# $n$

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

We have omitted some results that have been superseded by later experiments.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

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

The mass is known much more precisely in u (atomic mass units) than in MeV. The conversion from u to MeV, 1 u = 931.494013±0.000037 MeV/$c^2$ (MOHR 99, the 1998 CODATA value), involves the relatively poorly known electronic charge.

| *VALUE* (u) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **1.00866491578±0.00000000055** | MOHR | 99 | RVUE | 1998 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 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; see the previous data block. The conversion from u to MeV, 1 u = 931.494013±0.000037 MeV/$c^2$ (MOHR 99, the 1998 CODATA value), involves the relatively poorly known electronic charge.

| *VALUE* (MeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **939.565330±0.000038** | MOHR | 99 | RVUE | 1998 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 939.565331±0.000037 | [1] KESSLER | 99 | SPEC | $np \to d\gamma$ |
| 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 | $np \to d\gamma$ |
| 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 ± 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 ± 0.000000014 u.

## $\overline{n}$ MASS

| *VALUE* (MeV) | *EVTS* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **939.485±0.051** | 59 | [5] CRESTI | 86 | HBC | $\overline{p}p \to \overline{n}n$ |

[5] 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* |
|---|---|
| **$(9\pm5) \times 10^{-5}$ OUR EVALUATION** | |

## $m_n - m_p$

| *VALUE* (MeV) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **1.2933318±0.0000005** | [6] MOHR | 99 | RVUE | 1998 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 1.293318 ±0.000009 | [7] COHEN | 87 | RVUE | 1986 CODATA value |
| 1.2933328±0.0000072 | GREENE | 86 | SPEC | $np \to d\gamma$ |
| 1.293429 ±0.000036 | COHEN | 73 | RVUE | 1973 CODATA value |

[6] 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.

[7] 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

We now compile only direct measurements of the lifetime, not those inferred from decay correlation measurements. For the average, we only use measurements with an error less than 10 s.

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

For an early review, see EROZOLIMSKII 89 and papers that follow it in an issue of NIM devoted to the "Proceedings of the International Workshop on Fundamental Physics with Slow Neutrons" (Grenoble 1989). For later reviews and/or commentary, see FREEDMAN 90, SCHRECKENBACH 92, and PENDLEBURY 93.

| *VALUE* (s) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **885.7± 0.8 OUR AVERAGE** | | | | |
| 885.4± 0.9± 0.4 | ARZUMANOV | 00 | CNTR | UCN double bottle |
| 889.2± 3.0± 3.8 | BYRNE | 96 | CNTR | Penning trap |
| 882.6± 2.7 | [8] MAMPE | 93 | CNTR | Gravitational trap |
| 888.4± 3.1± 1.1 | NESVIZHEV... | 92 | CNTR | Gravitational trap |
| 887.6± 3.0 | MAMPE | 89 | CNTR | Gravitational trap |
| 891 ± 9 | SPIVAK | 88 | CNTR | Beam |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 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 |
| 877 ±10 | PAUL | 89 | CNTR | Storage ring |
| 876 ±10 ±19 | LAST | 88 | SPEC | Pulsed beam |

| | | | | | |
|---|---|---|---|---|---|
| 903 ±13 | KOSVINTSEV | 86 | CNTR | Gravitational trap |
| 937 ±18 | [9] BYRNE | 80 | CNTR | |
| 875 ±95 | KOSVINTSEV | 80 | CNTR | |
| 881 ± 8 | BONDAREN... | 78 | CNTR | See SPIVAK 88 |
| 918 ±14 | CHRISTENSEN | 72 | CNTR | |

[8] 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.

[9] This 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* |
|---|---|---|---|---|
| **−1.91304272±0.00000045** | MOHR | 99 | RVUE | 1998 CODATA value |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| −1.91304275±0.00000045 | COHEN | 87 | RVUE | 1986 CODATA value |
| −1.91304277±0.00000048 | [10] GREENE | 82 | MRS | |

[10] 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 and GOLUB 94 for reviews.

| *VALUE* ($10^{-25}$ e cm) | *CL%* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|---|
| **< 0.63** | 90 | [11] HARRIS | 99 | MRS | $d = (-0.1 \pm 0.36) \times 10^{-25}$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| < 0.97 | 90 | ALTAREV | 96 | MRS | $(+0.26 \pm 0.40 \pm 0.16) \times 10^{-25}$ |
| < 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 ±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 | $d = (4.0 \pm 7.5) \times 10^{-25}$ |

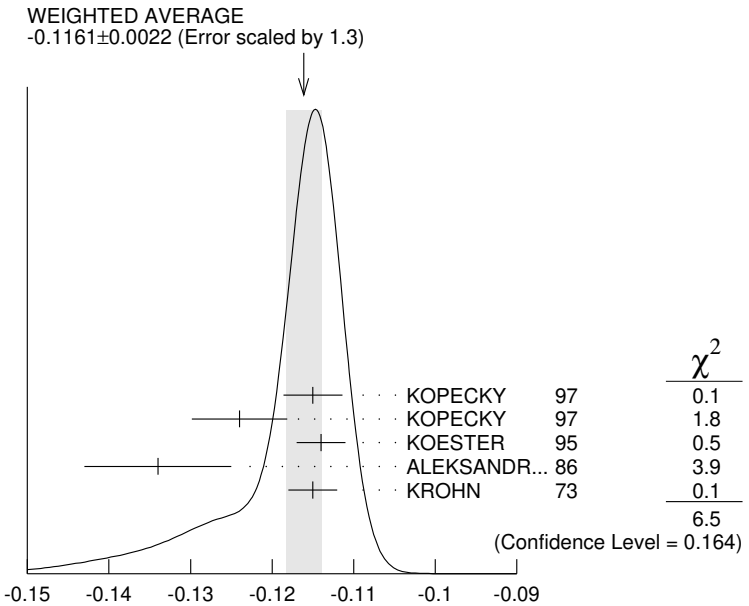
[11] This HARRIS 99 result includes the result of SMITH 90. However, the averaging of the results of these two experiments has been criticized by LAMOREAUX 00.

## *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* |
|---|---|---|---|---|
| **$-0.1161 \pm 0.0022$ 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) |
| $-0.115 \pm 0.003$ | [12] | KROHN | 73 | $ne$ scattering (Ne, Ar, Kr, Xe) |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $-0.113 \pm 0.003 \pm 0.004$ | | 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) |

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




*n* mean-square charge radius

## *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.

| *VALUE* ($10^{-4}$ fm$^3$) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **$9.8^{+\ 1.9}_{-\ 2.3}$ OUR AVERAGE** | Error includes scale factor of 1.1. | | | |
| $0.0 \pm 5.0$ | [13] KOESTER | 95 | CNTR | *n* Pb, *n* Bi transmission |
| $12.0 \pm 1.5 \pm 2.0$ | SCHMIEDM... | 91 | CNTR | *n* Pb transmission |
| $10.7^{+\ 3.3}_{-10.7}$ | ROSE | 90B | CNTR | $\gamma d \rightarrow \gamma np$ |
| $8 \pm 10$ | KOESTER | 88 | CNTR | *n* Pb, *n* Bi transmission |
| $12 \pm 10$ | SCHMIEDM... | 88 | CNTR | *n* Pb, *n* C transmission |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 13.6 | [14] KOLB | 00 | CNTR | $\gamma d \rightarrow \gamma np$ |
| $11.7^{+\ 4.3}_{-11.7}$ | ROSE | 90 | CNTR | See ROSE 90B |

[13] 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.

[14] 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$^3$.

## *n* MAGNETIC POLARIZABILITY $\beta_n$

| *VALUE* ($10^{-4}$ fm$^3$) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| 1.6 | [15] KOLB | 00 | CNTR | $\gamma d \rightarrow \gamma np$ |

[15] 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* |
|---|---|---|---|---|
| **$-$ 0.4 $\pm$ 1.1** | [16] BAUMANN | 88 | | Cold *n* deflection |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $-15 \pm 22$ | [17] GAEHLER | 82 | CNTR | Cold *n* deflection |

[16] The BAUMANN 88 error $\pm 1.1$ gives the 68% CL limits about the the value $-0.4$.

[17] The GAEHLER 82 error $\pm 22$ 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 $\Delta B=2$ 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.

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

## $n$ DECAY MODES

| | Mode | Fraction ($\Gamma_i/\Gamma$) | Confidence level |
|---|---|---|---|
| $\Gamma_1$ | $p e^- \overline{\nu}_e$ | 100 % | |
| $\Gamma_2$ | hydrogen-atom $\overline{\nu}_e$ | | |
| | **Charge conservation ($Q$) violating mode** | | |
| $\Gamma_3$ | $p \nu_e \overline{\nu}_e$ | $Q$ $<$ $8 \times 10^{-27}$ | 68% |

## $n$ BRANCHING RATIOS

### $\Gamma$(hydrogen-atom $\overline{\nu}_e$)/$\Gamma_{\text{total}}$ $\Gamma_2/\Gamma$

| *VALUE* | *CL%* | *DOCUMENT ID* | | *TECN* |
|---|---|---|---|---|
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $<3 \times 10^{-2}$ | 95 | [18] GREEN | 90 | RVUE |

[18] GREEN 90 infers that $\tau$(hydrogen-atom $\overline{\nu}_e$) $> 3 \times 10^4$ 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.

**$\Gamma(p\nu_e\overline{\nu}_e)/\Gamma_{\rm total}$** **$\Gamma_3/\Gamma$**

Forbidden by charge conservation.

| VALUE | CL% | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|---|
| **<8 $\times 10^{-27}$** | 68 | [19] NORMAN | 96 | RVUE | $^{71}$Ga $\rightarrow$ $^{71}$Ge neutrals |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | | |
| $<9.7 \times 10^{-18}$ | 90 | ROY | 83 | CNTR | $^{113}$Cd $\rightarrow$ $^{113m}$In neut. |
| $<7.9 \times 10^{-21}$ | | VAIDYA | 83 | CNTR | $^{87}$Rb $\rightarrow$ $^{87m}$Sr neut. |
| $<9 \times 10^{-24}$ | 90 | BARABANOV | 80 | CNTR | $^{71}$Ga $\rightarrow$ $^{71}$Ge X |
| $<3 \times 10^{-19}$ | | NORMAN | 79 | CNTR | $^{87}$Rb $\rightarrow$ $^{87m}$Sr neut. |

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

## BARYON DECAY PARAMETERS

Written 1996 by E.D. Commins (University of California, Berkeley).

### *Baryon semileptonic decays*

The typical spin-1/2 baryon semileptonic decay is described by a matrix element, the hadronic part of which may be written as:

$$\overline{B}_f \left[ f_1(q^2)\gamma_\lambda + i\ f_2(q^2)\sigma_{\lambda\mu}q^\mu + g_1(q^2)\gamma_\lambda\gamma_5 + g_3(q^2)\gamma_5 q_\lambda \right] B_i \ . \tag{1}$$

Here $B_i$ and $\overline{B}_f$ are spinors describing the initial and final baryons, and $q = p_i - p_f$, while the terms in $f_1$, $f_2$, $g_1$, and $g_3$ account for vector, induced tensor ("weak magnetism"), axial vector, and induced pseudoscalar contributions [1]. Second-class current contributions are ignored here. In the limit of zero momentum transfer, $f_1$ reduces to the vector coupling constant $g_V$, and $g_1$ reduces to the axial-vector coupling constant $g_A$. The latter coefficients are related by Cabibbo's theory [2], generalized to six quarks (and three mixing angles) by Kobayashi and Maskawa [3]. The $g_3$ term is negligible for transitions in which an $e^\pm$ is emitted, and gives a very small correction, which can be estimated by PCAC [4], for $\mu^\pm$ modes. Recoil effects include

weak magnetism, and are taken into account adequately by considering terms of first order in

$$\delta = \frac{m_i - m_f}{m_i + m_f} \ , \tag{2}$$

where $m_i$ and $m_f$ are the masses of the initial and final baryons.

The experimental quantities of interest are the total decay rate, the lepton-neutrino angular correlation, the asymmetry coefficients in the decay of a polarized initial baryon, and the polarization of the decay baryon in its own rest frame for an unpolarized initial baryon. Formulae for these quantities are derived by standard means [5] and are analogous to formulae for nuclear beta decay [6]. We use the notation of Ref. 6 in the Listings for neutron beta decay. For comparison with experiments at higher $q^2$, it is necessary to modify the form factors at $q^2 = 0$ by a "dipole" $q^2$ dependence, and for high-precision comparisons to apply appropriate radiative corrections [7].

The ratio $g_A/g_V$ may be written as

$$g_A/g_V = \, | \, g_A/g_V \, | \, e^{i\phi_{AV}} \ . \tag{3}$$

The presence of a "triple correlation" term in the transition probability, proportional to $\mathrm{Im}(g_A/g_V)$ and of the form

$$\boldsymbol{\sigma}_i \cdot (\mathbf{p}_\ell \times \mathbf{p}_\nu) \tag{4}$$

for initial baryon polarization or

$$\boldsymbol{\sigma}_f \cdot (\mathbf{p}_\ell \times \mathbf{p}_\nu) \tag{5}$$

for final baryon polarization, would indicate failure of time-reversal invariance. The phase angle $\phi$ has been measured precisely only in neutron decay (and in $^{19}$Ne nuclear beta decay), and the results are consistent with $T$ invariance.

***Hyperon nonleptonic decays***

The amplitude for a spin-1/2 hyperon decaying into a spin-1/2 baryon and a spin-0 meson may be written in the form

$$M = G_F\, m_\pi^2 \cdot \overline{B}_f\,(A - B\gamma_5)\,B_i\ , \tag{6}$$

where $A$ and $B$ are constants [1]. The transition rate is proportional to

$$\begin{aligned} R = {} & 1 + \gamma\,\widehat{\boldsymbol{\omega}}_f \cdot \widehat{\boldsymbol{\omega}}_i + (1-\gamma)(\widehat{\boldsymbol{\omega}}_f \cdot \widehat{\mathbf{n}})(\widehat{\boldsymbol{\omega}}_i \cdot \widehat{\mathbf{n}}) \\ & + \alpha(\widehat{\boldsymbol{\omega}}_f \cdot \widehat{\mathbf{n}} + \widehat{\boldsymbol{\omega}}_i \cdot \widehat{\mathbf{n}}) + \beta\widehat{\mathbf{n}} \cdot (\widehat{\boldsymbol{\omega}}_f \times \widehat{\boldsymbol{\omega}}_i)\ , \end{aligned} \tag{7}$$

where $\widehat{\mathbf{n}}$ is a unit vector in the direction of the final baryon momentum, and $\widehat{\boldsymbol{\omega}}_i$ and $\widehat{\boldsymbol{\omega}}_f$ are unit vectors in the directions of the initial and final baryon spins. (The sign of the last term in the above equation was incorrect in our 1988 and 1990 editions.) The parameters $\alpha$, $\beta$, and $\gamma$ are defined as

$$\begin{aligned} \alpha &= 2\,\mathrm{Re}(s^* p)/(\,|\,s\,|^2 + \,|\,p\,|^2)\ , \\ \beta &= 2\,\mathrm{Im}(s^* p)/(\,|\,s\,|^2 + \,|\,p\,|^2)\ , \\ \gamma &= (\,|\,s\,|^2 - \,|\,p\,|^2)/(\,|\,s\,|^2 + \,|\,p\,|^2)\ , \end{aligned} \tag{8}$$

where $s = A$ and $p = \,|\,\mathbf{p}_f\,|\,B/(E_f + m_f)$; here $E_f$ and $\mathbf{p}_f$ are the energy and momentum of the final baryon. The parameters $\alpha$, $\beta$, and $\gamma$ satisfy

$$\alpha^2 + \beta^2 + \gamma^2 = 1\ . \tag{9}$$

If the hyperon polarization is $\mathbf{P}_Y$, the polarization $\mathbf{P}_B$ of the decay baryons is

$$\mathbf{P}_B = \frac{(\alpha + \mathbf{P}_Y \cdot \widehat{\mathbf{n}})\widehat{\mathbf{n}} + \beta(\mathbf{P}_Y \times \widehat{\mathbf{n}}) + \gamma\widehat{\mathbf{n}} \times (\mathbf{P}_Y \times \widehat{\mathbf{n}})}{1 + \alpha\mathbf{P}_Y \cdot \widehat{\mathbf{n}}}\ . \tag{10}$$

Here $\mathbf{P}_B$ is defined in the rest system of the baryon, obtained by a Lorentz transformation along $\hat{\mathbf{n}}$ from the hyperon rest frame, in which $\hat{\mathbf{n}}$ and $\mathbf{P}_Y$ are defined.

An additional useful parameter $\phi$ is defined by

$$\beta = (1-\alpha^2)^{1/2} \sin\phi \ . \tag{11}$$

In the Listings, we compile $\alpha$ and $\phi$ for each decay, since these quantities are most closely related to experiment and are essentially uncorrelated. When necessary, we have changed the signs of reported values to agree with our sign conventions. In the Baryon Summary Table, we give $\alpha$, $\phi$, and $\Delta$ (defined below) with errors, and also give the value of $\gamma$ without error.

Time-reversal invariance requires, in the absence of final-state interactions, that $s$ and $p$ be relatively real, and therefore that $\beta = 0$. However, for the decays discussed here, the final-state interaction is strong. Thus

$$s = \mid s \mid e^{i\delta_s} \text{ and } p = \mid p \mid e^{i\delta_p} \ , \tag{12}$$

where $\delta_s$ and $\delta_p$ are the pion-baryon $s$- and $p$-wave strong interaction phase shifts. We then have

$$\beta = \frac{-2 \mid s \mid \mid p \mid}{\mid s \mid^2 + \mid p \mid^2} \sin(\delta_s - \delta_p) \ . \tag{13}$$

One also defines $\Delta = -\tan^{-1}(\beta/\alpha)$. If $T$ invariance holds, $\Delta = \delta_s - \delta_p$. For $\Lambda \to p\pi^-$ decay, the value of $\Delta$ may be compared with the $s$- and $p$-wave phase shifts in low-energy $\pi^- p$ scattering, and the results are consistent with $T$ invariance.

### *Radiative hyperon decays*

For the radiative decay of a polarized spin-1/2 hyperon, $B_i \to B_f \gamma$, the angular distribution of the direction $\hat{p}$ of the final spin-1/2 baryon in the hyperon rest frame is

$$\frac{d\Gamma_\gamma}{d\Omega} = \frac{\Gamma_\gamma}{4\pi} (1 + \alpha_\gamma \hat{p} \cdot \mathbf{P}_i) \ , \tag{14}$$

where $\mathbf{P}_i$ is the hyperon polarization and the asymmetry parameter $\alpha_\gamma$ is

$$\alpha_\gamma = \frac{2\mathrm{Re}\left[g_1'(0) f_M^*(0)\right]}{|g_1'(0)|^2 + |f_M(0)|^2} \ . \tag{15}$$

Here $f_M = \dfrac{(m_i - m_f)}{(m_i + m_f)}\left[(m_i + m_f) f_2' - f_1'\right]$, where $f_1'(q^2)$, $f_2'(q^2)$, and $g_1'(q^2)$ are the $\Delta Q = 0$ analogs of the $|\Delta Q| = 1$ form factors defined above.

## References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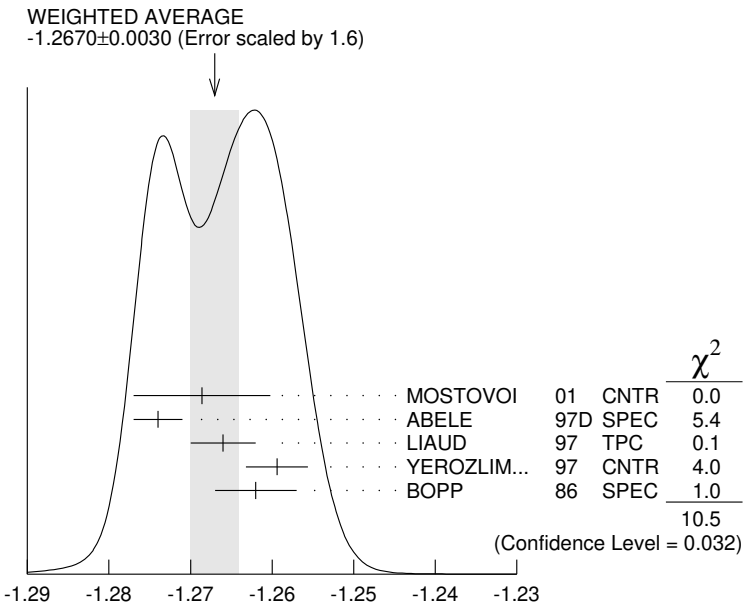
## $n \to p e^- \bar{\nu}_e$ DECAY PARAMETERS

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 and MOSTOVOI 96.

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

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **$-1.2670 \pm 0.0030$ OUR AVERAGE** | Error includes scale factor of 1.6. See the ideogram below. | | | |
| $-1.2686 \pm 0.0046 \pm 0.007$ | [20] MOSTOVOI | 01 | CNTR | $A$ and $B$ × polarizations |
| $-1.274 \pm 0.003$ | ABELE | 97D | SPEC | Cold $n$, polarized, $A$ |
| $-1.266 \pm 0.004$ | LIAUD | 97 | TPC | Cold $n$, polarized, $A$ |
| $-1.2594 \pm 0.0038$ | [21] YEROZLIM... | 97 | CNTR | Cold $n$, polarized, $A$ |
| $-1.262 \pm 0.005$ | BOPP | 86 | SPEC | Cold $n$, polarized, $A$ |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| $-1.266 \pm 0.004$ | SCHRECK... | 95 | TPC | See LIAUD 97 |
| $-1.2544 \pm 0.0036$ | EROZOLIM... | 91 | CNTR | See YEROZOLIMSKY 97 |
| $-1.226 \pm 0.042$ | MOSTOVOY | 83 | RVUE | |
| $-1.261 \pm 0.012$ | EROZOLIM... | 79 | CNTR | Cold $n$, polarized, $A$ |
| $-1.259 \pm 0.017$ | [22] STRATOWA | 78 | CNTR | $p$ recoil spectrum, $a$ |
| $-1.263 \pm 0.015$ | EROZOLIM... | 77 | CNTR | See EROZOLIMSKII 79 |
| $-1.250 \pm 0.036$ | [22] DOBROZE... | 75 | CNTR | See STRATOWA 78 |
| $-1.258 \pm 0.015$ | [23] KROHN | 75 | CNTR | Cold $n$, polarized, $A$ |
| $-1.263 \pm 0.016$ | [24] KROPF | 74 | RVUE | $n$ decay alone |
| $-1.250 \pm 0.009$ | [24] KROPF | 74 | RVUE | $n$ decay + nuclear ft |

[20] 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.
[21] YEROZOLIMSKY 97 makes a correction to the EROZOLIMSKII 91 value.
[22] These experiments measure the absolute value of $g_A/g_V$ only.
[23] KROHN 75 includes events of CHRISTENSEN 70.
[24] KROPF 74 reviews all data through 1972.



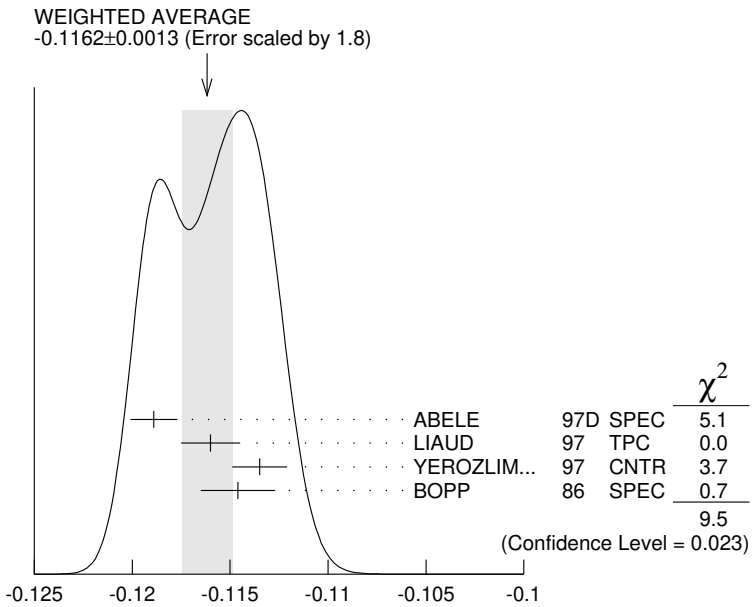

$\lambda \equiv g_A / g_V$

## $\beta$ 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.

| *VALUE* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **$-0.1162 \pm 0.0013$ OUR AVERAGE** | Error includes scale factor of 1.8. See the ideogram below. | | | |
| $-0.1189 \pm 0.0012$ | ABELE | 97D | SPEC | Cold *n*, polarized |
| $-0.1160 \pm 0.0009 \pm 0.0012$ | LIAUD | 97 | TPC | Cold *n*, polarized |
| $-0.1135 \pm 0.0014$ | [25] 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. • • • | | | | |
| $-0.1168 \pm 0.0017$ | [26] MOSTOVOI | 01 | CNTR | Inferred |
| $-0.1160 \pm 0.0009 \pm 0.0011$ | SCHRECK... | 95 | TPC | See LIAUD 97 |
| $-0.1116 \pm 0.0014$ | EROZOLIM... | 91 | CNTR | See YEROZOLIM-SKY 97 |
| $-0.114 \pm 0.005$ | [27] EROZOLIM... | 79 | CNTR | Cold *n*, polarized |
| $-0.113 \pm 0.006$ | [27] KROHN | 75 | CNTR | Cold *n*, polarized |

[25] YEROZOLIMSKY 97 makes a correction to the EROZOLIMSKII 91 value.
[26] MOSTOVOI 01 calculates this from its measurement of $\lambda = g_A/g_V$ above.
[27] These results are not corrected for radiative effects and weak magnetism, but the corrections are small compared to the errors.




$\beta$ asymmetry parameter $A$

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

This is the neutron-spin antineutrino-momentum correlation coefficient.

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **0.983 ±0.004 OUR AVERAGE** | | | | |
| 0.9801±0.0046 | SEREBROV | 98 | CNTR | Cold *n*, polarized |
| 0.9894±0.0083 | KUZNETSOV | 95 | CNTR | Cold *n*, polarized |
| 0.995 ±0.034 | CHRISTENSEN | 70 | CNTR | Cold *n*, polarized |
| 1.00 ±0.05 | EROZOLIM... | 70C | CNTR | Cold *n*, polarized |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 0.9876±0.0004 | [28] MOSTOVOI | 01 | CNTR | Inferred |

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

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

| VALUE | DOCUMENT ID | | TECN | COMMENT |
|---|---|---|---|---|
| **−0.102 ±0.005 OUR AVERAGE** | | | | |
| −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 | [29] MOSTOVOI | 01 | CNTR | Inferred |

[29] 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 $\sin(\phi_{AV}) = D(1+3\lambda^2)/2\lambda$.

| *VALUE* (°) | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **180.08±0.10 OUR AVERAGE** | | | | |
| 180.08±0.13 | LISING | 00 | CNTR | Polarized >93% |
| 179.71±0.39 | EROZOLIM... | 78 | CNTR | Cold *n*, polarized |
| 180.35±0.43 | EROZOLIM... | 74 | CNTR | Cold *n*, polarized |
| 180.14±0.22 | STEINBERG | 74 | CNTR | Cold *n*, polarized |
| • • • We do not use the following data for averages, fits, limits, etc. • • • | | | | |
| 181.1 ±1.3 | [30] KROPF | 74 | RVUE | *n* decay |

[30] 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* | *DOCUMENT ID* | | *TECN* | *COMMENT* |
|---|---|---|---|---|
| **(−0.6 ±1.0 ) × $10^{-3}$ OUR AVERAGE** | | | | |
| − 0.0006±0.0012±0.0005 | LISING | 00 | CNTR | Polarized >93% |
| + 0.0022±0.0030 | EROZOLIM... | 78 | CNTR | Cold *n*, polarized |
| − 0.0027±0.0050 | [31] EROZOLIM... | 74 | CNTR | Cold *n*, polarized |
| − 0.0011±0.0017 | STEINBERG | 74 | CNTR | Cold *n*, polarized |

[31] EROZOLIMSKII 78 says asymmetric proton losses and nonuniform beam polarization may give a systematic error up to 0.003, thus increasing the EROZOLIMSKII 74 error to 0.005. STEINBERG 74 and STEINBERG 76 estimate these systematic errors to be insignificant in their experiment.

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| KOLB | 00 | PRL 85 1388 | N.R. Kolb *et al.* | |
| LAMOREAUX | 00 | PR D61 051301R | S.K. Lamoreaux, R. Golub | |
| 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.* | |
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| NORMAN | 96 | PR D53 4086 | E.B. Norman, J.N. Bahcall, M. Goldhaber | (LBL+) |
| IGNATOVICH | 95 | JETPL 62 1 | V.K. Ignatovich | (JINR) |
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|---|---|---|---|---|
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| KUZNETSOV | 95 | PRL 75 794 | I.A. Kuznetsov *et al.* | (PNPI, KIAE, HARV+) |
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| ALTAREV | 92 | PL B276 242 | I.S. Altarev *et al.* | (PNPI) |
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| SCHRECK... | 92 | JPG 18 1 | K. Schreckenbach, W. Mampe | (ILLG) |
| ALBERICO | 91 | NP A523 488 | W.M. Alberico, A. de Pace, M. Pignone | (TORI) |
| DUBBERS | 91 | NP A527 239c | D. Dubbers | (ILLG) |
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| EROZOLIM... | 91 | PL B263 33 | B.G. Erozolimsky *et al.* | (PNPI, KIAE) |
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| FREEDMAN | 90 | CNPP A19 209 | S.J. Freedman | (ANL) |
| GREEN | 90 | JPG 16 L75 | K. Green, D. Thompson | (RAL) |
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| BRESSI | 89 | ZPHY C43 175 | G. Bressi *et al.* | (INFN, MILA, PAVI, ROMA) |
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| DOBROZE... | 75 | PR D11 510 | R. Dobrozemsky *et al.* | (SEIB) |
| KROHN | 75 | PL 55B 175 | V.E. Krohn, G.R. Ringo | (ANL) |
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