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

We have omitted some results that have been superseded by later experiments.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


\section*{\text{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.

\begin{table}[h]
\centering
\begin{tabular}{llll}
\hline
\textbf{VALUE (u)} & \textbf{DOCUMENT ID} & \textbf{TECN} & \textbf{COMMENT} \\
\hline
1.00866491595 & TIESINGA 21 & RVUE & 2018 CODATA value \\
1.00866491588 & MOHR 16 & RVUE & 2014 CODATA value \\
1.00866491600 & MOHR 12 & RVUE & 2010 CODATA value \\
1.00866491597 & MOHR 08 & RVUE & 2006 CODATA value \\
1.00866491560 & MOHR 05 & RVUE & 2002 CODATA value \\
1.00866491578 & MOHR 99 & RVUE & 1998 CODATA value \\
1.008665904 & COHEN 87 & RVUE & 1986 CODATA value \\
\hline
\end{tabular}
\end{table}

\section*{\text{n MASS (MeV)}}

The mass is known much more precisely in $u$ (atomic mass units) than in MeV. The conversion is: 1 $u = 931.494 \pm 0.00242(28)$ MeV/$c^2$ (2018 CODATA value, TIESINGA 21).

\begin{table}[h]
\centering
\begin{tabular}{llll}
\hline
\textbf{VALUE (MeV)} & \textbf{DOCUMENT ID} & \textbf{TECN} & \textbf{COMMENT} \\
\hline
939.56542052 & TIESINGA 21 & RVUE & 2018 CODATA value \\
939.5654133 & MOHR 16 & RVUE & 2014 CODATA value \\
939.565379 & MOHR 12 & RVUE & 2010 CODATA value \\
939.565346 & MOHR 08 & RVUE & 2006 CODATA value \\
939.565360 & MOHR 05 & RVUE & 2002 CODATA value \\
939.565331 & KESSLER 99 & SPEC & \text{n p $\rightarrow$ d}$ \gamma$
\text{\cite{1}} \\
939.565330 & MOHR 99 & RVUE & 1998 CODATA value \\
939.56565 & DIFILIPPO 94 & TRAP & Penning trap \\
939.56567 & MOHR 87 & RVUE & 1986 CODATA value \\
939.56564 & COHEN 86 & SPEC & \text{n p $\rightarrow$ d} $\gamma$
\text{\cite{3}} \\
939.5731 & COHEN 73 & RVUE & 1973 CODATA value \\
\hline
\end{tabular}
\end{table}

\text{\cite{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 $1.00866491637 \pm 0.00000000082$ u.

\text{\cite{2}} 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 $u$: $m = 1.008664919 \pm 0.000000014$ $u$.

### $\pi$ MASS

<table>
<thead>
<tr>
<th>VALUE (MeV)</th>
<th>EVTS</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>939.485 ± 0.051</td>
<td>59</td>
<td>CRESTI 86</td>
<td>HBC</td>
<td>$p_p \to \pi n$</td>
</tr>
</tbody>
</table>

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

\[
\frac{m_n - m_\pi}{m_n}
\]

A test of CPT invariance. Calculated from the $n$ and $\pi$ masses, above.

<table>
<thead>
<tr>
<th>VALUE</th>
<th>DOCUMENT ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>$(9 \pm 6) \times 10^{-5}$ OUR EVALUATION</td>
<td></td>
</tr>
</tbody>
</table>

### $m_n - m_p$

<table>
<thead>
<tr>
<th>VALUE (MeV)</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.29333236 ± 0.00000046</td>
<td>TIESINGA 21</td>
<td>RVUE</td>
<td>2018 CODATA value</td>
</tr>
</tbody>
</table>

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

1 The 2018 CODATA mass difference in $u$ is $m_n - m_p = 1.38844933(49) \times 10^{-3} u$.
2 The 2014 CODATA mass difference in $u$ is $m_n - m_p = 1.38844900(51) \times 10^{-3} u$.
3 The 2010 CODATA mass difference in $u$ is $m_n - m_p = 1.38844919(45) \times 10^{-3} u$.

4 Calculated by us from the MOHR 08 ratio $m_n/m_p = 1.00137841918(46)$. In $u$, $m_n - m_p = 1.38844920(46) \times 10^{-3} u$.
5 Calculated by us from the MOHR 05 ratio $m_n/m_p = 1.00137841870 \pm 0.0000000058$.

In $u$, $m_n - m_p = (1.3884487 \pm 0.0000006) \times 10^{-3} u$.
6 Calculated by us from the MOHR 99 ratio $m_n/m_p = 1.00137841887 \pm 0.0000000058$.

In $u$, $m_n - m_p = (1.3884489 \pm 0.0000006) \times 10^{-3} u$.
7 Calculated by us from the COHEN 87 ratio $m_n/m_p = 1.001378404 \pm 0.00000009$. In $u$, $m_n - m_p = 0.001388434 \pm 0.00000009 u$.

### $n$ MEAN LIFE

Limits on lifetimes for bound neutrons are given in the section “p PARTIAL MEAN LIVES.”
We average eight of the best nine measurements, those made with ultracold neutrons (UCN’s). If we include the one in-beam measurement with a comparable error (YUE 13), we get $878.6 \pm 0.6$ s, where the scale factor is now 2.2.

For a recent discussion of the long-standing disagreement between in-beam and UCN results, see CZARNECKI 18 (Physical Review Letters 120 202002 (2018)). For a full review of all matters concerning the neutron lifetime until about 2010, see WIETFELDT 11, F.E. Wietfeldt and G.L. Greene, “The neutron lifetime,” Reviews of Modern Physics 83 1173 (2011).

<table>
<thead>
<tr>
<th>VALUE (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$878.4 \pm 0.5$ OUR AVERAGE</td>
</tr>
</tbody>
</table>

below.

<table>
<thead>
<tr>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GONZALEZ 21</td>
<td>CNTR</td>
<td>UCN asym. magnetic trap</td>
</tr>
<tr>
<td>EZHOV 18</td>
<td>CNTR</td>
<td>UCN magneto-gravit. trap</td>
</tr>
<tr>
<td>PATTIE 18</td>
<td>CNTR</td>
<td>UCN asym. magnetic trap</td>
</tr>
<tr>
<td>SEREBROV 18</td>
<td>CNTR</td>
<td>UCN gravitational trap</td>
</tr>
<tr>
<td>ARZUMANOV 15</td>
<td>CNTR</td>
<td>UCN double bottle</td>
</tr>
<tr>
<td>STEYERL 12</td>
<td>CNTR</td>
<td>UCN material bottle</td>
</tr>
<tr>
<td>PICHLMAYER 10</td>
<td>CNTR</td>
<td>UCN material bottle</td>
</tr>
<tr>
<td>SEREBROV 05</td>
<td>CNTR</td>
<td>UCN gravitational trap</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>VALUE (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$877.75 \pm 0.28$</td>
</tr>
<tr>
<td>$878.3 \pm 1.6$</td>
</tr>
<tr>
<td>$877.7 \pm 0.7$</td>
</tr>
<tr>
<td>$881.5 \pm 0.7$</td>
</tr>
<tr>
<td>$880.2 \pm 1.2$</td>
</tr>
<tr>
<td>$882.5 \pm 1.4$</td>
</tr>
<tr>
<td>$880.7 \pm 1.3$</td>
</tr>
<tr>
<td>$887.5 \pm 0.7$</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GONZALEZ 21</td>
<td>CNTR</td>
<td>UCN asym. magnetic trap</td>
</tr>
<tr>
<td>EZHOV 18</td>
<td>CNTR</td>
<td>UCN magneto-gravit. trap</td>
</tr>
<tr>
<td>PATTIE 18</td>
<td>CNTR</td>
<td>UCN asym. magnetic trap</td>
</tr>
<tr>
<td>SEREBROV 18</td>
<td>CNTR</td>
<td>UCN gravitational trap</td>
</tr>
<tr>
<td>ARZUMANOV 15</td>
<td>CNTR</td>
<td>UCN double bottle</td>
</tr>
<tr>
<td>STEYERL 12</td>
<td>CNTR</td>
<td>UCN material bottle</td>
</tr>
<tr>
<td>PICHLMAYER 10</td>
<td>CNTR</td>
<td>UCN material bottle</td>
</tr>
<tr>
<td>SEREBROV 05</td>
<td>CNTR</td>
<td>UCN gravitational trap</td>
</tr>
</tbody>
</table>

1 PATTIE 18 uses a new technique, with a semi-toroidal magneto-gravitational asymmetric trap and a novel in situ $n$-detector.

2 ARZUMANOV 15 is a reanalysis of their 2008–2010 dataset, with improved systematic corrections of of ARZUMANOV 00 and ARZUMANOV 12.
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. WILSON 21 extract the value from the flux of n escaping the moon using data from the Lunar Prospector Neutron Spectrometer.

5. 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.

6. ARZUMANOV 12 reanalyzes its systematic corrections in ARZUMANOV 00 and obtains this corrected value.

7. 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.

8. The NESVIZHEVSKII 92 measurement has been withdrawn by A. Serebrov.

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

### n Magnetic Moment

See the “Quark Model” review.

<table>
<thead>
<tr>
<th>VALUE ($\mu_N$)</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-1.91304273 \pm 0.00000045$</td>
<td>TIESINGA 21</td>
<td>RVUE</td>
<td>2018 CODATA value</td>
</tr>
<tr>
<td>$-1.91304273 \pm 0.00000045$</td>
<td>MOHR 16</td>
<td>RVUE</td>
<td>2014 CODATA value</td>
</tr>
<tr>
<td>$-1.91304273 \pm 0.00000045$</td>
<td>MOHR 12</td>
<td>RVUE</td>
<td>2010 CODATA value</td>
</tr>
<tr>
<td>$-1.91304273 \pm 0.00000045$</td>
<td>MOHR 08</td>
<td>RVUE</td>
<td>2006 CODATA value</td>
</tr>
<tr>
<td>$-1.91304273 \pm 0.00000045$</td>
<td>MOHR 05</td>
<td>RVUE</td>
<td>2002 CODATA value</td>
</tr>
</tbody>
</table>

https://pdg.lbl.gov
$n$ 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 $|d_n|$.

<table>
<thead>
<tr>
<th>VALUE (10$^{-25}$ e cm)</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.18</td>
<td>90</td>
<td>1 ABEL 20</td>
<td>MRS</td>
<td>UCN</td>
</tr>
<tr>
<td>&lt; 0.22</td>
<td>90</td>
<td>2 SAHOO 17</td>
<td>MRS</td>
<td>199Hg atom EDM + theory</td>
</tr>
<tr>
<td>&lt; 0.16</td>
<td>90</td>
<td>3 PENDLEBURY 15</td>
<td>MRS</td>
<td>Supersedes BAKER 06</td>
</tr>
<tr>
<td>&lt; 0.30</td>
<td>90</td>
<td>4 SEREBROV 15</td>
<td>MRS</td>
<td>UCN's, $h\nu = 2\mu_B B \pm 2d_n E$</td>
</tr>
<tr>
<td>&lt; 0.55</td>
<td>90</td>
<td>5 BAKER 06</td>
<td>MRS</td>
<td>See SEREBROV 15</td>
</tr>
<tr>
<td>&lt; 0.55</td>
<td>90</td>
<td>6 HARRIS 99</td>
<td>MRS</td>
<td>$d = (−0.1 ± 0.36) \times 10^{−25}$</td>
</tr>
<tr>
<td>&lt; 0.97</td>
<td>90</td>
<td>ALTAREV 96</td>
<td>MRS</td>
<td>See SEREBROV 14</td>
</tr>
<tr>
<td>&lt; 1.1</td>
<td>95</td>
<td>ALTAREV 92</td>
<td>MRS</td>
<td>See ALTAREV 96</td>
</tr>
<tr>
<td>&lt; 1.2</td>
<td>95</td>
<td>SMITH 90</td>
<td>MRS</td>
<td>See HARRIS 99</td>
</tr>
<tr>
<td>&lt; 2.6</td>
<td>95</td>
<td>ALTAREV 86</td>
<td>MRS</td>
<td>$d = (−1.4 ± 0.6) \times 10^{−25}$</td>
</tr>
<tr>
<td>&lt; 0.3 ± 4.8</td>
<td>95</td>
<td>PENDLEBURY 84</td>
<td>MRS</td>
<td>Ultracold neutrons</td>
</tr>
<tr>
<td>&lt; 6</td>
<td>90</td>
<td>ALTAREV 81</td>
<td>MRS</td>
<td>$d = (2.1 ± 2.4) \times 10^{−25}$</td>
</tr>
<tr>
<td>&lt; 16</td>
<td>90</td>
<td>ALTAREV 79</td>
<td>MRS</td>
<td>$d = (4.0 ± 7.5) \times 10^{−25}$</td>
</tr>
</tbody>
</table>

1 ABEL 20 reports $d = (0.0 ± 1.1 ± 0.2) \times 10^{−26}$ e cm value corresponding to the listed limit.
2 SAHOO 17 develops theory to calculate this limit from the measured limit by GRANER 16 of the 199Hg atom EDM.
3 PENDLEBURY 15 reports $d = (−0.21 ± 1.82) \times 10^{−26}$ e cm value corresponding to the listed limit.
4 SEREBROV 14 includes the data of ALTAREV 96.
5 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.
6 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, $\langle r^2_n \rangle$, is related to the neutron-electron scattering length $b_{ne}$ by $\langle r^2_n \rangle = 3(m_e a_0/m_n)b_{ne}$, 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 (fm²)**

<table>
<thead>
<tr>
<th>DOCUMENT ID</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.1155 ± 0.0017 OUR AVERAGE</td>
<td></td>
</tr>
<tr>
<td>-0.115 ± 0.002 ± 0.003</td>
<td>KOPECKY 97 ne scattering (Pb)</td>
</tr>
<tr>
<td>-0.124 ± 0.003 ± 0.005</td>
<td>KOPECKY 97 ne scattering (Bi)</td>
</tr>
<tr>
<td>-0.114 ± 0.003</td>
<td>KOESTER 95 ne scattering (Pb, Bi)</td>
</tr>
<tr>
<td>-0.115 ± 0.003</td>
<td>1 KROHN 73 ne scattering (Ne, Ar, Kr, Xe)</td>
</tr>
</tbody>
</table>

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

1 KROHN 73 measured -0.112 ± 0.003 fm². This value is as corrected by KOESTER 76.
2 HEACOCK 21 extract the value from Pendelloesung interferometry to measure the neutron structure factors of silicon. This value is strongly anti-correlated with the mean-square thermal atomic displacement.
3 FILIN 20 extract the value based on their chiral-EFT calculation of the deuteron structure radius and use as input the atomic data for the difference of the deuteron and proton charge radii.

**n MAGNETIC RADIUS**

This is the rms magnetic radius, \( \sqrt{\langle r_M^2 \rangle} \).

**VALUE (fm)**

<table>
<thead>
<tr>
<th>DOCUMENT ID</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.864 ± 0.009 ± 0.008 OUR AVERAGE</td>
<td></td>
</tr>
<tr>
<td>0.89 ± 0.03</td>
<td>EPSTEIN 14 Using ( ep, en, \pi \pi ) data</td>
</tr>
<tr>
<td>0.862 ± 0.009 ± 0.008</td>
<td>BELUSHKIN 07 Dispersion analysis</td>
</tr>
</tbody>
</table>

**n ELECTRIC POLARIZABILITY \( \alpha_n \)**

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

For a very complete reviews of the polarizability of the nucleon and Compton scattering, see SCHUMACHER 05, updated in SCHUMACHER 19, and GRIESSHAMMER 12.

**VALUE (10⁻⁴ fm²)**

<table>
<thead>
<tr>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.8 ± 1.1 OUR AVERAGE</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.55 ± 1.25 ± 0.8</td>
<td>MYERS 14 CNTR ( \gamma d \rightarrow \gamma d )</td>
<td></td>
</tr>
<tr>
<td>12.5 ± 1.8 ( +1.6 ) ( -1.3 )</td>
<td>1 KOSSE0 03 CNTR ( \gamma d \rightarrow \gamma p n )</td>
<td></td>
</tr>
</tbody>
</table>

12.0 ± 1.5 ±2.0 SCHMIEDM... 91 CNTR n Pb transmission
10.7 +3.3 −10.7 ROSE 90B CNTR γd → γnp

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

8.8 ± 2.4 ± 3.0 2 LUNDIN 03 CNTR γd → γd
13.6 3 KOLB 00 CNTR γd → γnp
0.0 ± 5.0 4 KOESTER 95 CNTR n Pb, n Bi transmission
11.7 +4.3 −11.7 ROSE 90 CNTR See ROSE 90B
8 ±10 KOESTER 88 CNTR n Pb, n Bi transmission
12 ±10 SCHMIEDM... 88 CNTR n Pb, n C transmission

1 KOSsert 03 gets αn − βn = (9.8 ± 3.6 +2.1 −1.1 ± 2.2) × 10⁻⁴ fm³, and uses αn + βn = (15.2 ± 0.5) × 10⁻⁴ fm³ from LEVCHUK 00. Thus the errors on αn and βn are anti-correlated.
2 LUNDIN 03 measures αN − βN = (6.4 ± 2.4) × 10⁻⁴ fm³ and uses accurate values for αp and αp and a precise sum-rule result for αn + βn. The second error is a model uncertainty, and errors on αn and βn 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 × 10⁻⁴ fm³ but no upper limit from this experiment alone. Combined with results of ROSE 90, the 1-σ range is (7.6–14.0) × 10⁻⁴ fm³.
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 αn from data.

<table>
<thead>
<tr>
<th>n MAGNETIC POLARIZABILITY βn</th>
</tr>
</thead>
<tbody>
<tr>
<td>VALUE (10⁻⁴ fm³)</td>
</tr>
<tr>
<td>3.7 ±1.2 OUR AVERAGE</td>
</tr>
<tr>
<td>3.65±1.25±0.8 MYERS 14 CNTR γd → γd</td>
</tr>
<tr>
<td>2.7 ±1.8 +1.3 −1.6 1 KOSsert 03 CNTR γd → γp n</td>
</tr>
<tr>
<td>6.5 ±2.4 ±3.0 2 LUNDIN 03 CNTR γd → γd</td>
</tr>
</tbody>
</table>

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

1 KOSsert 03 gets αn − βn = (9.8 ± 3.6 +2.1 −1.1 ± 2.2) × 10⁻⁴ fm³, and uses αn + βn = (15.2 ± 0.5) × 10⁻⁴ fm³ from LEVCHUK 00. Thus the errors on αn and βn are anti-correlated.
2 LUNDIN 03 measures αN − βN = (6.4 ± 2.4) × 10⁻⁴ fm³ and uses accurate values for αp and αp and a precise sum-rule result for αn + βn. The second error is a model uncertainty, and errors on αn and βn are anticorrelated.
3 KOLB 00 obtains this value with an upper limit of 7.6 × 10⁻⁴ fm³ but no lower limit from this experiment alone. Combined with results of ROSE 90, the 1-σ range is (7.6–14.0) × 10⁻⁴ fm³.

<table>
<thead>
<tr>
<th>n CHARGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>VALUE (10⁻²¹ e)</td>
</tr>
<tr>
<td>− 0.2± 0.8 OUR AVERAGE</td>
</tr>
<tr>
<td>− 0.1± 1.1 1 BRESSI 11 CNTR Neutrality of SF₆</td>
</tr>
<tr>
<td>− 0.4± 1.1 2 BAUMANN 88 CNTR Cold n deflection</td>
</tr>
</tbody>
</table>

See also “|qp + qe|/e” in the proton Listings.
We do not use the following data for averages, fits, limits, etc. • • •

\[-15 \pm 22 \] \text{GAEHLER 82 CNTR Cold n deflection}

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

**LIMIT ON \(n\bar{n}\) OSCILLATIONS**

**Mean Time for \(n\bar{n}\) Transition**

A test of \(ΔB=2\) baryon number nonconservation. MOHAPATRA 80 and MOHAPATRA 89 discuss the theoretical motivations for looking for \(n\bar{n}\) 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 \(n \rightarrow \bar{n}\) 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 and PHILLIPS 16 for recent reviews.

<table>
<thead>
<tr>
<th>VALUE (s)</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&gt;4.7 \times 10^8)</td>
<td>90</td>
<td>ABE 21</td>
<td>CNTR</td>
<td>n bound in oxygen</td>
</tr>
<tr>
<td>(&gt;8.6 \times 10^7)</td>
<td>90</td>
<td>BALDO-CEOLIN 94</td>
<td>CNTR</td>
<td>Reactor (free) neutrons</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>VALUE (s)</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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<tbody>
<tr>
<td>(&gt;1.37 \times 10^8)</td>
<td>90</td>
<td>AHARMIM 17</td>
<td>SNO</td>
<td>n bound in deuteron</td>
</tr>
<tr>
<td>(&gt;2.7 \times 10^8)</td>
<td>90</td>
<td>ABE 15c</td>
<td>CNTR</td>
<td>n bound in oxygen</td>
</tr>
<tr>
<td>(&gt;1.3 \times 10^8)</td>
<td>90</td>
<td>CHUNG 02b</td>
<td>SOU2</td>
<td>n bound in iron</td>
</tr>
<tr>
<td>(&gt;1 \times 10^7)</td>
<td>90</td>
<td>BALDO-CEOLIN 94</td>
<td>CNTR</td>
<td>Reactor neutrons</td>
</tr>
<tr>
<td>(&gt;1.2 \times 10^8)</td>
<td>90</td>
<td>BERGER 90</td>
<td>FREJ</td>
<td>n bound in iron</td>
</tr>
<tr>
<td>(&gt;4.9 \times 10^5)</td>
<td>90</td>
<td>BRENNER 89</td>
<td>CNTR</td>
<td>Reactor neutrons</td>
</tr>
<tr>
<td>(&gt;4.7 \times 10^5)</td>
<td>90</td>
<td>BRENNER 89</td>
<td>CNTR</td>
<td>See BRENNER 90</td>
</tr>
<tr>
<td>(&gt;1.2 \times 10^8)</td>
<td>90</td>
<td>TAKITA 86</td>
<td>CNTR</td>
<td>n bound in oxygen</td>
</tr>
<tr>
<td>(&gt;1 \times 10^6)</td>
<td>90</td>
<td>FIDECCARO 85</td>
<td>CNTR</td>
<td>Reactor neutrons</td>
</tr>
<tr>
<td>(&gt;8.8 \times 10^7)</td>
<td>90</td>
<td>PARK 85b</td>
<td>CNTR</td>
<td></td>
</tr>
<tr>
<td>(&gt;3 \times 10^7)</td>
<td>90</td>
<td>BATTISTONI 84</td>
<td>NUSX</td>
<td></td>
</tr>
<tr>
<td>(&gt;0.27–1.1 \times 10^8)</td>
<td>90</td>
<td>JONES 84</td>
<td>CNTR</td>
<td></td>
</tr>
<tr>
<td>(&gt;2 \times 10^7)</td>
<td>90</td>
<td>CHERRY 83</td>
<td>CNTR</td>
<td></td>
</tr>
</tbody>
</table>

1 ABE 21 supersedes ABE 15c.
2 The AHARMIM 17 value is an unbounded limit (it does not assume a positive lifetime).
3 The bounded limit is \(1.23 \times 10^8\) sec.

**LIMIT ON \(nn\) OSCILLATIONS**

Lee and Yang (LEE 56) proposed the existence of mirror world in an attempt to restore global parity symmetry. A possible candidate for dark matter. Limits depend on assumptions about fields \(B\) and \(B'\). See the papers for details. See BEREZHIANI 18 for a recent discussion.

<table>
<thead>
<tr>
<th>VALUE (s)</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&gt;352)</td>
<td>95</td>
<td>ABE 21</td>
<td>CNTR</td>
<td>UCN, scan of (B) field</td>
</tr>
<tr>
<td>(&gt;448)</td>
<td>90</td>
<td>SEREBROV 09a</td>
<td>CNTR</td>
<td>Assumes (B' &lt; 100) nT</td>
</tr>
</tbody>
</table>

https://pdg.lbl.gov
We do not use the following data for averages, fits, limits, etc. • • • •

2 ALMAZAN 22 CNTR STEREO, hidden neutron search \( |m_n - m_{n'}| \geq 0 \).

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

> 17 95 3 BEREZHIANI 18 CNTR UCN, scan of \( B \) field
> 12 95 4 ALTAREV 09A CNTR UCN, scan \( 0 \leq B \leq 12.5 \) \( \mu T \)
> 414 90 SEREBROV 08 CNTR UCN, \( B \) field on & off
> 103 95 BAN 07 CNTR UCN, \( B \) field on & off

1 ABEL 21 determine several limits on the oscillation time as a function of the ratio mirror magnetic field \( B' \) to applied magnetic field \( B \). The quoted limit of 352 s is for \( B' = 0 \).
Lower limits on the oscillation time of 6 seconds are further obtained for any mirror field \( B' \) in the range 0.4–25.7 \( \mu T \).

2 ALMAZAN 22 reports an experimental constraint on the probability for neutron conversion into a hidden neutron, \( p < 3.1 \times 10^{-11} \) at 95% CL, which may be used to set a limit on the \( n' n \) oscillation time.

3 The \( B \) field was set to (0.09, 0.12, 0.21) G. Limits on oscillation time are valid for any mirror field \( B' \) in (0.08–0.17) G, and for aligned fields \( B \) and \( B' \). For larger values of \( B' \), the limits are significantly reduced.

4 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

<table>
<thead>
<tr>
<th>Mode</th>
<th>Fraction ((\Gamma_i/\Gamma))</th>
<th>Confidence level</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Gamma_1 )</td>
<td>( p e^- \bar{\nu}_e )</td>
<td>100 %</td>
</tr>
<tr>
<td>( \Gamma_2 )</td>
<td>( p e^- \bar{\nu}_e \gamma )</td>
<td>([a]) ((9.2\pm0.7) \times 10^{-3})</td>
</tr>
<tr>
<td>( \Gamma_3 )</td>
<td>hydrogen-atom ( \bar{\nu}_e )</td>
<td>&lt; 2.7 \times 10^{-3} 95%</td>
</tr>
</tbody>
</table>

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

\( \Gamma_4 \) \( p \nu_e \bar{\nu}_e \) \( Q < 8 \times 10^{-27} \) 68\%

#### Baryon number violating decay

\( \Gamma_5 \) \( e^+e^- \) invisible

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

### \( n \) BRANCHING RATIOS

\( \Gamma(p e^- \bar{\nu}_e \gamma)/\Gamma_{total} \) \( \Gamma_2/\Gamma \)

<table>
<thead>
<tr>
<th>VALUE (units ( 10^{-3} ))</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>( 9.17\pm0.24\pm0.64 )</td>
<td></td>
<td>1 BALES</td>
<td>16</td>
<td>RDK2</td>
</tr>
<tr>
<td>( 3.09\pm0.11\pm0.30 )</td>
<td></td>
<td>2 COOPER</td>
<td>10</td>
<td>CNTR</td>
</tr>
<tr>
<td>( 3.13\pm0.11\pm0.33 )</td>
<td></td>
<td>3 BECK</td>
<td>02</td>
<td>CNTR</td>
</tr>
<tr>
<td>&lt;6.9</td>
<td>90</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

1 BALES 16 gets a branching fraction of \((5.82 \pm 0.23 \pm 0.62) \times 10^{-3}\) for a photon energy range 0.4 to 14.0 keV, and with a different detector array, \((3.35 \pm 0.05 \pm 0.15) \times 10^{-3}\)

https://pdg.lbl.gov
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.

\[\Gamma(\text{hydrogen-atom } \nu_e)/\Gamma_{\text{total}} \quad \Gamma_3/\Gamma\]

<table>
<thead>
<tr>
<th>VALUE</th>
<th>CL %</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt; 0.27 \times 10^{-2})</td>
<td>95</td>
<td>1 CZARNECKI 18</td>
<td>RVUE</td>
<td>Lifetime analysis</td>
</tr>
<tr>
<td>(&lt; 3 \times 10^{-2})</td>
<td>95</td>
<td>2 GREEN 90</td>
<td>RVUE</td>
<td>1 CZARNECKI 18 limit from an analysis of experimental discrepancies on the neutron lifetime and axial coupling applies as well to other possible exotic neutron decays. 2 GREEN 90 infers that ( \tau(\text{hydrogen-atom } \nu_e) &gt; 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.</td>
</tr>
</tbody>
</table>

\[\Gamma(\nu \nu_e \nu_e)/\Gamma_{\text{total}} \quad \Gamma_4/\Gamma\]

Forbidden by charge conservation.

<table>
<thead>
<tr>
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<th>CL %</th>
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<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt; 8 \times 10^{-27})</td>
<td>68</td>
<td>1 NORMAN 96</td>
<td>RVUE</td>
<td>71Ge ( \rightarrow ) 71Ge neutrals</td>
</tr>
<tr>
<td>(&lt; 9.7 \times 10^{-18})</td>
<td>90</td>
<td>ROY 83</td>
<td>CNTR</td>
<td>113Cd ( \rightarrow ) 113mInneut.</td>
</tr>
<tr>
<td>(&lt; 7.9 \times 10^{-21})</td>
<td>90</td>
<td>VAIYDA 83</td>
<td>CNTR</td>
<td>87Rb ( \rightarrow ) 87mSrneut.</td>
</tr>
<tr>
<td>(&lt; 9 \times 10^{-24})</td>
<td>90</td>
<td>BARABANOV 80</td>
<td>CNTR</td>
<td>71Ga ( \rightarrow ) 71GeX</td>
</tr>
<tr>
<td>(&lt; 3 \times 10^{-19})</td>
<td>90</td>
<td>NORMAN 79</td>
<td>CNTR</td>
<td>87Rb ( \rightarrow ) 87mSrneut.</td>
</tr>
</tbody>
</table>

1 NORMAN 96 gets this limit by attributing SAGE and GALLEX counting rates to the charge-nonconserving transition 71Ga \( \rightarrow \) 71Ge+neutrals rather than to solar-neutrino reactions.

\[\Gamma(e^+ e^- \text{invisible})/\Gamma_{\text{total}} \quad \Gamma_5/\Gamma\]

Baryon number violating decay

<table>
<thead>
<tr>
<th>VALUE</th>
<th>CL %</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>(&lt; 0.01)</td>
<td>90</td>
<td>1 KLOPF 19</td>
<td>CNTR</td>
<td>re-interpretation of MUND 13</td>
</tr>
<tr>
<td>(&lt; 1 \times 10^{-4})</td>
<td>90</td>
<td>2 SUN 18</td>
<td>SPEC</td>
<td>Ultracold n, polarized</td>
</tr>
</tbody>
</table>

1 KLOPF 19 value is for baryon number violating decay of neutron to electrons plus an invisible state, \( \chi \). The limit is valid for KE(\(e^+ e^-\)) range between 32 keV and 664 keV, strengthening to few \( \times 10^{-4}\) above approximately 100 keV.

2 SUN 18 value is for baryon number violating decay of neutron to electrons plus an invisible state, \( \chi \). The limit is valid for 644 keV \( > KE(e^+ e^-) > 100 \) keV. Assuming this decay \( \chi e e \) is the only allowed \( \chi \) decay channel, a 0.01 BR is ruled out for 644 keV \( > E(e^+ e^-) > 100 \) keV at over 5\( \sigma \).
\[ n \to p e^{-\nu_e} \text{ DECAY PARAMETERS} \]

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 \( \lambda \), 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.

\[ \lambda \equiv g_A / g_V \]

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</thead>
<tbody>
<tr>
<td>(-1.2754 \pm 0.0013) OUR AVERAGE</td>
<td></td>
<td></td>
<td>Error includes scale factor of 2.7. See the ideogram below.</td>
</tr>
<tr>
<td>(-1.2796 \pm 0.0062)</td>
<td>1 HASSAN 21</td>
<td>SPEC</td>
<td>Proton recoil spectrum</td>
</tr>
<tr>
<td>(-1.2677 \pm 0.0028)</td>
<td>2 BECK 20</td>
<td>SPEC</td>
<td>Proton recoil spectrum</td>
</tr>
<tr>
<td>(-1.27641 \pm 0.00045 \pm 0.00033)</td>
<td>3 MAERKISCH 19</td>
<td>SPEC</td>
<td>pulsed cold ( n ), polarized</td>
</tr>
<tr>
<td>(-1.2772 \pm 0.0020)</td>
<td>4 BROWN 18</td>
<td>UCNA</td>
<td>Ultracold ( n ), polarized</td>
</tr>
<tr>
<td>(-1.2748 \pm 0.0008 \pm 0.0010 \pm 0.0011)</td>
<td>5 MUND 13</td>
<td>SPEC</td>
<td>Cold ( n ), polarized</td>
</tr>
<tr>
<td>(-1.275 \pm 0.006 \pm 0.015)</td>
<td>6 SCHUMANN 08</td>
<td>CNTR</td>
<td>Cold ( n ), polarized</td>
</tr>
<tr>
<td>(-1.2686 \pm 0.0046 \pm 0.0007)</td>
<td>7 MOSTOVOI 01</td>
<td>CNTR</td>
<td>( A ) and ( B \times ) polarizations</td>
</tr>
<tr>
<td>(-1.266 \pm 0.004)</td>
<td>8 LIAUD 97</td>
<td>TPC</td>
<td>Cold ( n ), polarized, ( A )</td>
</tr>
<tr>
<td>(-1.2594 \pm 0.0038)</td>
<td>9 DARIUS 17</td>
<td>SPEC</td>
<td>Cold ( n ), unpolarized</td>
</tr>
<tr>
<td>(-1.262 \pm 0.005)</td>
<td>10 MENDEHALL 13</td>
<td>UCNA</td>
<td>See BROWN 18</td>
</tr>
<tr>
<td>(-1.27607 \pm 0.00068)</td>
<td>11 PLASTER 12</td>
<td>UCNA</td>
<td>See MENDEHALL 13</td>
</tr>
<tr>
<td>(-1.284 \pm 0.014)</td>
<td>12 ABELE 02</td>
<td>SPEC</td>
<td>Cold ( n ), polarized, ( A )</td>
</tr>
<tr>
<td>(-1.2755 \pm 0.0030)</td>
<td>13 ABELE 97</td>
<td>SPEC</td>
<td>Cold ( n ), polarized, ( A )</td>
</tr>
<tr>
<td>(-1.27590 \pm 0.00239 \pm 0.00331 \pm 0.00377)</td>
<td>14 SCHRECK... 95</td>
<td>TPC</td>
<td>See LIAUD 97</td>
</tr>
<tr>
<td>(-1.27590 \pm 0.000409 \pm 0.000445)</td>
<td>15 EROZOLIM... 91</td>
<td>CNTR</td>
<td>See YEROZOLIM-SKY 97</td>
</tr>
<tr>
<td>(-1.226 \pm 0.042)</td>
<td>16 MOSTOVOY 83</td>
<td>RVUE</td>
<td>Cold ( n ), polarized, ( A )</td>
</tr>
<tr>
<td>(-1.261 \pm 0.012)</td>
<td>17 EROZOLIM... 79</td>
<td>CNTR</td>
<td>Cold ( n ), polarized, ( A )</td>
</tr>
<tr>
<td>(-1.259 \pm 0.017)</td>
<td>18 STRATOWA 78</td>
<td>CNTR</td>
<td>( p ) recoil spectrum, ( a )</td>
</tr>
<tr>
<td>(-1.263 \pm 0.015)</td>
<td>19 EROZOLIM... 77</td>
<td>CNTR</td>
<td>See EROZOLIMSKII 79</td>
</tr>
<tr>
<td>(-1.250 \pm 0.036)</td>
<td>20 DOBROZE... 75</td>
<td>CNTR</td>
<td>See STRATOWA 78</td>
</tr>
<tr>
<td>(-1.258 \pm 0.015)</td>
<td>21 KROHN 75</td>
<td>CNTR</td>
<td>Cold ( n ), polarized, ( A )</td>
</tr>
<tr>
<td>(-1.263 \pm 0.016)</td>
<td>22 KROPF 74</td>
<td>RVUE</td>
<td>( n ) decay alone</td>
</tr>
<tr>
<td>(-1.250 \pm 0.009)</td>
<td>23 KROPF 74</td>
<td>RVUE</td>
<td>( n ) decay + nuclear ft</td>
</tr>
</tbody>
</table>

WEIGHTED AVERAGE

\[-1.2754 \pm 0.0013 \text{ (Error scaled by 2.7)}\]

\[
\lambda \equiv \frac{g_A}{g_V}
\]

1 HASSAN 21 include earlier data of DARIUS 17. The value is extracted from the angular correlation coefficient \(a\).

2 BECK 20 calculates this value from the measurement of the \(\beta\)-decay \(e^{-}\bar{\nu}_e\) angular correlation coefficient \(a\).

3 MAERKISCH 19 gets \(A = -0.11985 \pm 0.00017 \pm 0.00012\).

4 BROWN 18 gets \(A = -0.12054 \pm 0.00044 \pm 0.00068\) and \(\lambda = -1.2783 \pm 0.0022\). We quote the combined values that include the earlier UCNA measurements (MENDENHALL 13).

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

6 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.

7 YEROZOLIMSKY 97 makes a correction to the EROZOLIMSKII 91 value.

8 SAUL 20 quote this value of \(\lambda\) under the SM assumption of the Fierz term \(b = 0\). In a combined fit authors extract a value of \(\lambda = -1.2792 \pm 0.0060\).

9 DARIUS 17 calculates this value from the measurement of the \(a\) parameter (see below). Data is included in HASSAN 21.

10 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.

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

12 This is the combined result of ABELE 02 and ABELE 97D.

13 These experiments measure the absolute value of \(g_A/g_V\) only.

14 KROHN 75 includes events of CHRISTENSEN 70.

15 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.

\[
\begin{align*}
-A &= -0.11958 \pm 0.00021 \\
&\text{OUR AVERAGE} \\
\end{align*}
\]

Error includes scale factor of 1.2. See the ideogram below.

<table>
<thead>
<tr>
<th>VALUE</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.11985 ± 0.00017</td>
<td>1 MAERKISCH</td>
<td>SPEC</td>
<td>pulsed cold ( n ), polarized</td>
</tr>
<tr>
<td>-0.12015 ± 0.00034</td>
<td>2 BROWN</td>
<td>UCNA</td>
<td>Ultracold ( n ), polarized</td>
</tr>
<tr>
<td>-0.11926 ± 0.00036</td>
<td>3 MUND</td>
<td>SPEC</td>
<td>Cold ( n ), polarized</td>
</tr>
<tr>
<td>-0.1160 ± 0.0009</td>
<td>LIAUD</td>
<td>TPC</td>
<td>Cold ( n ), polarized</td>
</tr>
<tr>
<td>-0.1135 ± 0.0014</td>
<td>4 YEROZLIM-</td>
<td>CNTR</td>
<td>Cold ( n ), polarized</td>
</tr>
<tr>
<td>-0.1146 ± 0.0019</td>
<td>BOPP</td>
<td>SPEC</td>
<td>Cold ( n ), polarized</td>
</tr>
</tbody>
</table>

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

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<tr>
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</tr>
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<tbody>
<tr>
<td>-0.11972 ± 0.00025</td>
<td>5 SAUL</td>
<td>SPEC</td>
<td>Cold ( n ), polarized</td>
</tr>
<tr>
<td>-0.11952 ± 0.00110</td>
<td>6 MENDENHALL</td>
<td>UCNA</td>
<td>See BROWN 18</td>
</tr>
<tr>
<td>-0.11966 ± 0.00089</td>
<td>7 PLASTER</td>
<td>UCNA</td>
<td>See MENDENHALL 13</td>
</tr>
<tr>
<td>-0.11966 ± 0.00089</td>
<td>LIU</td>
<td>UCNA</td>
<td>See PLASTER 12</td>
</tr>
<tr>
<td>-0.1138 ± 0.0046</td>
<td>PATTIE</td>
<td>SPEC</td>
<td>Ultracold ( n ), polarized</td>
</tr>
<tr>
<td>-0.1189 ± 0.0007</td>
<td>8 ABELE</td>
<td>SPEC</td>
<td>See MUND 13</td>
</tr>
<tr>
<td>-0.1168 ± 0.0017</td>
<td>9 MOSTOVOI</td>
<td>CNTR</td>
<td>Inferred</td>
</tr>
<tr>
<td>-0.1189 ± 0.0012</td>
<td>ABELE</td>
<td>SPEC</td>
<td>Cold ( n ), polarized</td>
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<tr>
<td>-0.1160 ± 0.0009</td>
<td>SCHRECK...</td>
<td>TPC</td>
<td>See LIAUD 97</td>
</tr>
<tr>
<td>-0.1116 ± 0.0014</td>
<td>EROZOLIM...</td>
<td>CNTR</td>
<td>See YEROZOLIM-SKY 97</td>
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<td>-0.114 ± 0.005</td>
<td>10 EROZOLIM-SKY</td>
<td>CNTR</td>
<td>Cold ( n ), polarized</td>
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<tr>
<td>-0.113 ± 0.006</td>
<td>10 KROHN</td>
<td>CNTR</td>
<td>Cold ( n ), polarized</td>
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WEIGHTED AVERAGE

\(-0.11958\pm0.00021\) (Error scaled by 1.2)

\( e^- \) asymmetry parameter \( A \)

1 MAERKISCH 19 further derive a value for the CKM-element \( |V_{ud}| = 0.97351 \pm 0.00060 \), using \( \tau_n = 879.7(8) \) sec and the relation from CZARNECKI 18.
This MUND 13 value makes earlier PERKEO II measurements (ABELE 02 and ABELE 97D), with a correction to those results.

YEROZOLIMSKY 97 makes a correction to the EROZOLIMKII 91 value.

Under the SM assumption that the Fierz term $b = 0$, SAUL 20 obtain the quoted asymmetry parameter $A$ and $\lambda = -1.27607 \pm 0.00068$, and $b = 0.017 \pm 0.021$.

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.

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

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

$\nu_e$ 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.

<table>
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<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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<tr>
<td>0.9876±0.0004</td>
<td>1 MOSTOVOI 01 CNTR</td>
<td>Inferred</td>
<td></td>
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</table>

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

0.9800 ± 0.0004
KOLESNIK 03 CNTR
Cold n, polarized

0.9762 ± 0.0007
KOLESNIK 03 CNTR
Cold n, polarized

0.9769 ± 0.0007
KOLESNIK 03 CNTR
Cold n, polarized

0.9776 ± 0.0007
KOLESNIK 03 CNTR
Cold n, polarized

0.9780 ± 0.0007
KOLESNIK 03 CNTR
Cold n, polarized

0.9800 ± 0.0004
KOLESNIK 03 CNTR
Cold n, polarized

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.

<table>
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<td>$-0.2377 \pm 0.0010 \pm 0.0024$</td>
<td>SCHUMANN 08</td>
<td>CNTR</td>
<td>Cold $n$, polarized</td>
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$e^-\nu_e$ 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.

<table>
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<tr>
<td>$-0.1049 \pm 0.0013$ OUR AVERAGE</td>
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<td>$-0.10782 \pm 0.00124 \pm 0.00133$</td>
<td>HASSAN 21</td>
<td>SPEC</td>
<td>Proton recoil spectrum</td>
</tr>
<tr>
<td>$-0.10430 \pm 0.00084$</td>
<td>BECK 20</td>
<td>SPEC</td>
<td>Proton recoil spectrum</td>
</tr>
<tr>
<td>$-0.1054 \pm 0.0055$</td>
<td>BYRNE 02</td>
<td>SPEC</td>
<td>Proton recoil spectrum</td>
</tr>
<tr>
<td>$-0.1017 \pm 0.0051$</td>
<td>STRATOWA 78</td>
<td>CNTR</td>
<td>Proton recoil spectrum</td>
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<tr>
<td>$-0.091 \pm 0.039$</td>
<td>GRIGOREV 68</td>
<td>SPEC</td>
<td>Proton recoil spectrum</td>
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</table>

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<td>$-0.1090 \pm 0.0030 \pm 0.0028$</td>
<td>DARIUS 17</td>
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<td>Cold $n$, unpolarized</td>
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<td>$-0.1045 \pm 0.0014$</td>
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WEIGHTED AVERAGE $-0.1049 \pm 0.0013$ (Error scaled by 1.8)

$e^-\nu_e$ Angular correlation coefficient $a$

1 The result of HASSAN 21 includes the data of DARIUS 17, and thus supersedes those entries. HASSAN 21 uses the asymmetry in time-of-flight between the beta electron and recoil proton in delayed coincidence.
DARIUS 17 exploits a "wishbone" correlation, where the $p$ time of flight is correlated with the momentum of the electron in delayed coincidence. Data is included in HASSAN 21.

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 $180^\circ$. 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.

### Table: $\phi_{AV}$, Phase of $g_A$ Relative to $g_V$ ($^\circ$)

<table>
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<tr>
<th>VALUE ($^\circ$)</th>
<th>CL%</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
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<td>180.017 ± 0.026</td>
<td>OUR AVERAGE</td>
<td></td>
<td></td>
<td>See the ideogram below.</td>
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<tr>
<td>180.012 ± 0.028</td>
<td>68</td>
<td>CHUPP</td>
<td>12</td>
<td>CNTR Cold $n$, polarized &gt; 91%</td>
</tr>
<tr>
<td>180.04 ± 0.09</td>
<td></td>
<td>SOLDNER</td>
<td>04</td>
<td>CNTR Cold $n$, polarized</td>
</tr>
<tr>
<td>180.08 ± 0.13</td>
<td></td>
<td>LISING</td>
<td>00</td>
<td>CNTR Polarized &gt; 93%</td>
</tr>
</tbody>
</table>

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

Weighed Average

180.017 ± 0.026 (Error scaled by 1.0)

$\phi_{AV}$, Phase of $g_A$ Relative to $g_V$ ($^\circ$)

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.

<table>
<thead>
<tr>
<th>VALUE (units ( 10^{-4} ))</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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<tbody>
<tr>
<td>-1.2 ± 2.0 OUR AVERAGE</td>
<td>CHUPP 12 CNTR</td>
<td>Cold ( n ), polarized &gt; 91%</td>
<td></td>
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<tr>
<td>-0.94 ± 1.89 ± 0.97</td>
<td>CHUPP 12 CNTR</td>
<td>Cold ( n ), polarized &gt; 91%</td>
<td></td>
</tr>
<tr>
<td>-2.8 ± 6.4 ± 3.0</td>
<td>SOLDNER 04 CNTR</td>
<td>Cold ( n ), polarized</td>
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</tr>
<tr>
<td>-6 ± 12 ± 5</td>
<td>LISING 00 CNTR</td>
<td>Polarized &gt; 93%</td>
<td></td>
</tr>
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</table>

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

-0.96 ± 1.89 ± 1.01 MUMM 11 CNTR See CHUPP 12
+22 ± 30 EROZOLIMSKII 78 CNTR Cold \( n \), polarized
-27 ± 50 EROZOLIMSKII 74 CNTR Cold \( n \), polarized
-11 ± 17 STEINBERG 74 CNTR Cold \( n \), polarized

TRIPLE CORRELATION COEFFICIENT \( D \) (units \( 10^{-4} \))

\(^1\) 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.

<table>
<thead>
<tr>
<th>VALUE ( +0.004 ± 0.012 ± 0.005 )</th>
<th>DOCUMENT ID</th>
<th>TECN</th>
<th>COMMENT</th>
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<tr>
<td>+0.004 ± 0.012 ± 0.005</td>
<td>KOZELA 12 CNTR</td>
<td>Mott polarimeter</td>
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</table>

https://pdg.lbl.gov Page 17 Created: 12/4/2023 14:09
We do not use the following data for averages, fits, limits, etc.

\[ +0.008 \pm 0.015 \pm 0.005 \]

\[ 0.017 \pm 0.020 \pm 0.003 \]

**Fierz Interference Term \( b \)**

The coefficient of the Fierz interference term, \( b \), probes additional contributions to the differential decay rate of the neutron from scalar or tensor current interactions, beyond the Standard Model.

In a combined fit SAUL 20 extract this best fit value of the Fierz interference term \( b \) and the values \( A = -0.1209 \pm 0.0015 \) and \( \lambda = -1.2792 \pm 0.0060 \). For \( b \) it translates into a 90\% CL region of \(-0.018 \leq b \leq 0.052 \) as a function of \( A \).

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**REFERENCES**

We have omitted some papers that have been superseded by later experiments. See our earlier editions.
<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Reference</th>
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<td>Y.A. Mostovoy</td>
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<td>NORMAN</td>
<td>PR D53 4086</td>
<td>E.B. Norman, J.N. Bahcall, M. Goldhaber</td>
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<td>KOESTER</td>
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<td>L. Koester et al.</td>
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<td>S. Kopecky et al.</td>
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<td>GOLUB</td>
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<td>D. Dubbers et al.</td>
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