (IMB Collab.)
BATTISTONI 84 PL 133B 454 G. Battistoni *et al.* (NUSEX Collab.)
JONES 84 PRL 52 720 T.W. Jones *et al.* (IMB Collab.)
PENDLEBURY 84 PL 136B 327 J.M. Pendlebury *et al.* (SUSS, HARV, RAL+)
CHERRY 83 PRL 50 1354 M.L. Cherry *et al.* (PENN, BNL)
DOVER 83 PR D27 1090 C.B. Dover, A. Gal, J.M. Richard (BNL)

| | | | | |
|---|---|---|---|---|
| KABIR | 83 | PRL 51 231 | P.K. Kabir | (HARV) |
| MOSTOVOY | 83 | JETPL 37 196 | Y.A. Mostovoy | (KIAE) |
| | | Translated from ZETFP 37 162. | | |
| ROY | 83 | PR D28 1770 | A. Roy *et al.* | (TATA) |
| VAIDYA | 83 | PR D27 486 | S.C. Vaidya *et al.* | (TATA) |
| GAEHLER | 82 | PR D25 2887 | R. Gahler, J. Kalus, W. Mampe | (BAYR, ILLG) |
| GREENE | 82 | Metrologia 18 93 | G.L. Greene *et al.* | (YALE, HARV, ILLG+) |
| ALTAREV | 81 | PL 102B 13 | I.S. Altarev *et al.* | (PNPI) |
| BARABANOV | 80 | JETPL 32 359 | I.R. Barabanov *et al.* | (PNPI) |
| | | Translated from ZETFP 32 384. | | |
| BYRNE | 80 | PL 92B 274 | J. Byrne *et al.* | (SUSS, RL) |
| KOSVINTSEV | 80 | JETPL 31 236 | Y.Y. Kosvintsev *et al.* | (JINR) |
| | | Translated from ZETFP 31 257. | | |
| MOHAPATRA | 80 | PRL 44 1316 | R.N. Mohapatra, R.E. Marshak | (CUNY, VPI) |
| ALTAREV | 79 | JETPL 29 730 | I.S. Altarev *et al.* | (PNPI) |
| | | Translated from ZETFP 29 794. | | |
| EROZOLIM... | 79 | SJNP 30 356 | B.G. Erozolimsky *et al.* | (KIAE) |
| | | Translated from YAF 30 692. | | |
| NORMAN | 79 | PRL 43 1226 | E.B. Norman, A.G. Seamster | (WASH) |
| BONDAREN... | 78 | JETPL 28 303 | L.N. Bondarenko *et al.* | (KIAE) |
| | | Translated from ZETFP 28 328. | | |
| Also | | Smolenice Conf. | P.G. Bondarenko | (KIAE) |
| EROZOLIM... | 78 | SJNP 28 48 | B.G. Erozolimsky *et al.* | (KIAE) |
| | | Translated from YAF 28 98. | | |
| STRATOWA | 78 | PR D18 3970 | C. Stratowa, R. Dobrozemsky, P. Weinzierl | (SEIB) |
| EROZOLIM... | 77 | JETPL 23 663 | B.G. Erozolimsky *et al.* | (KIAE) |
| | | Translated from ZETFP 23 720. | | |
| KOESTER | 76 | PRL 36 1021 | L. Koester *et al.* | |
| STEINBERG | 76 | PR D13 2469 | R.I. Steinberg *et al.* | (YALE, ISNG) |
| DOBROZE... | 75 | PR D11 510 | R. Dobrozemsky *et al.* | (SEIB) |
| KROHN | 75 | PL 55B 175 | V.E. Krohn, G.R. Ringo | (ANL) |
| EROZOLIM... | 74 | JETPL 20 345 | B.G. Erozolimsky *et al.* | |
| | | Translated from ZETFP 20 745. | | |
| KROPF | 74 | ZPHY 267 129 | H. Kropf, E. Paul | (LINZ) |
| Also | | NP A154 160 | H. Paul | (VIEN) |
| STEINBERG | 74 | PRL 33 41 | R.I. Steinberg *et al.* | (YALE, ISNG) |
| COHEN | 73 | JPCRD 2 664 | E.R. Cohen, B.N. Taylor | (RISC, NBS) |
| KROHN | 73 | PR D8 1305 | V.E. Krohn, G.R. Ringo | |
| CHRISTENSEN | 72 | PR D5 1628 | C.J. Christensen *et al.* | (RISO) |
| CHRISTENSEN | 70 | PR C1 1693 | C.J. Christensen, V.E. Krohn, G.R. Ringo | (ANL) |
| EROZOLIM... | 70C | PL 33B 351 | B.G. Erozolimsky *et al.* | (KIAE) |
| GRIGOREV | 68 | SJNP 6 239 | V.K. Grigoriev *et al.* | (ITEP) |
| | | Translated from YAF 6 329. | | |
| KROHN | 66 | PR 148 1303 | V.E. Krohn, G.R. Ringo | |
| LEE | 56 | PR 104 254 | T.D. Lee, C.N. Yang | (COLU, BNL) |