



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

We have omitted some results that have been superseded by later experiments.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 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.

<u>VALUE (<i>u</i>)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>1.00866491588 ± 0.0000000049</b>	MOHR	16	RVUE 2014 CODATA value
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
1.00866491600 ± 0.0000000043	MOHR	12	RVUE 2010 CODATA value
1.00866491597 ± 0.0000000043	MOHR	08	RVUE 2006 CODATA value
1.00866491560 ± 0.0000000055	MOHR	05	RVUE 2002 CODATA value
1.00866491578 ± 0.0000000055	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,  $1 \text{ u} = 931.494\,0054(57) \text{ MeV}/c^2$  (MOHR 16, the 2014 CODATA value), involves the relatively poorly known electronic charge.

<u>VALUE (MeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>939.5654133 ± 0.000058</b>	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	<sup>1</sup> KESSLER	99	SPEC $np \rightarrow d\gamma$
939.565330 ± 0.000038	MOHR	99	RVUE 1998 CODATA value
939.56565 ± 0.00028	<sup>2,3</sup> DIFILIPPO	94	TRAP Penning trap
939.56563 ± 0.00028	COHEN	87	RVUE 1986 CODATA value
939.56564 ± 0.00028	<sup>3,4</sup> GREENE	86	SPEC $np \rightarrow d\gamma$
939.5731 ± 0.0027	<sup>3</sup> COHEN	73	RVUE 1973 CODATA value

<sup>1</sup>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  $1.00866491637 \pm 0.00000000082 \text{ u}$ .

<sup>2</sup>The mass is known much more precisely in *u*:  $m = 1.0086649235 \pm 0.0000000023 \text{ u}$ . We use the 1986 CODATA conversion factor to get the mass in MeV.

<sup>3</sup>These determinations are not independent of the  $m_n - m_p$  measurements below.

<sup>4</sup>The mass is known much more precisely in *u*:  $m = 1.008664919 \pm 0.000000014 \text{ u}$ .

### $\bar{n}$ MASS

<u>VALUE (MeV)</u>	<u>EVTS</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>939.485 ± 0.051</b>	59	<sup>1</sup> CRESTI	86 HBC	$\bar{p}p \rightarrow \bar{n}n$

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

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

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

<u>VALUE</u>	<u>DOCUMENT ID</u>
<b>(9 ± 6) × 10<sup>-5</sup> OUR EVALUATION</b>	

### $m_n - m_p$

<u>VALUE (MeV)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>1.29333205 ± 0.00000051</b>	<sup>1</sup> MOHR	16 RVUE	2014 CODATA value
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
1.29333217 ± 0.00000042	<sup>2</sup> MOHR	12 RVUE	2010 CODATA value
1.29333214 ± 0.00000043	<sup>3</sup> MOHR	08 RVUE	2006 CODATA value
1.2933317 ± 0.0000005	<sup>4</sup> MOHR	05 RVUE	2002 CODATA value
1.2933318 ± 0.0000005	<sup>5</sup> MOHR	99 RVUE	1998 CODATA value
1.293318 ± 0.000009	<sup>6</sup> 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

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

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

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

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

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

<sup>6</sup> 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 seven of the best eight measurements, those made with ultra-cold neutrons (UCN's). If we include the one in-beam measurement with a comparable error (YUE 13), we get  $879.6 \pm 0.8$  s, where the scale factor is now 2.0.

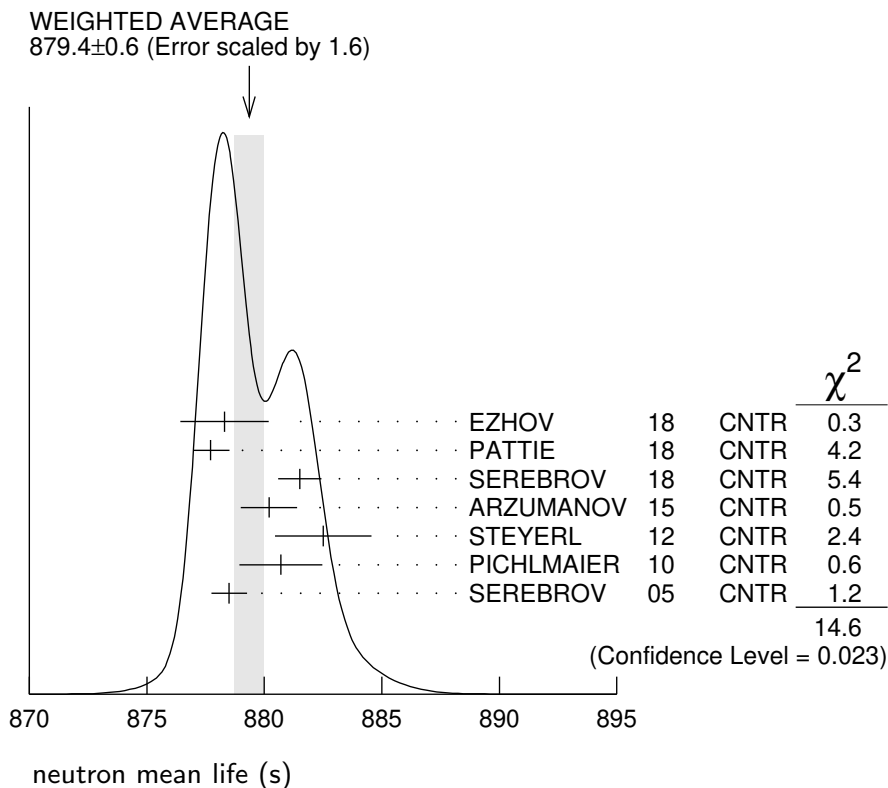
For a recent discussion of the long-standing disagreement between in-beam and UCN results, see CZARNECKI 18 (Physical Review Letters **120** 202002 (2018)). For a full review of all matters concerning the neutron lifetime until about 2010, see WIETFELDT 11, F.E. Wietfeldt and G.L. Greene, “The neutron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

<u>VALUE (s)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>879.4 ± 0.6 OUR AVERAGE</b>	Error includes scale factor of 1.6. See the ideogram below.		
878.3 ± 1.6 ± 1.0	EZHOV	18	CNTR UCN magneto-gravit. trap
877.7 ± 0.7 <sup>+</sup> <sub>-</sub> 0.4 0.2	<sup>1</sup> PATTIE	18	CNTR UCN asym. magnetic trap
881.5 ± 0.7 ± 0.6	SEREBROV	18	CNTR UCN gravitational trap
880.2 ± 1.2	<sup>2</sup> ARZUMANOV	15	CNTR UCN double bottle
882.5 ± 1.4 ± 1.5	<sup>3</sup> 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
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
887.7 ± 1.2 ± 1.9	<sup>4</sup> YUE	13	CNTR In-beam <i>n</i> , trapped <i>p</i>
881.6 ± 0.8 ± 1.9	<sup>5</sup> 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
889.2 ± 3.0 ± 3.8	BYRNE	96	CNTR Penning trap
882.6 ± 2.7	<sup>6</sup> MAMPE	93	CNTR UCN material bottle
888.4 ± 3.1 ± 1.1	<sup>7</sup> 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	<sup>8</sup> BYRNE	80	CNTR
875 ± 95	KOSVINTSEV	80	CNTR
881 ± 8	BONDAREN...	78	CNTR See SPIVAK 88
918 ± 14	CHRISTENSEN72	CNTR	

<sup>1</sup> PATTIE 18 uses a new technique, with a semi-toroidal magneto-gravitational asymmetric trap and a novel in situ *n*-detector.

<sup>2</sup> ARZUMANOV 15 is a reanalysis of their 2008–2010 dataset, with improved systematic corrections of of ARZUMANOV 00 and ARZUMANOV 12.

- <sup>3</sup> STEYERL 12 is a detailed reanalysis of neutron storage loss corrections to the raw data of MAMPE 89, and it replaces that value.
- <sup>4</sup> 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.
- <sup>5</sup> ARZUMANOV 12 reanalyzes its systematic corrections in ARZUMANOV 00 and obtains this corrected value.
- <sup>6</sup> 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.
- <sup>7</sup> The NESVIZHEVSKII 92 measurement has been withdrawn by A. Serebrov.
- <sup>8</sup> The BYRNE 80 measurement has been withdrawn (J. Byrne, private communication, 1990).



### ***n* MAGNETIC MOMENT**

See the "Quark Model" review.

<u>VALUE (<math>\mu_N</math>)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>−1.91304273 ± 0.00000045</b>	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	<sup>1</sup> GREENE	82	MRS

<sup>1</sup> GREENE 82 measures the moment to be  $(1.04187564 \pm 0.00000026) \times 10^{-3}$  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  $|d_n|$ .

<u>VALUE (<math>10^{-25}</math> e cm)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
< <b>0.18</b>	90	<sup>1</sup> ABEL 20	MRS	UCN
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
< 0.22	95	<sup>2</sup> SAHOO 17		<sup>199</sup> Hg atom EDM + theory
< 0.16	95	GRANER 16	MRS	<sup>199</sup> Hg atom EDM + theory
< 0.30	90	<sup>3</sup> PENDLEBURY 15	MRS	Supersedes BAKER 06
< 0.55	90	SEREBROV 15	MRS	UCN's, $h\nu = 2\mu_n B \pm 2d_n E$
< 0.55	90	<sup>4</sup> SEREBROV 14	MRS	See SEREBROV 15
< 0.29	90	<sup>5</sup> BAKER 06	MRS	See PENDLEBURY 15
< 0.63	90	<sup>6</sup> 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 ± 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	$d = (4.0 \pm 7.5) \times 10^{-25}$

<sup>1</sup> ABEL 20 reports  $d = (0.0 \pm 1.1 \pm 0.2) \times 10^{-26}$  e cm value corresponding to the listed limit.

<sup>2</sup> SAHOO 17 develops theory to calculate this limit from the measured limit by GRANER 16 of the <sup>199</sup>Hg atom EDM.

<sup>3</sup> PENDLEBURY 15 reports  $d = (-0.21 \pm 1.82) \times 10^{-26}$  e cm value corresponding to the listed limit.

<sup>4</sup> SEREBROV 14 includes the data of ALTAREV 96.

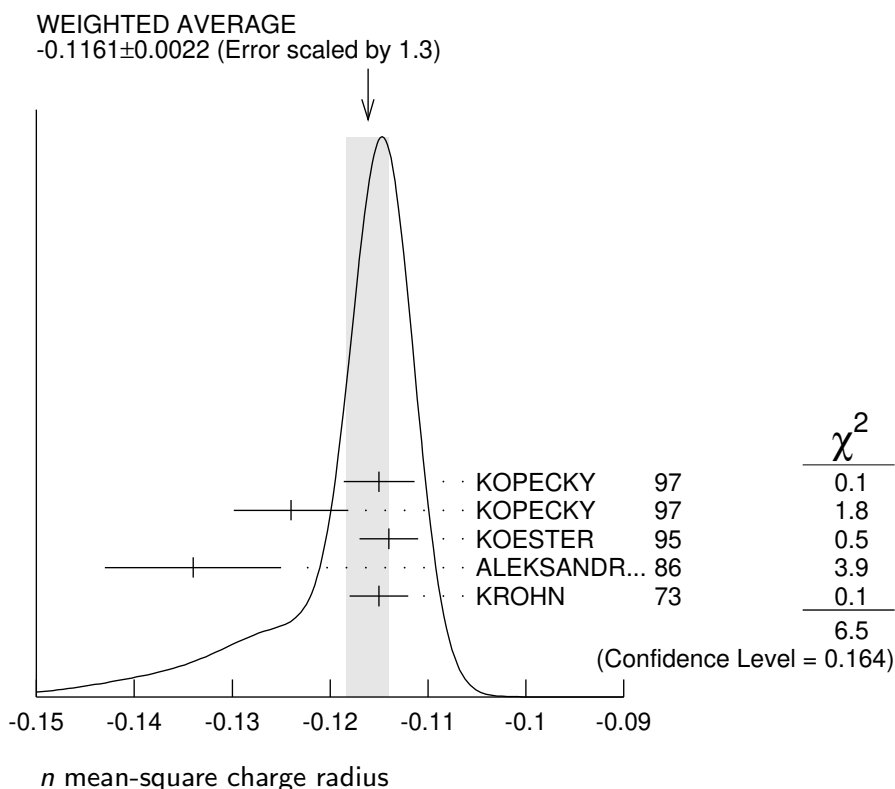
<sup>5</sup> LAMOREAUX 07 faults BAKER 06 for not including in the estimate of systematic error an effect due to the Earth's rotation. BAKER 07 replies (1) that the effect was included implicitly in the analysis and (2) that further analysis confirms that the BAKER 06 limit is correct as is. See also SILENKO 07.

<sup>6</sup> 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 <sup>2</sup> )	DOCUMENT ID	COMMENT
<b>-0.1161 ± 0.0022 OUR AVERAGE</b>		Error includes scale factor of 1.3. See the ideogram below.
-0.115 ± 0.002 ± 0.003	KOPECKY 97	$ne$ scattering (Pb)
-0.124 ± 0.003 ± 0.005	KOPECKY 97	$ne$ scattering (Bi)
-0.114 ± 0.003	KOESTER 95	$ne$ scattering (Pb, Bi)
-0.134 ± 0.009	ALEKSANDR...86	$ne$ scattering (Bi)
-0.115 ± 0.003	<sup>1</sup> KROHN 73	$ne$ scattering (Ne, Ar, Kr, Xe)
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●		
-0.106 +0.007 -0.005	<sup>2</sup> FILIN 20	chiral EFT analysis
-0.117 +0.007 -0.011	BELUSHKIN 07	Dispersion analysis
-0.113 ± 0.003 ± 0.004	KOPECKY 95	$ne$ scattering (Pb)
-0.114 ± 0.003	KOESTER 86	$ne$ scattering (Pb, Bi)
-0.118 ± 0.002	KOESTER 76	$ne$ scattering (Pb)
-0.120 ± 0.002	KOESTER 76	$ne$ scattering (Bi)
-0.116 ± 0.003	KROHN 66	$ne$ scattering (Ne, Ar, Kr, Xe)



<sup>1</sup> This value is as corrected by KOESTER 76.

<sup>2</sup> 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)	DOCUMENT ID	TECN	COMMENT
<b>0.864<sup>+0.009</sup><sub>-0.008</sub> OUR AVERAGE</b>			
0.89 ± 0.03	EPSTEIN	14	Using $e p$ , $e n$ , $\pi\pi$ data
0.862 <sup>+0.009</sup> <sub>-0.008</sub>	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 SCHMIED-MAYER 89.

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

VALUE ( $10^{-4}$ fm <sup>3</sup> )	DOCUMENT ID	TECN	COMMENT
<b>11.8 ± 1.1 OUR AVERAGE</b>			
11.55 ± 1.25 ± 0.8	MYERS	14	CNTR $\gamma d \rightarrow \gamma d$
12.5 ± 1.8 <sup>+1.6</sup> <sub>-1.3</sub>	<sup>1</sup> KOSSERT	03	CNTR $\gamma d \rightarrow \gamma p n$
12.0 ± 1.5 ± 2.0	SCHMIEDM...	91	CNTR $n$ Pb transmission
10.7 <sup>+3.3</sup> <sub>-10.7</sub>	ROSE	90B	CNTR $\gamma d \rightarrow \gamma n p$
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●			
8.8 ± 2.4 ± 3.0	<sup>2</sup> LUNDIN	03	CNTR $\gamma d \rightarrow \gamma d$
13.6	<sup>3</sup> KOLB	00	CNTR $\gamma d \rightarrow \gamma n p$
0.0 ± 5.0	<sup>4</sup> KOESTER	95	CNTR $n$ Pb, $n$ Bi transmission
11.7 <sup>+4.3</sup> <sub>-11.7</sub>	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

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

<sup>2</sup> LUNDIN 03 measures  $\alpha_N - \beta_N = (6.4 \pm 2.4) \times 10^{-4}$  fm<sup>3</sup> and uses accurate values for  $\alpha_p$  and  $\alpha_n$  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 are included in the analysis of MYERS 14.

<sup>3</sup> KOLB 00 obtains this value with a lower limit of  $7.6 \times 10^{-4}$  fm<sup>3</sup> 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<sup>3</sup>.

<sup>4</sup> 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 $\beta_n$

<u>VALUE (<math>10^{-4}</math> fm<sup>3</sup>)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>3.7 ± 1.2 OUR AVERAGE</b>			
3.65 ± 1.25 ± 0.8	MYERS	14	CNTR $\gamma d \rightarrow \gamma d$
2.7 ± 1.8 <sup>+1.3</sup> / <sub>-1.6</sub>	<sup>1</sup> KOSSERT	03	CNTR $\gamma d \rightarrow \gamma p n$
6.5 ± 2.4 ± 3.0	<sup>2</sup> LUNDIN	03	CNTR $\gamma d \rightarrow \gamma d$
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1.6	<sup>3</sup> KOLB	00	CNTR $\gamma d \rightarrow \gamma n p$
<sup>1</sup> KOSSERT 03 gets $\alpha_n - \beta_n = (9.8 \pm 3.6^{+2.1}_{-1.1} \pm 2.2) \times 10^{-4}$ fm <sup>3</sup> , and uses $\alpha_n + \beta_n = (15.2 \pm 0.5) \times 10^{-4}$ fm <sup>3</sup> from LEVCHUK 00. Thus the errors on $\alpha_n$ and $\beta_n$ are anti-correlated.			
<sup>2</sup> LUNDIN 03 measures $\alpha_N - \beta_N = (6.4 \pm 2.4) \times 10^{-4}$ fm <sup>3</sup> and uses accurate values for $\alpha_p$ and $\alpha_n$ 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.			
<sup>3</sup> KOLB 00 obtains this value with an upper limit of $7.6 \times 10^{-4}$ fm <sup>3</sup> 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 <sup>3</sup> .			

## $n$ CHARGE

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

<u>VALUE (<math>10^{-21}</math> e)</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>– 0.2 ± 0.8 OUR AVERAGE</b>			
– 0.1 ± 1.1	<sup>1</sup> BRESSI	11	Neutrality of SF <sub>6</sub>
– 0.4 ± 1.1	<sup>2</sup> BAUMANN	88	Cold $n$ deflection
• • • We do not use the following data for averages, fits, limits, etc. • • •			
– 15 ± 22	<sup>3</sup> GAEHLER	82	CNTR Cold $n$ deflection
<sup>1</sup> As a limit, this BRESSI 11 value is $< 1 \times 10^{-21}$ e.			
<sup>2</sup> The BAUMANN 88 error $\pm 1.1$ gives the 68% CL limits about the the value – 0.4.			
<sup>3</sup> 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  $\Delta B=2$  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.

<u>VALUE (s)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b>&gt; 4.7 × 10<sup>8</sup></b>	90	<sup>1</sup> ABE	21	CNTR $n$ bound in oxygen
<b>&gt; 8.6 × 10<sup>7</sup></b>	90	BALDO-...	94	CNTR Reactor (free) neutrons



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

$>1.37 \times 10^8$	90	<sup>2</sup> AHARMIM	17	SNO	$n$ bound in deuteron
$>2.7 \times 10^8$	90	ABE	15C	CNTR	$n$ bound in oxygen
$>1.3 \times 10^8$	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	

<sup>1</sup> ABE 21 supersedes ABE 15C.

<sup>2</sup> The AHARMIM 17 value is an unbounded limit (it does not assume a positive lifetime).  
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.

<u>VALUE (s)</u>	<u>CL%</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
>352	95	<sup>1</sup> ABEL	21	CNTR UCN, scan of $B$ field
<b>&gt;448</b>	90	SEREBROV	09A	CNTR Assumes $B' < 100$ nT
> 17	95	<sup>2</sup> BEREZHIANI	18	CNTR UCN, scan of $B$ field
> 12	95	<sup>3</sup> ALTAREV	09A	CNTR UCN, scan $0 \leq B \leq 12.5 \mu\text{T}$
>414	90	SEREBROV	08	CNTR UCN, $B$ field on & off
>103	95	BAN	07	CNTR UCN, $B$ field on & off

<sup>1</sup> 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  $\mu\text{T}$ .

<sup>2</sup> 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.

<sup>3</sup> 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
$\Gamma_1$ $p e^- \bar{\nu}_e$	100 %	
$\Gamma_2$ $p e^- \bar{\nu}_e \gamma$	[a] $(9.2 \pm 0.7) \times 10^{-3}$	
$\Gamma_3$ hydrogen-atom $\bar{\nu}_e$	$< 2.7 \times 10^{-3}$	95%

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

$\Gamma_4$ $p \nu_e \bar{\nu}_e$	$Q$ $< 8 \times 10^{-27}$	68%
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**Baryon number violating decay**

$\Gamma_5$ $e^+ e^-$ invisible		
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[a] This limit is for  $\gamma$  energies between 0.4 and 782 keV.

 **$n$  BRANCHING RATIOS** **$\Gamma(p e^- \bar{\nu}_e \gamma)/\Gamma_{\text{total}}$   $\Gamma_2/\Gamma$** 

VALUE (units $10^{-3}$ )	CL%	DOCUMENT ID	TECN	COMMENT
<b><math>9.17 \pm 0.24 \pm 0.64</math></b>		<sup>1</sup> BALES	16	RDK2 Two different set-ups
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$3.09 \pm 0.11 \pm 0.30$		<sup>2</sup> COOPER	10	CNTR See BALES 16
$3.13 \pm 0.11 \pm 0.33$		NICO	06	CNTR See COOPER 10
$< 6.9$	90	<sup>3</sup> BECK	02	CNTR $\gamma, p, e^-$ coincidence

<sup>1</sup> 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,  $(3.35 \pm 0.05 \pm 0.15) \times 10^{-3}$  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.

<sup>2</sup> This COOPER 10 result is for  $\gamma$  energies between 15 and 340 keV.

<sup>3</sup> This BECK 02 limit is for  $\gamma$  energies between 35 and 100 keV.

 **$\Gamma(\text{hydrogen-atom } \bar{\nu}_e)/\Gamma_{\text{total}}$   $\Gamma_3/\Gamma$** 

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<b><math>&lt; 0.27 \times 10^{-2}</math></b>	95	<sup>1</sup> CZARNECKI	18	Lifetime analysis
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$< 3 \times 10^{-2}$	95	<sup>2</sup> GREEN	90	RVUE

<sup>1</sup> 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.

<sup>2</sup> GREEN 90 infers that  $\tau(\text{hydrogen-atom } \bar{\nu}_e) > 3 \times 10^4$  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.

 **$\Gamma(p \nu_e \bar{\nu}_e)/\Gamma_{\text{total}}$   $\Gamma_4/\Gamma$** 

Forbidden by charge conservation.

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
<b><math>&lt; 8 \times 10^{-27}</math></b>	68	<sup>1</sup> NORMAN	96	RVUE $^{71}\text{Ga} \rightarrow ^{71}\text{Ge}$ neutrals
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$< 9.7 \times 10^{-18}$	90	ROY	83	CNTR $^{113}\text{Cd} \rightarrow ^{113m}\text{In}$ neut.

$<7.9 \times 10^{-21}$		VAIDYA	83	CNTR	$^{87}\text{Rb} \rightarrow ^{87m}\text{Sr}_{\text{neut.}}$
$<9 \times 10^{-24}$	90	BARABANOV	80	CNTR	$^{71}\text{Ga} \rightarrow ^{71}\text{GeX}$
$<3 \times 10^{-19}$		NORMAN	79	CNTR	$^{87}\text{Rb} \rightarrow ^{87m}\text{Sr}_{\text{neut.}}$

<sup>1</sup>NORMAN 96 gets this limit by attributing SAGE and GALLEX counting rates to the charge-nonconserving transition  $^{71}\text{Ga} \rightarrow ^{71}\text{Ge} + \text{neutrals}$  rather than to solar-neutrino reactions.

**$\Gamma(e^+e^- \text{ invisible})/\Gamma_{\text{total}}$**   **$\Gamma_5/\Gamma$**   
 Baryon number violating decay

VALUE	CL%	DOCUMENT ID	TECN	COMMENT
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• • • We do not use the following data for averages, fits, limits, etc. • • •

$<0.01$	90	<sup>1</sup> KLOPF	19	CNTR re-interpretation of MUND 13
$<1 \times 10^{-4}$	90	<sup>2</sup> SUN	18	SPEC Ultracold $n$ , polarized

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

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

See the related review(s):  
[Baryon Decay Parameters](#)

**$n \rightarrow pe^-\bar{\nu}_e$  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, MOSTOVOI 96, NICO 05, SEVERIJNS 06, and ABELE 08.

**$\lambda \equiv g_A / g_V$**

VALUE	DOCUMENT ID	TECN	COMMENT
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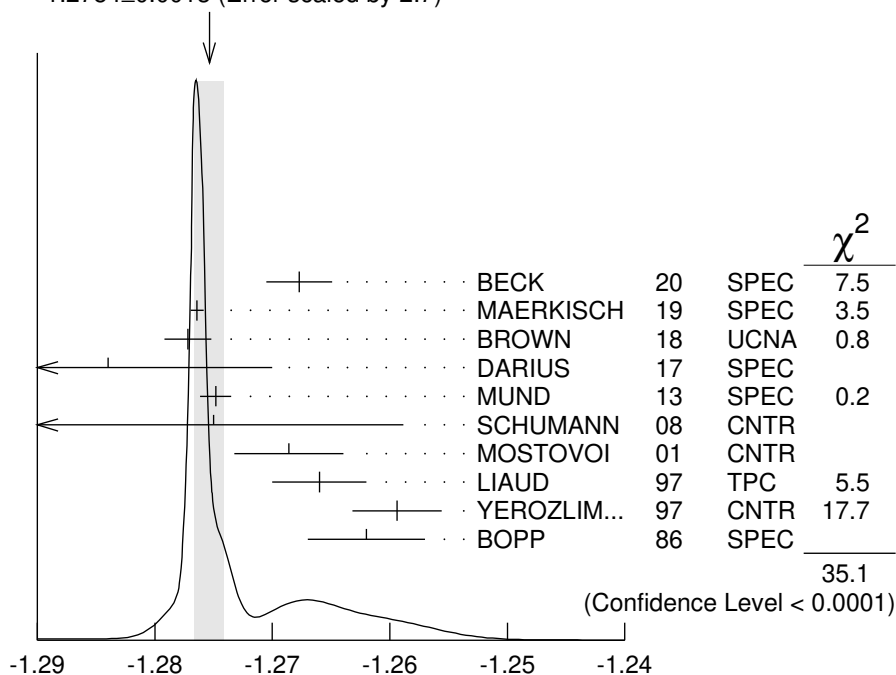
**$-1.2754 \pm 0.0013$  OUR AVERAGE** Error includes scale factor of 2.7. See the ideogram below.

$-1.2677 \pm 0.0028$	<sup>1</sup> BECK	20	SPEC Proton recoil spectrum
$-1.27641 \pm 0.00045 \pm 0.00033$	<sup>2</sup> MAERKISCH	19	SPEC pulsed cold $n$ , polarized
$-1.2772 \pm 0.0020$	<sup>3</sup> BROWN	18	UCNA Ultracold $n$ , polarized
$-1.284 \pm 0.014$	<sup>4</sup> DARIUS	17	SPEC Cold $n$ , unpolarized
$-1.2748 \pm 0.0008 \begin{smallmatrix} +0.0010 \\ -0.0011 \end{smallmatrix}$	<sup>5</sup> MUND	13	SPEC Cold $n$ , polarized
$-1.275 \pm 0.006 \pm 0.015$	SCHUMANN	08	CNTR Cold $n$ , polarized
$-1.2686 \pm 0.0046 \pm 0.0007$	<sup>6</sup> MOSTOVOI	01	CNTR $A$ and $B \times$ polarizations
$-1.266 \pm 0.004$	LIAUD	97	TPC Cold $n$ , polarized, $A$
$-1.2594 \pm 0.0038$	<sup>7</sup> 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. • • •

-1.27607 ± 0.00068	<sup>8</sup> SAUL	20	SPEC	Cold <i>n</i> , polarized, <i>A</i>
-1.2755 ± 0.0030	<sup>9</sup> MENDENHALL13	UCNA	See BROWN 18	
-1.27590 ± 0.00239 <sup>+0.00331</sup> <sub>-0.00377</sub>	<sup>10</sup> PLASTER	12	UCNA	See MENDENHALL 13
-1.27590 <sup>+0.00409</sup> <sub>-0.00445</sub>	LIU	10	UCNA	See PLASTER 12
-1.2739 ± 0.0019	<sup>11</sup> ABELE	02	SPEC	See MUND 13
-1.274 ± 0.003	ABELE	97D	SPEC	Cold <i>n</i> , polarized, <i>A</i>
-1.266 ± 0.004	SCHRECK...	95	TPC	See LIAUD 97
-1.2544 ± 0.0036	EROZOLIM...	91	CNTR	See YEROZOLIM-SKY 97
-1.226 ± 0.042	MOSTOVOY	83	RVUE	
-1.261 ± 0.012	EROZOLIM...	79	CNTR	Cold <i>n</i> , polarized, <i>A</i>
-1.259 ± 0.017	<sup>12</sup> STRATOWA	78	CNTR	<i>p</i> recoil spectrum, <i>a</i>
-1.263 ± 0.015	EROZOLIM...	77	CNTR	See EROZOLIMSKII 79
-1.250 ± 0.036	<sup>12</sup> DOBROZE...	75	CNTR	See STRATOWA 78
-1.258 ± 0.015	<sup>13</sup> KROHN	75	CNTR	Cold <i>n</i> , polarized, <i>A</i>
-1.263 ± 0.016	<sup>14</sup> KROPF	74	RVUE	<i>n</i> decay alone
-1.250 ± 0.009	<sup>14</sup> KROPF	74	RVUE	<i>n</i> decay + nuclear ft

WEIGHTED AVERAGE  
-1.2754 ± 0.0013 (Error scaled by 2.7)



$$\lambda \equiv g_A / g_V$$

<sup>1</sup> BECK 20 calculates this value from the measurement of the  $\beta$ -decay  $e-\bar{\nu}_e$  angular correlation coefficient *a*.

<sup>2</sup> MAERKISCH 19 gets  $A = -0.11985 \pm 0.00017 \pm 0.00012$ .

<sup>3</sup> 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).

<sup>4</sup> DARIUS 17 calculates this value from the measurement of the *a* parameter (see below).

- <sup>5</sup> This MUND 13 value includes earlier PERKEO II measurements (ABELE 02 and ABELE 97D).
- <sup>6</sup> 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.
- <sup>7</sup> YEROZOLIMSKY 97 makes a correction to the EROZOLIMSKII 91 value.
- <sup>8</sup> 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  $\lambda = -1.2792 \pm 0.0060$ .
- <sup>9</sup> 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.
- <sup>10</sup> This PLASTER 12 value is identical with that given in LIU 10, but the experiment is now described in detail.
- <sup>11</sup> This is the combined result of ABELE 02 and ABELE 97D.
- <sup>12</sup> These experiments measure the absolute value of  $g_A/g_V$  only.
- <sup>13</sup> KROHN 75 includes events of CHRISTENSEN 70.
- <sup>14</sup> KROPF 74 reviews all data through 1972.

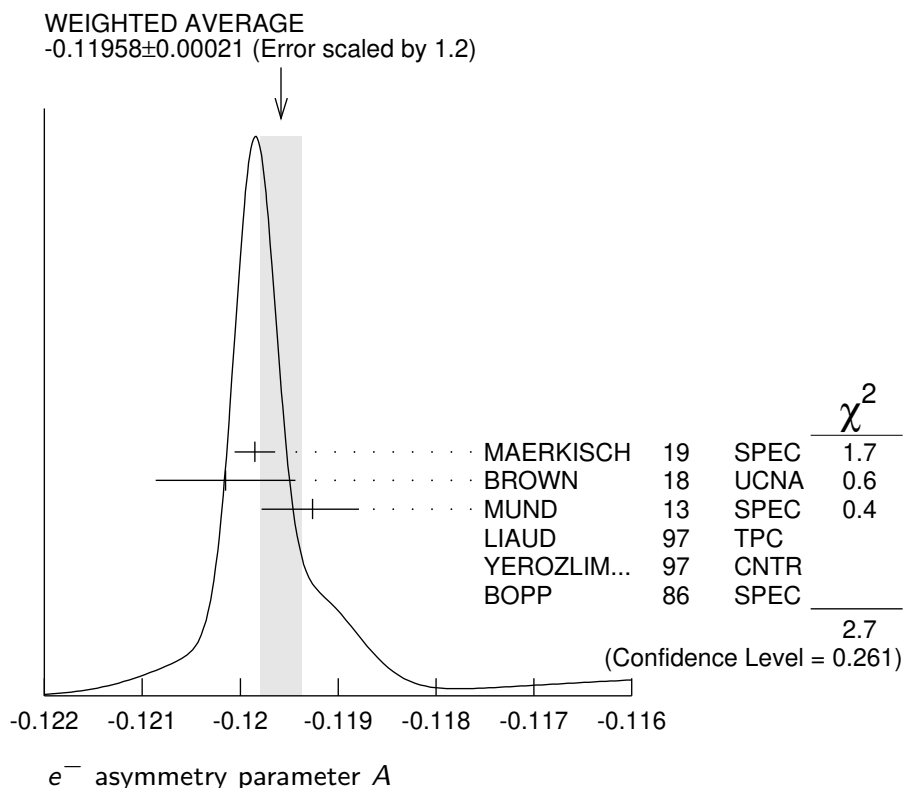
## $e^-$ ASYMMETRY PARAMETER $A$

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
<b><math>-0.11958 \pm 0.00021</math> OUR AVERAGE</b>	Error includes scale factor of 1.2. See the ideogram below.		
$-0.11985 \pm 0.00017 \pm 0.00012$	<sup>1</sup> MAERKISCH 19	SPEC	pulsed cold $n$ , polarized
$-0.12015 \pm 0.00034 \pm 0.00063$	<sup>2</sup> BROWN 18	UCNA	Ultracold $n$ , polarized
$-0.11926 \pm 0.00031 \begin{smallmatrix} +0.00036 \\ -0.00042 \end{smallmatrix}$	<sup>3</sup> MUND 13	SPEC	Cold $n$ , polarized
$-0.1160 \pm 0.0009 \pm 0.0012$	LIAUD 97	TPC	Cold $n$ , polarized
$-0.1135 \pm 0.0014$	<sup>4</sup> 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. • • •			
$-0.11972 \pm 0.00025$	<sup>5</sup> SAUL 20	SPEC	Cold $n$ , polarized
$-0.11952 \pm 0.00110$	<sup>6</sup> MENDENHALL13	UCNA	See BROWN 18
$-0.11966 \pm 0.00089 \begin{smallmatrix} +0.00123 \\ -0.00140 \end{smallmatrix}$	<sup>7</sup> PLASTER 12	UCNA	See MENDENHALL 13
$-0.11966 \pm 0.00089 \begin{smallmatrix} +0.00123 \\ -0.00140 \end{smallmatrix}$	LIU 10	UCNA	See PLASTER 12
$-0.1138 \pm 0.0046 \pm 0.0021$	PATTIE 09	SPEC	Ultracold $n$ , polarized
$-0.1189 \pm 0.0007$	<sup>8</sup> ABELE 02	SPEC	See MUND 13
$-0.1168 \pm 0.0017$	<sup>9</sup> 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 YEROZOLIM-SKY 97
$-0.114 \pm 0.005$	<sup>10</sup> EROZOLIM... 79	CNTR	Cold $n$ , polarized
$-0.113 \pm 0.006$	<sup>10</sup> KROHN 75	CNTR	Cold $n$ , polarized

- <sup>1</sup> 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.
- <sup>2</sup> 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).
- <sup>3</sup> This MUND 13 value includes earlier PERKEO II measurements (ABELE 02 and ABELE 97D), with a correction to those results.

- 4 YEROZOLIMSKY 97 makes a correction to the EROZOLIMSKII 91 value.
- 5 Under the SM assumption that the Fierz term  $b = 0$ , SAUL 20 obtain the quoted asymmetry parameter  $A$  and  $\lambda = -1.27607 \pm 0.00068$ . In a combined fit authors extract the values  $A = -0.1209 \pm 0.0015$ ,  $\lambda = -1.2792 \pm 0.0060$ , and  $b = 0.017 \pm 0.021$ .
- 6 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.
- 7 This PLASTER 12 value is identical with that given in LIU 10, but the experiment is now described in detail.
- 8 This is the combined result of ABELE 02 and ABELE 97D.
- 9 MOSTOVOI 01 calculates this from its measurement of  $\lambda = g_A/g_V$  above.
- 10 These results are not corrected for radiative effects and weak magnetism, but the corrections are small compared to the errors.

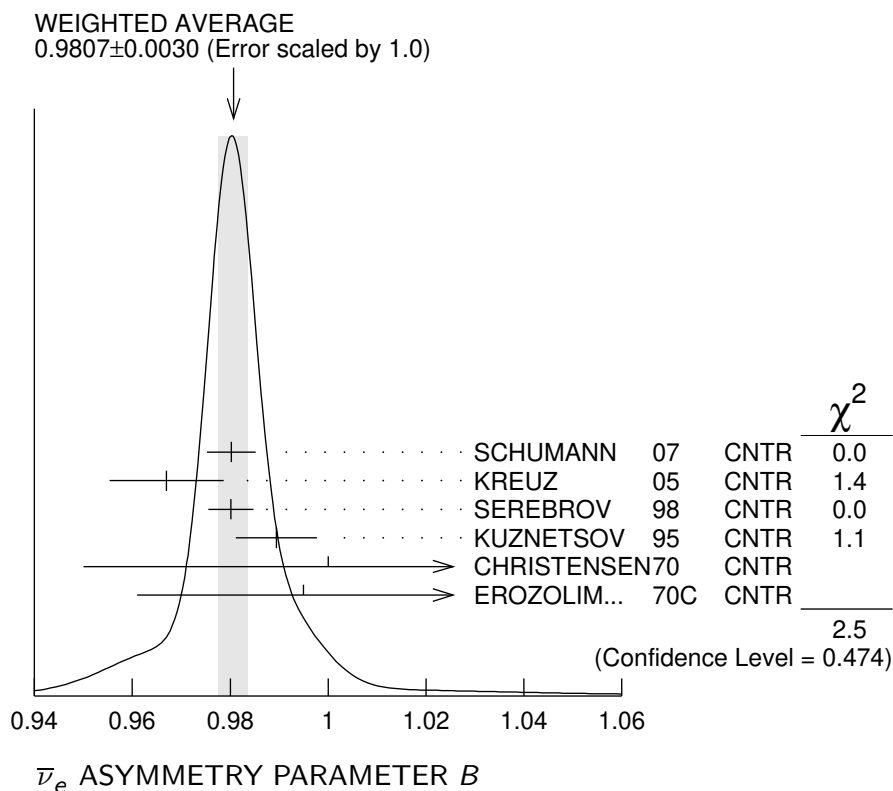


### $\bar{\nu}_e$ ASYMMETRY PARAMETER $B$

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.

<u>VALUE</u>	<u>DOCUMENT ID</u>	<u>TECN</u>	<u>COMMENT</u>
<b><math>0.9807 \pm 0.0030</math> OUR AVERAGE</b>	See the ideogram below.		
$0.9802 \pm 0.0034 \pm 0.0036$	SCHUMANN 07	CNTR	Cold $n$ , polarized
$0.967 \pm 0.006 \pm 0.010$	KREUZ 05	CNTR	Cold $n$ , polarized
$0.9801 \pm 0.0046$	SEREBROV 98	CNTR	Cold $n$ , polarized
$0.9894 \pm 0.0083$	KUZNETSOV 95	CNTR	Cold $n$ , polarized
$1.00 \pm 0.05$	CHRISTENSEN70	CNTR	Cold $n$ , polarized
$0.995 \pm 0.034$	EROZOLIM... 70C	CNTR	Cold $n$ , polarized
• • • We do not use the following data for averages, fits, limits, etc. • • •			
$0.9876 \pm 0.0004$	<sup>1</sup> MOSTOVOI 01	CNTR	Inferred

<sup>1</sup>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
<b>-0.2377 ± 0.0010 ± 0.0024</b>	SCHUMANN 08	CNTR	Cold $n$ , polarized

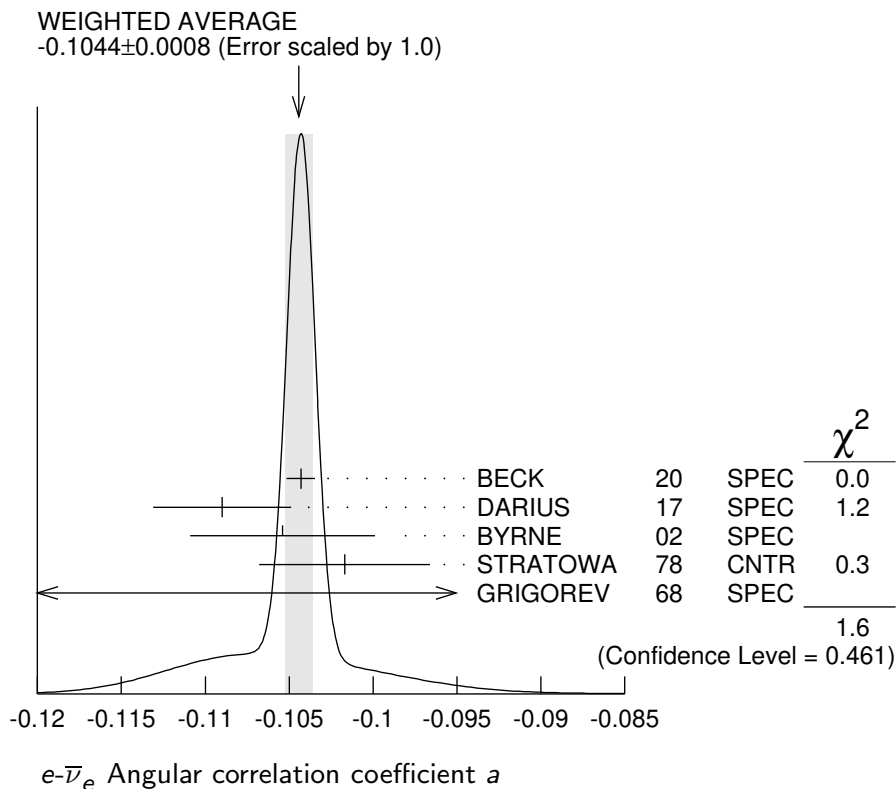
### $e\bar{\nu}_e$ ANGULAR CORRELATION COEFFICIENT $a$

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
<b>-0.1044 ± 0.0008 OUR AVERAGE</b>	See the ideogram below.		
-0.10430 ± 0.00084	BECK 20	SPEC	Proton recoil spectrum
-0.1090 ± 0.0030 ± 0.0028	<sup>1</sup> DARIUS 17	SPEC	Cold $n$ , unpolarized
-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	<sup>2</sup> MOSTOVOI 01	CNTR	Inferred

<sup>1</sup>DARIUS 17 exploits a "wishbone" correlation, where the  $p$  time of flight is correlated with the momentum of the electron in delayed coincidence.

<sup>2</sup>MOSTOVOI 01 calculates this from its measurement of  $\lambda=g_A/g_V$  above.



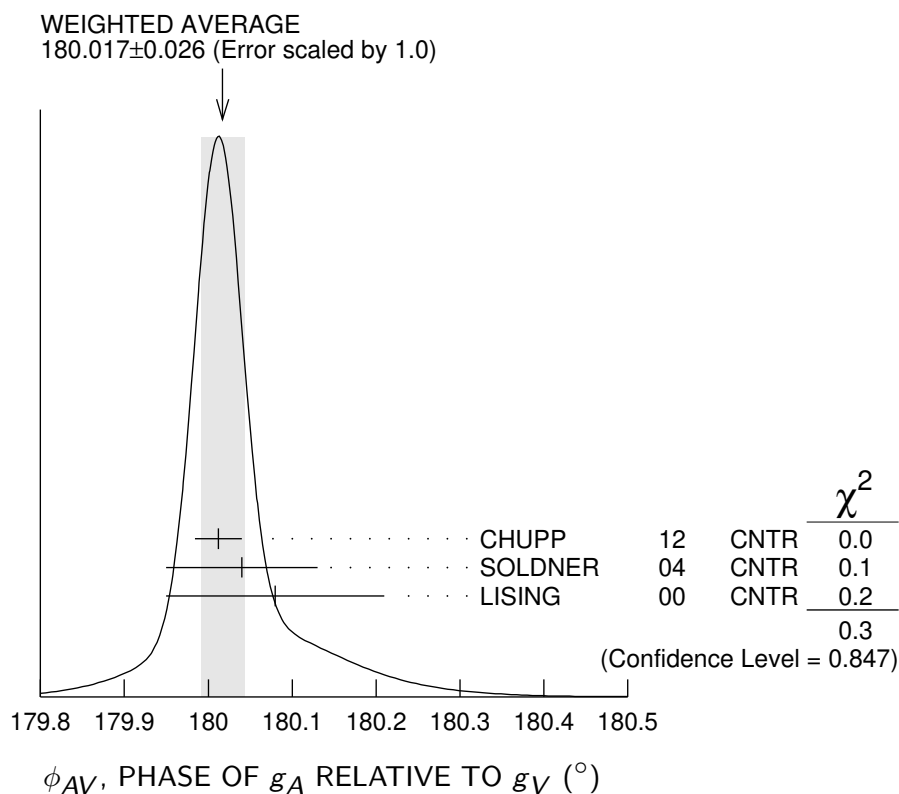
### $\phi_{AV}$ , PHASE OF $g_A$ RELATIVE TO $g_V$

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.

VALUE ( $^\circ$ )	CL%	DOCUMENT ID	TECN	COMMENT
<b><math>180.017 \pm 0.026</math></b>	<b>OUR AVERAGE</b>	See the ideogram below.		
$180.012 \pm 0.028$	68	CHUPP	12	CNTR Cold $n$ , polarized > 91%
$180.04 \pm 0.09$		SOLDNER	04	CNTR Cold $n$ , polarized
$180.08 \pm 0.13$		LISING	00	CNTR Polarized > 93%
● ● ● We do not use the following data for averages, fits, limits, etc. ● ● ●				
$180.013 \pm 0.028$		MUMM	11	CNTR See CHUPP 12
$179.71 \pm 0.39$		EROZOLIM...	78	CNTR Cold $n$ , polarized
$180.35 \pm 0.43$		EROZOLIM...	74	CNTR Cold $n$ , polarized
$181.1 \pm 1.3$		<sup>1</sup> KROPF	74	RVUE $n$ decay
$180.14 \pm 0.22$		STEINBERG	74	CNTR Cold $n$ , polarized

<sup>1</sup>KROPF 74 reviews all data through 1972.



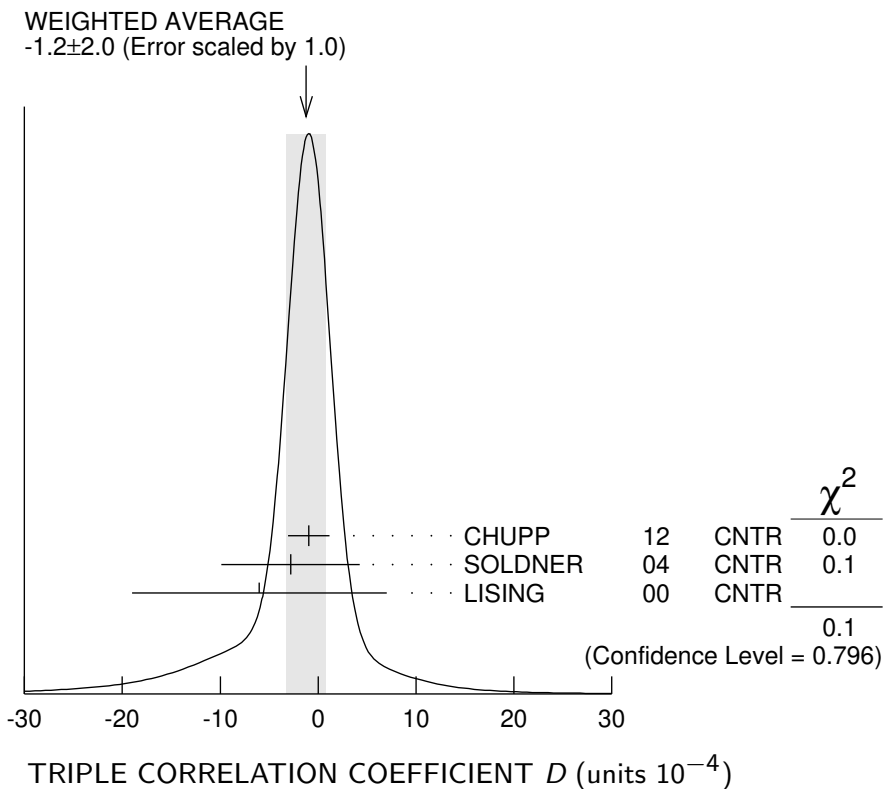


### TRIPLE CORRELATION COEFFICIENT $D$

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
<b><math>- 1.2 \pm 2.0</math> OUR AVERAGE</b>	See the ideogram below.		
$- 0.94 \pm 1.89 \pm 0.97$	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
$-27 \pm 50$	<sup>1</sup> EROZOLIM...	74	CNTR Cold $n$ , polarized
$-11 \pm 17$	STEINBERG	74	CNTR Cold $n$ , polarized

<sup>1</sup>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
<b><math>+0.004 \pm 0.012 \pm 0.005</math></b>	<sup>1</sup> 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

<sup>1</sup> 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  $N = +0.067 \pm 0.011 \pm 0.004$ .

### 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.

VALUE	DOCUMENT ID	TECN	COMMENT
<b><math>0.017 \pm 0.020 \pm 0.003</math></b>	<sup>1</sup> SAUL	20	SPEC Cold $n$ , polarized

<sup>1</sup> 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  $A$ .

**n** REFERENCES

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

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ABEL	21	PL B812 135993	C. Abel <i>et al.</i>	(nEDM Collab.)
ABEL	20	PRL 124 081803	C. Abel <i>et al.</i>	(nEDM Collab.)
BECK	20	PR C101 055506	M. Beck <i>et al.</i>	(aSPECT Collab.)
FILIN	20	PRL 124 082501	A.A. Filin <i>et al.</i>	
SAUL	20	PRL 125 112501	H. Saul <i>et al.</i>	(PERKEO III Collab.)
KLOPF	19	PRL 122 222503	M. Klopff <i>et al.</i>	(PERKEO II Collab.)
MAERKISCH	19	PRL 122 242501	B. Maerkisch <i>et al.</i>	(TUM, ILL, +)
BEREZHIANI	18	EPJ C78 717	Z. Berezhiani <i>et al.</i>	(AQUI, INFN, ILLG+)
BROWN	18	PR C97 035505	M.A.-P. Brown <i>et al.</i>	(UCNA Collab.)
CZARNECKI	18	PRL 120 202002	A. Czarnecki, W.J. Marciano, A. Sirlin	(ALBE+)
EZHOF	18	JETPL 107 671	V.F. Ezhov <i>et al.</i>	(PNPI, LENSU, CAEN+)
PATTIE	18	SCI 360 627	R.W. Pattie Jr. <i>et al.</i>	(LASL, IND, NCSU+)
SEREBROV	18	PR C97 055503	A.P. Serebrov <i>et al.</i>	(PNPI, ILLG, RAL)
Also		JETPL 106 623	A.P. Serebrov <i>et al.</i>	(PNPI, ILLG, RAL)
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AHARMIM	17	PR D96 092005	B. Aharmin <i>et al.</i>	(SNO Collab.)
DARIUS	17	PRL 119 042502	G. Darius <i>et al.</i>	(aCORN at NIST)
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PENDLEBURY	15	PR D92 092003	J.M. Pendlebury <i>et al.</i>	(ETHZ, PSI, SUSS)
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YUE	13	PRL 111 222501	A.T. Yue <i>et al.</i>	(UMD, NIST, TENN, ORNL+)
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CHUPP	12	PR C86 035505	T.E. Chupp <i>et al.</i>	(MICH, UCB, WASH+)
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MUMM	11	PRL 107 102301	H.P. Mumm <i>et al.</i>	(NIST, WASH, MICH, LBL+)
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SEVERIJNS	06	RMP 78 991	N. Severijns, M. Beck, O. Naviliat-Cuncic	(LEUV+)
KREUZ	05	PL B619 263	M. Kreuz <i>et al.</i>	(HEID, ILLG, MAINZ, KARL+)
MOHR	05	RMP 77 1	P.J. Mohr, B.N. Taylor	(NIST)
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SCHUMACHER	05	PPNP 55 567	M. Schumacher	(GOET)
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ABELE	02	PRL 88 211801	H. Abele <i>et al.</i>	(PERKEO-II Collab.)
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CHUNG	02B	PR D66 032004	J. Chung <i>et al.</i>	(SOUDAN-2 Collab.)
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LEVCHUK	00	NP A674 449	M.I. Levchuk, A.I. L'vov	(BELA, LEBD)
LISING	00	PR C62 055501	L.J. Lising <i>et al.</i>	(NIST emiT Collab.)
HARRIS	99	PRL 82 904	P.G. Harris <i>et al.</i>	
KESSLER	99	PL A255 221	E.G. Kessler Jr <i>et al.</i>	
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SEREBROV	98	JETP 86 1074	A.P. Serebrov <i>et al.</i>	
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ABELE	97D	PL B407 212	H. Abele <i>et al.</i>	(HEIDP, ILLG)
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LIAUD	97	NP A612 53	P. Liaud <i>et al.</i>	(ILLG, LAPP)
YEROZLIM...	97	PL B412 240	B.G. Eroozlimsky <i>et al.</i>	(HARV, PNPI, KIAE)
ALTAREV	96	PAN 59 1152	I.S. Altarev <i>et al.</i>	(PNPI)
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BONDAREN...	96	JETPL 64 416	L.N. Bondarenko <i>et al.</i>	(KIAE)
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BYRNE	96	EPL 33 187	J. Byrne <i>et al.</i>	(SUSS, ILLG)
MOSTOVOI	96	PAN 59 968	Y.A. Mostovoy	(KIAE)
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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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SCHRECK...	95	PL B349 427	K. Schreckenbach <i>et al.</i>	(TUM, ILLG, LAPP)
BALDO-...	94	ZPHY C63 409	M. Baldo-Ceolin <i>et al.</i>	(HEID, ILLG, PADO+)
DIFILIPPO	94	PRL 73 1481	F. DiFilippo <i>et al.</i>	(MIT)
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GOLUB	94	PRPL 237C 1	R. Golub, K. Lamoreaux	(HAHN, WASH)
MAMPE	93	JETPL 57 82	B. Mampe <i>et al.</i>	(KIAE)
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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. Eroozlimsky <i>et al.</i>	(PNPI, KIAE)
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SCHMIEDM...	91	PRL 66 1015	J. Schmiedmayer <i>et al.</i>	(TUW, ORNL)
WOOLCOCK	91	MPL A6 2579	W.S. Woolcock	(CANB)
ALFIMENKOV	90	JETPL 52 373	V.P. Alfimenkov <i>et al.</i>	(PNPI, JINR)
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BALDO-...	90	PL B236 95	M. Baldo-Ceolin <i>et al.</i>	(PADO, PAVI, HEIDP+)
BERGER	90	PL B240 237	C. Berger <i>et al.</i>	(FREJUS Collab.)
BRESSI	90	NC 103A 731	G. Bressi <i>et al.</i>	(PAVI, ROMA, MILA)
BYRNE	90	PRL 65 289	J. Byrne <i>et al.</i>	(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 <i>et al.</i>	(GOET, MPCM, MAINZ)
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SMITH	90	PL B234 191	K.F. Smith <i>et al.</i>	(SUSS, RAL, HARV+)
BRESSI	89	ZPHY C43 175	G. Bressi <i>et al.</i>	(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 <i>et al.</i>	(LAPP, SAVO, ISNG+)
MAMPE	89	PRL 63 593	W. Mampe <i>et al.</i>	(ILLG, RISL, SUSS, URI)
MOHAPATRA	89	NIM A284 1	R.N. Mohapatra	(UMD)
PAUL	89	ZPHY C45 25	W. Paul <i>et al.</i>	(BONN, WUPP, MPIK, ILLG)
SCHMIEDM...	89	NIM A284 137	J. Schmiedmayer, H. Rauch, P. Riehs	(WIEN)
BAUMANN	88	PR D37 3107	J. Baumann <i>et al.</i>	(BAYR, MUNI, ILLG)
KOESTER	88	ZPHY A329 229	L. Koester, W. Waschkowski, J. Meier	(MUNI, TUM)
LAST	88	PRL 60 995	I. Last <i>et al.</i>	(HEIDP, ILLG, ANL)
SCHMIEDM...	88	PRL 61 1065	J. Schmiedmayer, H. Rauch, P. Riehs	(TUW)
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SPIVAK	88	JETP 67 1735	P.E. Spivak	(KIAE)
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COHEN	87	RMP 59 1121	E.R. Cohen, B.N. Taylor	(RISC, NBS)
ALEKSANDR...	86	SJNP 44 900	Yu.A. Aleksandrov <i>et al.</i>	
		Translated from YAF 44 1384.		
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BOPP	86	PRL 56 919	P. Bopp <i>et al.</i>	(HEIDP, ANL, ILLG)
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CRESTI	86	PL B177 206	M. Cresti <i>et al.</i>	(PADO)
Also		PL B200 587 (erratum)	M. Cresti <i>et al.</i>	(PADO)
GREENE	86	PRL 56 819	G.L. Greene <i>et al.</i>	(NBS, ILLG)
KOESTER	86	Physica B137 282	L. Koester <i>et al.</i>	
KOSVINTSEV	86	JETPL 44 571	Y.Y. Kosvintsev, V.I. Morozov, G.I. Terekhov	(KIAE)
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TAKITA	86	PR D34 902	M. Takita <i>et al.</i>	(KEK, TOKY+)
DOVER	85	PR C31 1423	C.B. Dover, A. Gal, J.M. Richard	(BNL)
FIDECARO	85	PL 156B 122	G. Fidecaro <i>et al.</i>	(CERN, ILLG, PADO+)
PARK	85B	NP B252 261	H.S. Park <i>et al.</i>	(IMB Collab.)
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JONES	84	PRL 52 720	T.W. Jones <i>et al.</i>	(IMB Collab.)
PENDLEBURY	84	PL 136B 327	J.M. Pendlebury <i>et al.</i>	(SUSS, HARV, RAL+)
CHERRY	83	PRL 50 1354	M.L. Cherry <i>et al.</i>	(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)
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ROY	83	PR D28 1770	A. Roy <i>et al.</i>	(TATA)
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GAHLER	82	PR D25 2887	R. Gahler, J. Kalus, W. Mampe	(BAYR, ILLG)
GREENE	82	Metrologia 18 93	G.L. Greene <i>et al.</i>	(YALE, HARV, ILLG+)
ALTAREV	81	PL 102B 13	I.S. Altarev <i>et al.</i>	(PNPI)
BARABANOV	80	JETPL 32 359	I.R. Barabanov <i>et al.</i>	(PNPI)
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KOSVINTSEV	80	JETPL 31 236	Y.Y. Kosvintsev <i>et al.</i>	(JINR)
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MOHAPATRA	80	PRL 44 1316	R.N. Mohapatra, R.E. Marshak	(CUNY, VPI)
ALTAREV	79	JETPL 29 730	I.S. Altarev <i>et al.</i>	(PNPI)
		Translated from ZETFP 29 794.		
EROZOLIM...	79	SJNP 30 356	B.G. Erokolimsky <i>et al.</i>	(KIAE)
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NORMAN	79	PRL 43 1226	E.B. Norman, A.G. Seamster	(WASH)
BONDAREN...	78	JETPL 28 303	L.N. Bondarenko <i>et al.</i>	(KIAE)
		Translated from ZETFP 28 328.		
Also		Smolenice Conf.	P.G. Bondarenko	(KIAE)
EROZOLIM...	78	SJNP 28 48	B.G. Erokolimsky <i>et al.</i>	(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. Erokolimsky <i>et al.</i>	(KIAE)
		Translated from ZETFP 23 720.		
KOESTER	76	PRL 36 1021	L. Koester <i>et al.</i>	
STEINBERG	76	PR D13 2469	R.I. Steinberg <i>et al.</i>	(YALE, ISNG)
DOBROZE...	75	PR D11 510	R. Dobrozemsky <i>et al.</i>	(SEIB)
KROHN	75	PL 55B 175	V.E. Krohn, G.R. Ringo	(ANL)
EROZOLIM...	74	JETPL 20 345	B.G. Erokolimsky <i>et al.</i>	
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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 <i>et al.</i>	(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 <i>et al.</i>	(RISO)
CHRISTENSEN	70	PR C1 1693	C.J. Christensen, V.E. Krohn, G.R. Ringo	(ANL)
EROZOLIM...	70C	PL 33B 351	B.G. Erokolimsky <i>et al.</i>	(KIAE)
GRIGOREV	68	SJNP 6 239	V.K. Grigoriev <i>et al.</i>	(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)

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