n

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

We have omitted some results that have been superseded by later experiments.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

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

n MASS (atomic mass units u)

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

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

n MASS (MeV)

The mass is known much more precisely in u (atomic mass units) than in MeV. The conversion from u to MeV, 1 u = 931.494 061(21) MeV/c^2 (MOHR 12, the 2010 CODATA value), involves the relatively poorly known electronic charge.

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

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

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

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

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

$\overline{n}$ MASS

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

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

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

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

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

$m_n - m_p$

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

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

[2] 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.

[3] 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.

[4] 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.

[5] 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."

The mean life of the neutron, 878.5 ± 0.8 s, obtained by SEREBROV 05 (for a more detailed account, see SEREBROV 08A; and for comments on the systematic error for this result, see STEYERL 10) was so far from our average of seven other measurements, 885.7 ± 0.8 s, that it made no sense to include it in our average. Thus our 2006, 2008, and 2010 *Reviews* stayed with 885.7 ± 0.8 s; but we noted that in light of SEREBROV 05 our value should be regarded as suspect until further experiments clarified matters.

However, after our 2010 *Review*, PICHLMAIER 10 obtained a mean life of 880.7 ± 1.8 s, and we averaged the best seven results to get 881.5 ± 1.5 s for our 2011 off-year web update. Since then, ARZUMANOV 12, responding to comments of SEREBROV 10B, recalculated the systematic corrections to its 2000 measurement (ARZUMANOV 00) and lowered its value from 885.4 ± 0.9 ± 0.4 s to 881.6 ± 0.8 ± 1.9 s. And STEYERL 12 reanalyzed systematic corrections to MAMPE 89 and lowered its value from 887.6 ± 3.0 to 882.5 ± 1.4 ± 1.5 s. Thus the trend is definitely toward a shorter lifetime.

There seems little better to do than to again average the best seven measurements. The result, 880.3 ± 1.1 s (including a scale factor of 1.9), is 5.4 seconds lower than the value we gave in 2010—a drop of 6.8 old and 4.9 new standard deviations.

For a full review of all matters concerning the neutron lifetime, see F.E. Wietfeldt and G.L. Greene, "The neutron lifetime," Reviews of Modern Physics **83** 1173 (2011). In particular, there is a full discussion of the experimental methods and results; and an average lifetime is obtained making several different selections of those results. (The revised ARZUMANOV 12 mean life was not yet available.)

VALUE (s)	*DOCUMENT ID*		*TECN*	*COMMENT*
880.3± 1.1 OUR AVERAGE	Error includes scale factor of 1.9. See the ideogram below.			
887.7± 1.2± 1.9	[1] YUE	13	CNTR	In-beam *n*, trapped *p*
881.6± 0.8± 1.9	[2] ARZUMANOV	12	CNTR	UCN double bottle
882.5± 1.4± 1.5	[3] STEYERL	12	CNTR	UCN material bottle
880.7± 1.3± 1.2	PICHLMAIER	10	CNTR	UCN material bottle
878.5± 0.7± 0.3	SEREBROV	05	CNTR	UCN gravitational trap
889.2± 3.0± 3.8	BYRNE	96	CNTR	Penning trap
882.6± 2.7	[4] MAMPE	93	CNTR	UCN material bottle
• • • We do not use the following data for averages, fits, limits, etc. • • •				
886.3± 1.2± 3.2	NICO	05	CNTR	See YUE 13
886.8± 1.2± 3.2	DEWEY	03	CNTR	See NICO 05
885.4± 0.9± 0.4	ARZUMANOV	00	CNTR	See ARZUMANOV 12
888.4± 3.1± 1.1	[5] 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	[6] BYRNE	80	CNTR	
875 ±95	KOSVINTSEV	80	CNTR	
881 ± 8	BONDAREN...	78	CNTR	See SPIVAK 88
918 ±14	CHRISTENSEN	72	CNTR	

[1] 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.

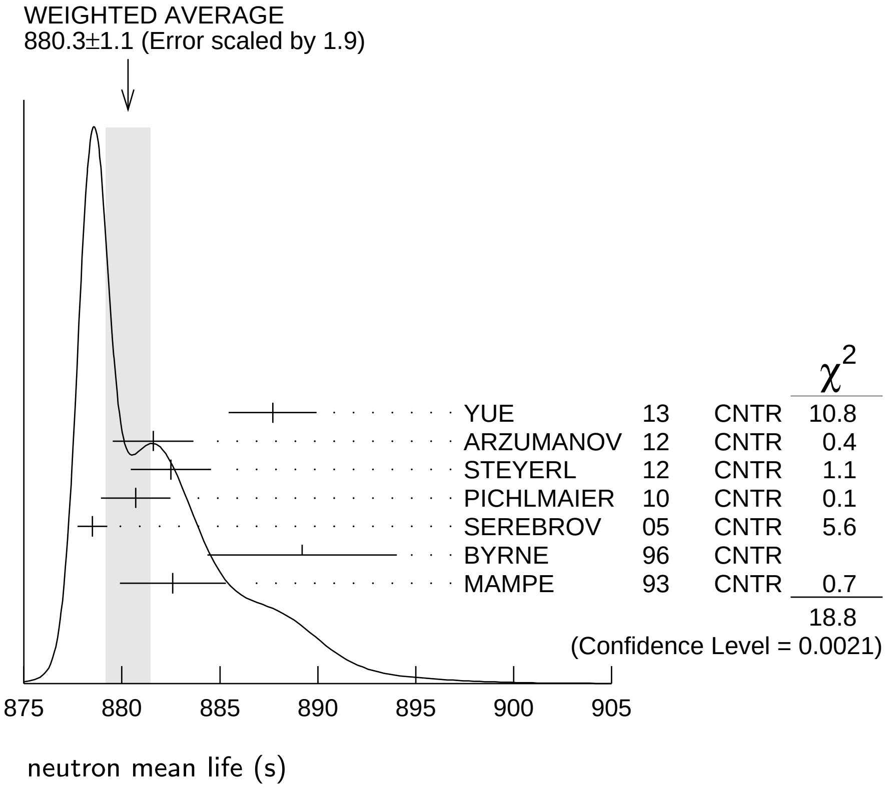
[2] ARZUMANOV 12 reanalyzes its systematic corrections in ARZUMANOV 00 and obtains this corrected value.

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

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

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

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



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n MAGNETIC MOMENT

See the "Note on Baryon Magnetic Moments" in the Λ Listings.

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

[1] GREENE 82 measures the moment to be $(1.04187564 \pm 0.00000026) \times 10^{-3}$ 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.

VALUE (10^{-25} *e* cm)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 0.29	90	[1] BAKER	06	MRS	UCN's, $h\nu = 2\mu_n B \pm 2d_n E$

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

VALUE (10^{-25} *e* cm)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
< 0.55	90	[2] SEREBROV	14	MRS	UCN (early result)
< 0.63	90	[3] 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	$d = (4.0 \pm 7.5) \times 10^{-25}$

[1] 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.

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

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

n MEAN-SQUARE CHARGE RADIUS

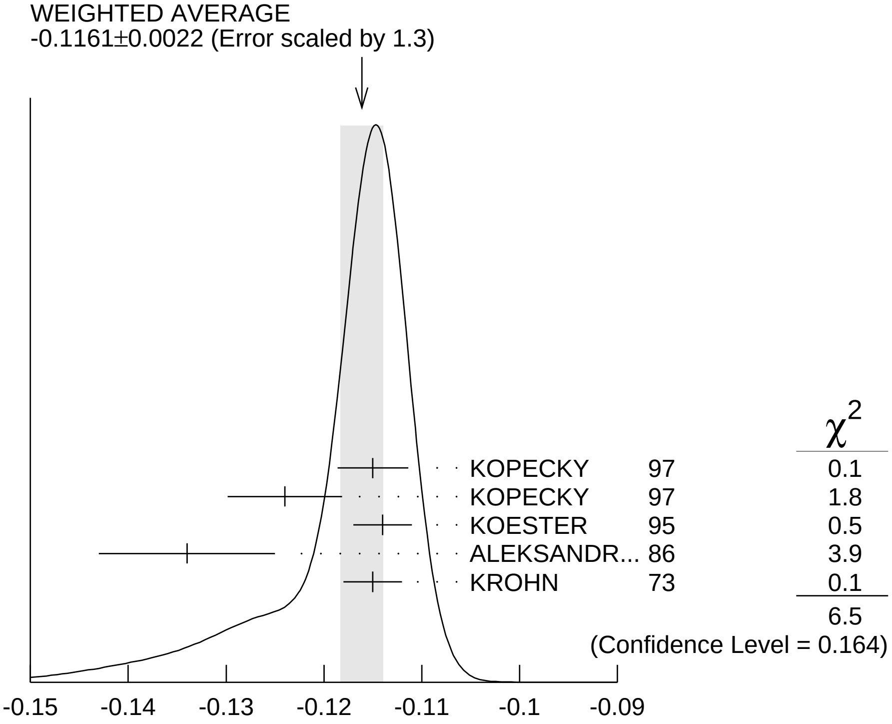
The mean-square charge radius of the neutron, $\langle r_n^2 \rangle$, is related to the neutron-electron scattering length b_{ne} by $\langle r_n^2 \rangle = 3(m_e a_0/m_n) b_{ne}$, where m_e and m_n are the masses of the electron and neutron, and a_0 is the Bohr radius. Numerically, $\langle r_n^2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

VALUE (fm^2)	*DOCUMENT ID*		*COMMENT*
−0.1161±0.0022 OUR AVERAGE	Error includes scale factor of 1.3. See the ideogram below.		
−0.115 ±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	[1] KROHN	73	*ne* scattering (Ne, Ar, Kr, Xe)

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

$-0.117\ {}^{+0.007}_{-0.011}$	BELUSHKIN	07	Dispersion analysis
$-0.113 \pm 0.003 \pm 0.004$	KOPECKY	95	$n\,e$ scattering (Pb)
-0.114 ± 0.003	KOESTER	86	$n\,e$ scattering (Pb, Bi)
-0.118 ± 0.002	KOESTER	76	$n\,e$ scattering (Pb)
-0.120 ± 0.002	KOESTER	76	$n\,e$ scattering (Bi)
-0.116 ± 0.003	KROHN	66	$n\,e$ scattering (Ne, Ar, Kr, Xe)

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



n mean-square charge radius

n MAGNETIC RADIUS

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

VALUE (fm)	*DOCUMENT ID*		*COMMENT*
$\mathbf{0.862^{+0.009}_{-0.008}}$	BELUSHKIN	07	Dispersion analysis

n ELECTRIC POLARIZABILITY α_n

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

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

VALUE (10^{-4} fm^3)	*DOCUMENT ID*		*TECN*	*COMMENT*
11.8 ± 1.1 OUR AVERAGE				
$11.55 \pm 1.25 \pm 0.8$	MYERS	14	CNTR	$\gamma d \rightarrow \gamma d$
$12.5 \pm 1.8\ ^{+1.6}_{-1.3}$	[1] KOSSERT	03	CNTR	$\gamma d \rightarrow \gamma p n$
$12.0 \pm 1.5 \pm 2.0$	SCHMIEDM...	91	CNTR	n Pb transmission
$10.7\ ^{+\ 3.3}_{-10.7}$	ROSE	90B	CNTR	$\gamma d \rightarrow \gamma n p$
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$8.8 \pm 2.4 \pm 3.0$	[2] LUNDIN	03	CNTR	$\gamma d \rightarrow \gamma d$
13.6	[3] KOLB	00	CNTR	$\gamma d \rightarrow \gamma n p$
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 $\alpha_n - \beta_n = (9.8 \pm 3.6^{+2.1}_{-1.1} \pm 2.2) \times 10^{-4}$ fm^3, and uses $\alpha_n + \beta_n = (15.2 \pm 0.5) \times 10^{-4}$ fm^3 from LEVCHUK 00. Thus the errors on α_n and β_n are anti-correlated.

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

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

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

n MAGNETIC POLARIZABILITY β_n

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

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

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

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

n CHARGE

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

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

[1] As a limit, this BRESSI 11 value is $< 1 \times 10^{-21}$ *e*.

[2] The BAUMANN 88 error ±1.1 gives the 68% CL limits about the the value −0.4.

[3] The GAEHLER 82 error ±22 gives the 90% CL limits about the the value −15.

LIMIT ON $n\overline{n}$ OSCILLATIONS

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

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

VALUE (s)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>1.3 × 10⁸	90	CHUNG	02B	SOU2	*n* bound in iron
>8.6 × 10⁷	90	BALDO-...	94	CNTR	Reactor (free) neutrons
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$>1 \times 10^{7}$	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	
$> 2.7 \times 10^{7}$–1.1×10^{8}		JONES	84	CNTR	
$>2 \times 10^{7}$		CHERRY	83	CNTR	

LIMIT ON nn' OSCILLATIONS

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

VALUE (s)	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
>414	90	SEREBROV	08	CNTR	UCN, B field on & off
• • • We do not use the following data for averages, fits, limits, etc. • • •					

> 12	95	[1] ALTAREV	09A	CNTR	UCN, scan $0 \leq B \leq 12.5$ μT
>103	95	BAN	07	CNTR	UCN, B field on & off

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

n DECAY MODES

	Mode		Fraction (Γ_i/Γ)	Confidence level
Γ_1	$p e^- \overline{\nu}_e$		100 %	
Γ_2	$p e^- \overline{\nu}_e \gamma$	[a]	$(3.09 \pm 0.32) \times 10^{-3}$	
Γ_3	hydrogen-atom $\overline{\nu}_e$			

Charge conservation (Q) violating mode

Γ_4	$p \nu_e \overline{\nu}_e$	Q	$< 8 \times 10^{-27}$	68%

[a] This limit is for γ energies between 15 and 340 keV.

n BRANCHING RATIOS

$\Gamma(p e^- \overline{\nu}_e \gamma)/\Gamma_{\text{total}}$ Γ_2/Γ

VALUE (units 10^{-3})	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
3.09±0.11±0.30		[1] COOPER	10	CNTR	γ, p, e^- coincidence
• • • We do not use the following data for averages, fits, limits, etc. • • •					
3.13±0.11±0.33		NICO	06	CNTR	See COOPER 10
<6.9	90	[2] BECK	02	CNTR	γ, p, e^- coincidence

[1] This COOPER 10 result is for γ energies between 15 and 340 keV.

[2] This BECK 02 limit is for γ energies between 35 and 100 keV.

$\Gamma(\text{hydrogen-atom } \overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_3/Γ

VALUE	*CL%*	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •				
$<3 \times 10^{-2}$	95	[1] GREEN	90	RVUE

[1] GREEN 90 infers that $\tau(\text{hydrogen-atom}\overline{\nu}_e) > 3 \times 10^4$ s by comparing neutron lifetime measurements made in storage experiments with those made in β-decay experiments. However, the result depends sensitively on the lifetime measurements, and does not of course take into account more recent measurements of same.

$\Gamma(p \nu_e \overline{\nu}_e)/\Gamma_{\text{total}}$ Γ_4/Γ

Forbidden by charge conservation.

VALUE	*CL%*	*DOCUMENT ID*		*TECN*	*COMMENT*
$<8 \times 10^{-27}$	68	[1] NORMAN	96	RVUE	^{71}Ga $\rightarrow$ ^{71}Ge neutrals
• • • We do not use the following data for averages, fits, limits, etc. • • •					
$<9.7 \times 10^{-18}$	90	ROY	83	CNTR	^{113}Cd $\rightarrow$ ^{113m}In neut.
$<7.9 \times 10^{-21}$		VAIDYA	83	CNTR	^{87}Rb $\rightarrow$ ^{87m}Sr neut.
$<9 \times 10^{-24}$	90	BARABANOV	80	CNTR	^{71}Ga $\rightarrow$ ^{71}GeX
$<3 \times 10^{-19}$		NORMAN	79	CNTR	^{87}Rb $\rightarrow$ ^{87m}Sr neut.

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

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$n \rightarrow p e^- \overline{\nu}_e$ DECAY PARAMETERS

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

$\lambda \equiv g_A / g_V$

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

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

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

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

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

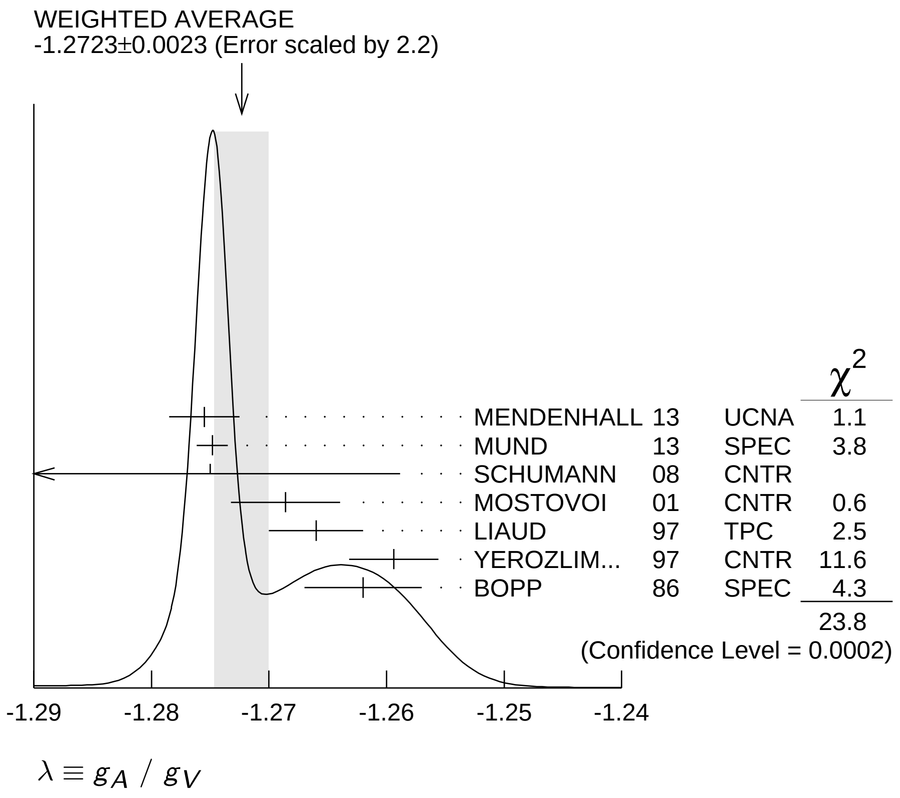
[5] This PLASTER 12 value is identical with that given in LIU 10, but the experiment is now described in detail.

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

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

[8] KROHN 75 includes events of CHRISTENSEN 70.

[9] KROPF 74 reviews all data through 1972.



e^- ASYMMETRY PARAMETER A

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

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

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

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

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

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

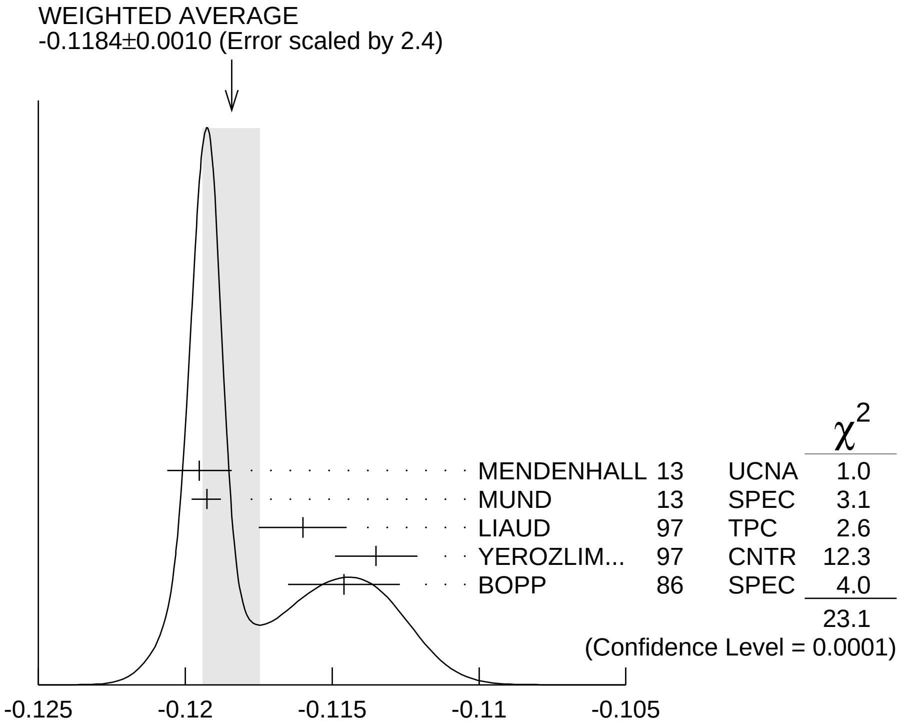
[3] YEROZOLIMSKY 97 makes a correction to the EROZOLIMSKII 91 value.

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

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

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

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



e^- asymmetry parameter A

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

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

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

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

PROTON ASYMMETRY PARAMETER *C*

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

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

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

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

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

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

ϕ_{AV}, PHASE OF g_A RELATIVE TO g_V

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

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

[1] KROPF 74 reviews all data through 1972.

TRIPLE CORRELATION COEFFICIENT *D*

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

VALUE (units 10^{-4})	*DOCUMENT ID*		*TECN*	*COMMENT*
− 1.2 ± 2.0 OUR AVERAGE				
− 0.94± 1.89±0.97	CHUPP	12	CNTR	Cold *n*, polarized > 91%
− 2.8 ± 6.4 ±3.0	SOLDNER	04	CNTR	Cold *n*, polarized
− 6 ±12 ±5	LISING	00	CNTR	Polarized > 93%
• • • 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	EROZOLIM...	78	CNTR	Cold *n*, polarized
−27 ±50	[1] EROZOLIM...	74	CNTR	Cold *n*, polarized
−11 ±17	STEINBERG	74	CNTR	Cold *n*, polarized

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

TRIPLE CORRELATION COEFFICIENT *R*

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

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

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

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MUND	13	PRL 110 172502	D. Mund *et al.*	(HEID, ILLG)
YUE	13	PRL 111 222501	A.T. Yue *et al.*	(UMD, NIST, TENN, ORNL+)
ARZUMANOV	12	JETPL 95 224	S.S. Arzumanov *et al.*	(KIAE)
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CHRISTENSEN 72 PR D5 1628 C.J. Christensen *et al.* (RISO)
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