Eidgenössische Technische Hochschule Zürich
Swiss Federal Institute of Technology Zurich

Supervisory Control and Data Acquisition system of the n2EDM experiment

Master Thesis

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Abstract

Just as nowadays no serious experiment can be built and conducted by a single person, the experiment itself cannot consist of a single tool. The n2EDM experiment aims to achieve an ambitious goal: to measure the electric dipole moment of neutron with a new level of precision. Such challenging project demands the need for the complex and well-connected system. This thesis intends to describe the development of new and improvement of existing components, such as:

- **COM handler** — an adapter translating the POSIX pipes to the TCP/IP connections. Every node in the system is connected with others through it.
- **Sequencer** — a software node orchestrating other nodes. It follows the user-generated script allowing one to describe the reproducible behaviour of the whole DAQ system with a human-readable set of commands.
- **Proxy for the remote magnetometers** — a smart bridge between the pool of the remote magnetometers and a standard TCP/IP interface of the COM handler.
- **Surrounding field compensation system** — a system for active stabilisation of the magnetic field. It uses the data collected by the remote magnetometers and a set of controlled coils to minimise the fluctuations of the magnetic field in the area of the experiment. Better description when I start working on it.

These pieces are essential for the n2EDM experiment to function, so the aim was to make them error-resistant, extendable and easy to support for the future developers.

Contents

Chapter 1

Introduction

Out of S. Okubo's effect
At high temperature
A fur coat is sewed for the Universe
Shaped for its crooked figure

A. D. Sakharov [15]

We interact with matter every day. Even you, the reader, are probably made out of matter! However, antimatter is so rare that it is considered to cost a few hundred millions Swiss francs per gram [4], making it the most expensive substance in the universe. Why does such a stunning difference in the abundance exist?

First step to solving this problem is to define what are the required conditions that would allow the disbalance to evolve. Those conditions [5] were described [15] by Andrei Sakharov in 1967:

- Violation of baryon number conservation
- *C*- and *CP*-symmetry violation
- Processes take place far from thermal equilibrium

Let's take a look at the *CP*-symmetry and prove that a non-zero electric dipole moment of an elementary particle would indeed break it. We would select neutron as a particle of choice.

The neutron in the ground state has spin of $I = 1/2$ and can be characterised completely by a single quantum number of a spin projection $m_I = \pm 1/2$. We can write down a Hamiltonian [8] of this neutron in external electric and magnetic fields $\vec{E}$ and $\vec{B}$:

$$\mathcal{H} = -\frac{d_n \vec{I} \cdot \vec{E} + \mu_n \vec{I} \cdot \vec{B}}{I} \quad (1.1)$$

with d_n and μ_n being the electric and magnetic moments of the neutron [9].

It does not make sense to discuss the potential violation of the symmetries before we define them. Fundamental symmetries are blended into the fabric of our Universe by providing sufficient conditions [12] for the conservation laws. In our analysis we would consider three symmetries of the Standard Model: C, P and T.

- (C)harge —- replaces every particle with its antiparticle: $q \to -q$
- (P)arity — inverts the physical space: $\vec{r} \to -\vec{r}$
- (T)ime — turns the time back: $t \to -t$

How would the P and T inversions affect [5] the Hamiltonian from Eq. 1.1?

Parity transformation only act on a polar vector of the electric field: $\vec{E} \to -\vec{E}$, both $\vec{B}$ and $\vec{I}$ are conserved. This brings us to

$$P\mathcal{H} = -\frac{d_n \vec{I} \cdot \left(-\vec{E}\right) + \mu_n \vec{I} \cdot \vec{B}}{I} \neq \mathcal{H} \quad (1.2)$$

Time reversal would affect only axial vectors $\vec{B}$ and $\vec{I}$: $\vec{B} \to -\vec{B}$, $\vec{I} \to -\vec{I}$, the field $\vec{E}$ is left as is:

$$T\mathcal{H} = -\frac{d_n \left(-\vec{I}\right) \cdot \vec{E} + \mu_n \left(-\vec{I}\right) \cdot \left(-\vec{B}\right)}{I} \neq \mathcal{H} \quad (1.3)$$

Assuming that the *CPT* invariance [16] is conserved, we derive the violation of a *CP*-symmetry, which provides us motivation to measure the EDM of the neutron.

"Wait a minute," could have said an attentive reader at this point. "Does not Standard Model predict a non-zero EDM of the neutron already? I am still not convinced why would you want to conduct this experiment."

And an attentive reader would have had a completely fair point! Indeed, Standard Model predicts [10] the following:

$$d_n \approx 2 \cdot 10^{-32}\ e \cdot \mathrm{cm} \quad (1.4)$$

However, we would still like to measure d_n for the reasons listed below:

- The only way to prove the theory is to check it experimentally. So far no one has measured d_n with a precision close to the predicted value

- The result that can be achieved by using Standard Model is too weak to explain the baryogenesis [5], yet baryogenesis has clearly happened
- If we go beyond Standard Model to find a mechanism, through which the Universe as we know it could have been formed, we need to cut off theories that do not agree with experimental data. This is something that this experiment does perfectly: on the Fig. 11 one can see all theoretical models that the measurement of the neutron EDM has ruled out, allowing the scientists to focus on more prominent theories.

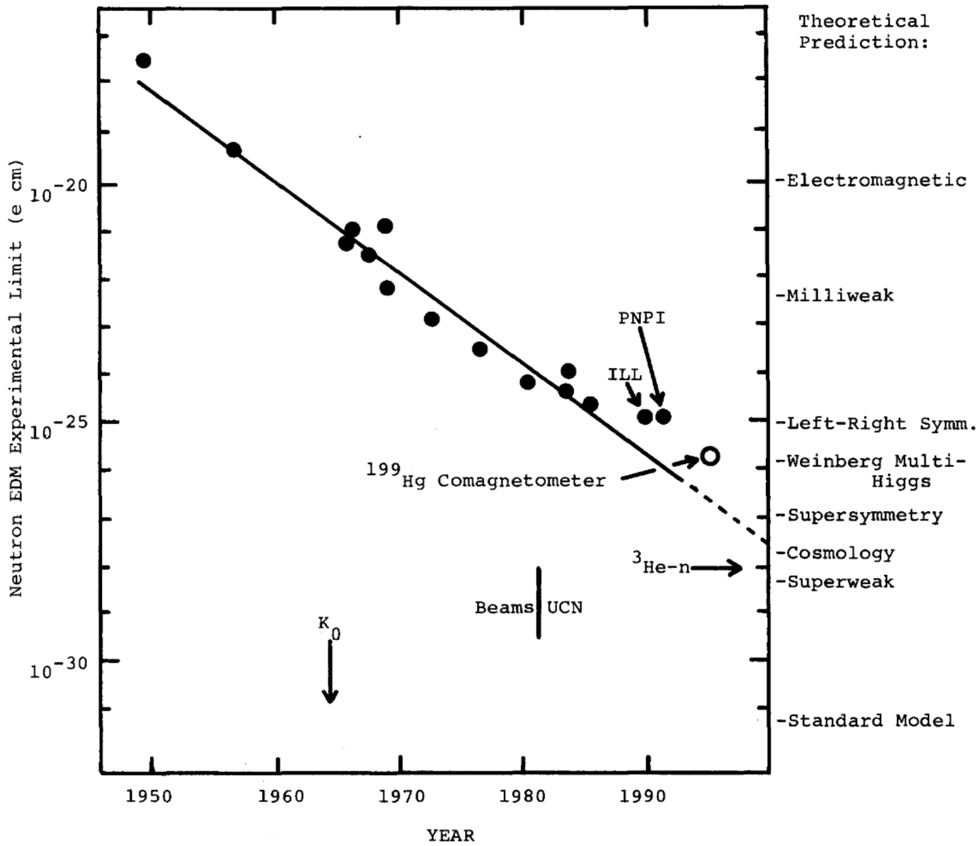

Figure 11: Measurement history of the neutron EDM [8]

Hopefully these reasons would convince even the most demanding reader in the need to conduct the n2EDM experiment. But what is *n2EDM* exactly? We will try to explain that in the next chapter.

Chapter 2

The n2EDM experiment

Knowledge is power and our knowledge of the physical property that can be measured to show the violation of the *CP*-symmetry is an important first step in solving the riddle of the baryogenesis. Now we just need to get our hands dirty with some experimental data. It will be obtained over the course of the n2EDM experiment currently being built at PSI (Paul Scherrer Institute, Villigen, Switzerland).

What will be measured? Electric dipole moment of the neutron. The neutrons were chosen for the following reasons:

- They are electrically neutral[1], which means that they would not be dragged by the electric field $\vec{E}$
- There are nuclear reactions that allow to produce them efficiently, like fission or spallation (which is already available in PSI and will be used)
- They can be cooled down to become UCNs (ultracold neutrons)

What are ultracold neutrons and why do we like them? We call [6] a neutron ultracold when it has a kinetic energy $E_{kin} \leq 300$ neV. Such low energy brings the following experimental benefits:

- Ease of collection, since the neutrons would behave similar to ping-pong balls, bouncing from the surface of a neutron vessel.
- Possibility to store [19] the neutrons up to their lifetime of ≈ 886 s [18].
- Weakening of a so-called $\vec{v} \times \vec{E}$ effect [14], which arises from the coupling of a particle spin $\vec{I}$ itself with an electric field $\vec{E}$. This would bring the effective Hamiltonian closer to one mentioned in Eq. 1.1.

[1] Which is quite important for an experiment based in Switzerland

What precision do we expect? By using only the Standard Model it is possible to get an estimation [10] of the neutron EDM at the following level:

$$d_n \approx 2 \cdot 10^{-32}\ e \cdot \mathrm{cm} \tag{2.1}$$

The **n2EDM** experiment is conceptually following the footsteps of the results obtained by the **nEDM** collaboration. By analysing the data obtained at ILL, Grenoble it was possible to achieve [13] an impressive record of d_n precision:

$$|d_n| < 3.6 \cdot 10^{-26}\ e \cdot \mathrm{cm}\ (95\%\ \mathrm{CL}). \tag{2.2}$$

This leaves us with 6 more orders of magnitude to go. The n2EDM experiment aims to cut this number to five, improving [2] the precision tenfold.

What method will be used? Same as in the original nEDM experiment, Ramsey method of the time separated oscillating fields.

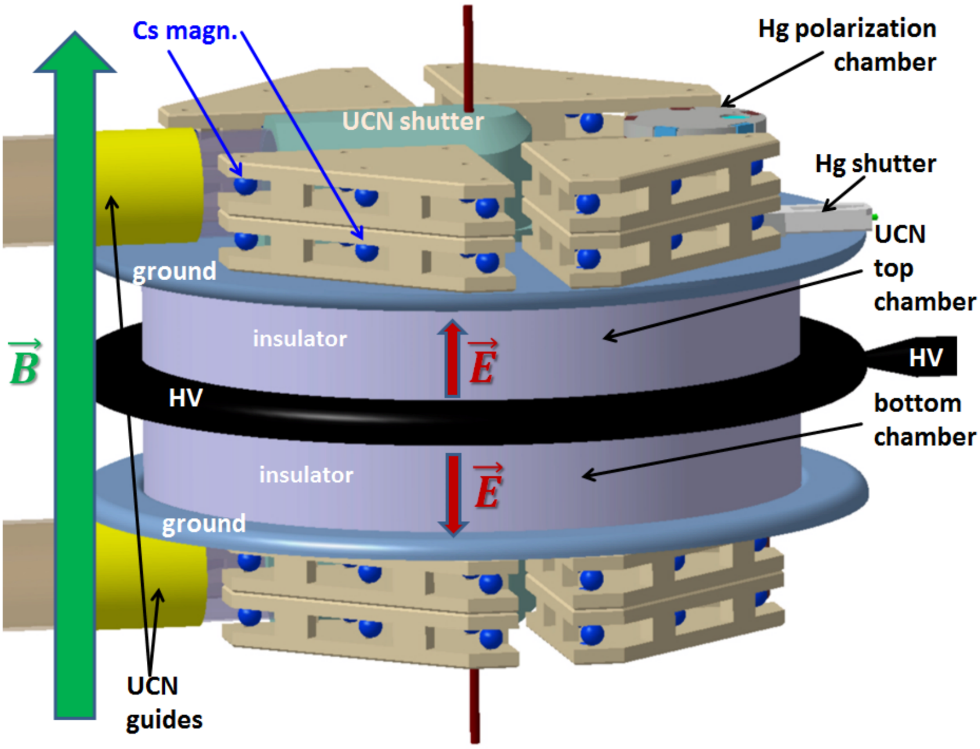

Figure 21: Double chamber design [2].

One can see that the precession chamber pictured in the Fig. 21 features fields $\vec{E}$ and $\vec{B}$ that are codirectional in one chamber and contradirectional in another. In both chambers the neutron can be described with the Hamiltonian from Eq. 1.1. Let's take a look at its Larmor precession.

In the case of the **codirectional** fields we can write

$$h\nu_{\uparrow\uparrow} = -2\left(\mu_n B_{\uparrow\uparrow} + d_n E_{\uparrow\uparrow}\right). \tag{2.3}$$

If the fields are **contradirectional** we will get

$$h\nu_{\uparrow\downarrow} = -2\left(\mu_n B_{\uparrow\downarrow} - d_n E_{\uparrow\downarrow}\right). \tag{2.4}$$

By combining Eq. 2.3 and Eq. 2.4 we can express the neutron electric dipole moment d_n through the fields E and B, magnetic moment μ_n and Larmor frequencies $\nu_{\uparrow\uparrow}$ and $\nu_{\uparrow\downarrow}$ as

$$d_n = \frac{h\left(\nu_{\uparrow\downarrow} - \nu_{\uparrow\uparrow}\right) - 2\mu_n\left(B_{\uparrow\uparrow} - B_{\uparrow\downarrow}\right)}{2\left(E_{\uparrow\uparrow} + E_{\uparrow\downarrow}\right)}. \tag{2.5}$$

Why is the double chamber design important? The idea of a double chamber pioneered [1] in 1980. The biggest improvement that it brings is the ability to measure the Larmor frequency for the codirectional and the contradirectional cases **simultaneously**. This feature allows to strongly reduce [2] any time dependent systematic effects.

How does n2EDM look like schematically? You can see it on the Fig. 22.

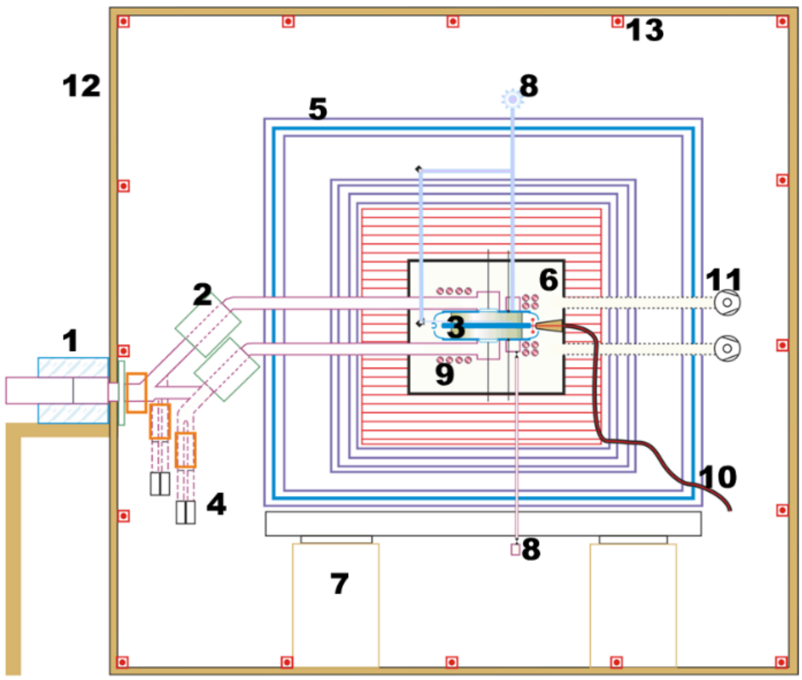

Figure 22: Schema of the experimental setup [2].

It features [2] the following:

1. A 5 T superconductive polarizer magnet to align the spin of UCNs before they enter precession chambers
2. Switches to control the filling and emptying of the UCN chambers
3. Two precession chambers, portrayed in details on Fig. 21
4. Four spin projection detectors — for every chamber we count amount of neutrons with spins up and down
5. Magnetically shielded room to protect the storage chambers and the vacuum vessel
6. The vacuum vessel
7. Four granite pillars supporting an Al plate
8. The Hg magnetometer to measure the average magnetic fields
9. The Cs magnetometer to measure the gradients of the magnetic field
10. A high voltage cable
11. The molecular pumps generating vacuum in the vacuum vessel
12. Insulation shell, thermally stabilized by air-conditioning (not shown)
13. Surrounding field compensation (SFC) system is designed to actively minimise the magnetic perturbations of the environment

Figure 23: Recent photo of the n2EDM experiment [7].

How does n2EDM actually look at the moment? Like it is shown on the Fig. 23.

Chapter 3

The n2EDM DAQ system

In order to measure the neutron EDM and question the theoretical predictions mentioned in the chapter 1 it is not enough to do a single cycle of the experimental setup from the chapter 2. Everything comes at a price and pushing the limits of precision is not an exception. The analysis [14] of the previous nEDM experiment was based on data collected between 1998 and 2002, with each data-taking run lasting about 1–2 days. Thus a solid and performant data acquisition and control (DAQ) system is strongly needed.

Why cannot we just reuse the DAQ from nEDM? Apart from an experimental setup containing new modules and equipment there are [3] other reasons for us to consider designing a new generation of the DAQ system:

- Complexity of the codebase (one of the projects consisted of approximately 748 332 LabView VIs) was limiting modifications
- Inability to test or debug the DAQ system without the complete experimental environment, including the hardware, being connected. This was blocking data acquisition or the regular shift routine
- No standardisation in connecting various hardware devices to the DAQ, resulting in the code repetition
- Windows operating system lock-in

What principles is the n2EDM DAQ built on? The new **n2EDM** DAQ aims to address the main pain points and limitations of the old **nEDM** DAQ by selecting to follow the design ideas listed below:

- **TCP/IP communication**: by relying on the TCP/IP as the transport layer we can guarantee deliverability of messages in the same order as they were sent. By being an industrial standard it also simplifies connection of the new hardware nodes to the system. Not specifically TCP/IP-related bonus is that by optically decoupling our hardware it is possible to automatically provide electrical insulation

- **SCPI syntax**: all commands should be written following a human-readable specification [17]. This would standardise the environment and allow for the simpler debugging
- **Script control**: what can be better than a single SCPI command? Only a human-readable repeatable set of commands, providing an ability to program the behaviour of the experimental setup
- **Modularity**: usage of the small loosely connected independent modules improves robustness and encourages testing. Additionally if modules can be tested without the presence of each other it also becomes simpler to implement the End-to-End (E2E) testing of the whole system with the aim of being able to arbitrary replace physical equipment with its software-only analogs. This brings us closer to an ability to run the n2EDM experiment in a simulation mode
- **Linux based**: apart from being free (both as in "free as a speech" and "free as a beer") the development ecosystem of Linux provides much more opportunities compared to the Windows one. Even though the recent release [11] of the Windows Subsystem for Linux made the difference less painful, one might still prefer to run the programs directly on Linux with zero overhead

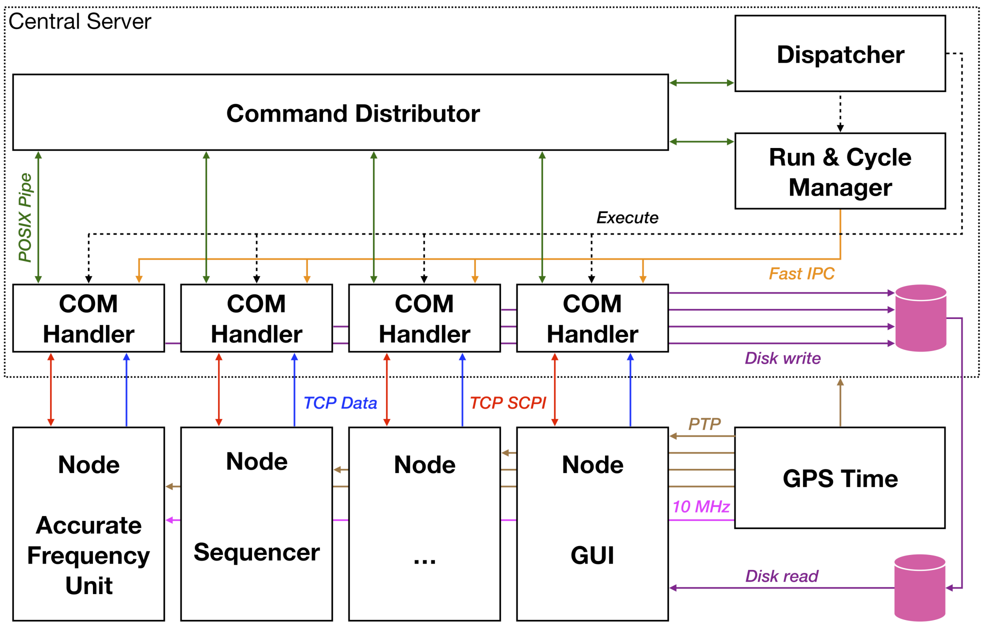

Figure 31: Schematic view of the n2EDM DAQ system. Based on [3].

Bibliography

[1] I. S. Altarev, Yu V. Borisov, A. B. Brandin, A. I. Egorov, V. F. Ezhov, S. N. Ivanov, V. M. Lobashov, V. A. Nazarenko, G. D. Porsev, V. L. Ryabov, A. P. Serebrov, and R. R. Taldaev. A search for the electric dipole moment of the neutron using ultracold neutrons. *Nuclear Physics, Section A*, 341(2):269–283, 1980. doi:10.1016/0375-9474(80)90313-9.

[2] I.S. Altarev, Yu.V. Borisov, A.B. Brandin, A.I. Egorov, V.F. Ezhov, S.N. Ivanov, V.M. Lobashov, V.A. Nazarenko, G.D. Porsev, V.L. Ryabov, A.P. Serebrov, and R.R. Taldaev. A search for the electric dipole moment of the neutron using ultracold neutrons. *Nuclear Physics A*, 341(2):269–283, jun 1980. URL: http://arxiv.org/abs/1811.02340https://linkinghub.elsevier.com/retrieve/pii/0375947480903139, arXiv:1811.02340, doi:10.1016/0375-9474(80)90313-9.

[3] Georg Bison, Jochen Krempel, Dieter Ries, Romain Virot, and Jacek Zejma. N2EDMDAQTDR — second neutron electric dipole moment experiment data acquisition technical design report v0.9. Technical report, 2018.

[4] Alvaro de Rújula and Rolf Landua. Antimatter Questions & Answers, 2001. URL: https://archive.ph/20080421220420/http://livefromcern.web.cern.ch/livefromcern/antimatter/FAQ1.html.

[5] Dirk Dubbers and Michael G. Schmidt. The neutron and its role in cosmology and particle physics. *Reviews of Modern Physics*, 83(4), 2011. doi:10.1103/RevModPhys.83.1111.

[6] Enrico Fermi. Motion of neutrons in hydrogenous substances. *Ricerca Scientifica*, 7(2):13–52, 1936.

[7] Elsa Germann. Software development for the Supervisory Control and Data Acquisition system of the n2EDM experiment. *Master Thesis*, ETH Zürich, 2019.

[8] R. Golub and Steve K. Lamoreaux. Neutron electric-dipole moment, ultracold neutrons and polarized 3He. *Physics Reports*, 237(1):1–62, 1994. doi:10.1016/0370-1573(94)90084-1.

[9] R. Golub and J. M. Pendlebury. The electric dipole moment of the neutron. *Contemporary Physics*, 13(6):519–558, nov 1972. URL: http://www.tandfonline.com/doi/abs/10.1080/00107517208228016, doi:10.1080/00107517208228016.

[10] I. B. Khriplovich and A. R. Zhitnitsky. What is the value of the neutron electric dipole moment in the Kobayashi-Maskawa model? *Physics Letters B*, 109(6):490–492, 1982. doi:10.1016/0370-2693(82)91121-2.

[11] Craig Loewen. Announcing WSL 2, 2019. URL: https://devblogs.microsoft.com/commandline/announcing-wsl-2/.

[12] E. Noether. Invariante Variationsprobleme. *Nachrichten von der Gesellschaft der Wissenschaften zu Göttingen, Mathematisch-Physikalische Klasse*, 1918:235–257, 1918. URL: http://eudml.org/doc/59024.

[13] J. M. Pendlebury, S. Afach, N. J. Ayres, C. A. Baker, G. Ban, G. Bison, K. Bodek, M. Burghoff, P. Geltenbort, K. Green, W. C. Griffith, M. van der Grinten, Z. D. Grujić, P. G. Harris, V. Hélaine, P. Iaydjiev, S. N. Ivanov, M. Kasprzak, Y. Kermaidic, K. Kirch, H.-C. Koch, S. Komposch, A. Kozela, J. Krempel, B. Lauss, T. Lefort, Y. Lemière, D. J. R. May, M. Musgrave, O. Naviliat-Cuncic, F. M. Piegsa, G. Pignol, P. N. Prashanth, G. Quéméner, M. Rawlik, D. Rebreyend, J. D. Richardson, D. Ries, S. Roccia, D. Rozpedzik, A. Schnabel, P. Schmidt-Wellenburg, N. Severijns, D. Shiers, J. A. Thorne, A. Weis, O. J. Winston, E. Wursten, J. Zejma, and G. Zsigmond. Revised experimental upper limit on the electric dipole moment of the neutron. *Physical Review D*, 92(9):092003, nov 2015. URL: https://link.aps.org/doi/10.1103/PhysRevD.92.092003, arXiv:1509.04411, doi:10.1103/PhysRevD.92.092003.

[14] J. M. Pendlebury, W. Heil, Yu. Sobolev, P. G. Harris, J. D. Richardson, R. J. Baskin, D. D. Doyle, P. Geltenbort, K. Green, M. G. D. van der Grinten, P. S. Iaydjiev, S. N. Ivanov, D. J. R. May, and K. F. Smith. Geometric-phase-induced false electric dipole moment signals for particles in traps. *Physical Review A*, 70(3):032102, sep 2004. URL: https://link.aps.org/doi/10.1103/PhysRevA.70.032102, doi:10.1103/PhysRevA.70.032102.

[15] D. Sakharov. Violation of *CP* invariance, *C* asymmetry, and baryon asymmetry of the universe. *Soviet Physics - Uspekhi*, 34(5):392–393, 1991. doi:10.1070/PU1991v034n05ABEH002497.

[16] Julian Schwinger. The Theory of Quantized Fields. I. *Physical Review*, 82(6):914–927, jun 1951. URL: https://link.aps.org/doi/10.1103/PhysRev.82.914, doi:10.1103/PhysRev.82.914.

[17] SCPI Consortium. *Standard Commands for Programmable Instruments (SCPI)*, volume 1. 1999. URL: http://www.ivifoundation.org/docs/SCPI-99.PDF.

[18] M. Tanabashi, K. Hagiwara, K. Hikasa, K. Nakamura, Y. Sumino, F. Takahashi, J. Tanaka, K. Agashe, G. Aielli, C. Amsler, M. Antonelli, D. M. Asner, H. Baer, Sw. Banerjee, R. M. Barnett, T. Basaglia, C. W. Bauer, J. J. Beatty, V. I. Belousov, J. Beringer, S. Bethke, A. Bettini, H. Bichsel, O. Biebel, K. M. Black, E. Blucher, O. Buchmuller, V. Burkert, M. A. Bychkov, R. N. Cahn, M. Carena, A. Ceccucci, A. Cerri, D. Chakraborty, M.-C. Chen, R. S. Chivukula, G. Cowan, O. Dahl, G. D'Ambrosio, T. Damour, D. de Florian, A. de Gouvêa, T. DeGrand, P. de Jong, G. Dissertori, B. A. Dobrescu, M. D'Onofrio, M. Doser, M. Drees, H. K. Dreiner, D. A. Dwyer, P. Eerola, S. Eidelman, J. Ellis, J. Erler, V. V. Ezhela, W. Fetscher, B. D. Fields, R. Firestone, B. Foster, A. Freitas, H. Gallagher, L. Garren, H.-J. Gerber, G. Gerbier, T. Gershon, Y. Gershtein, T. Gherghetta, A. A. Godizov, M. Goodman, C. Grab, A. V. Gritsan, C. Grojean, D. E. Groom, M. Grünewald, A. Gurtu, T. Gutsche, H. E. Haber, C. Hanhart, S. Hashimoto, Y. Hayato, K. G. Hayes, A. Hebecker, S. Heinemeyer, B. Heltsley, J. J. Hernández-Rey, J. Hisano, A. Höcker, J. Holder, A. Holtkamp, T. Hyodo, K. D. Irwin, K. F. Johnson, M. Kado, M. Karliner, U. F. Katz, S. R. Klein, E. Klempt, R. V. Kowalewski, F. Krauss, M. Kreps, B. Krusche, Yu. V. Kuyanov, Y. Kwon, O. Lahav, J. Laiho, J. Lesgourgues, A. Liddle, Z. Ligeti, C.-J. Lin, C. Lippmann, T. M. Liss, L. Littenberg, K. S. Lugovsky, S. B. Lugovsky, A. Lusiani, Y. Makida, F. Maltoni, T. Mannel, A. V. Manohar, W. J. Marciano, A. D. Martin, A. Masoni, J. Matthews, U.-G. Meißner, D. Milstead, R. E. Mitchell, K. Mönig, P. Molaro, F. Moortgat, M. Moskovic, H. Murayama, M. Narain, P. Nason, S. Navas, M. Neubert, P. Nevski, Y. Nir, K. A. Olive, S. Pagan Griso, J. Parsons, C. Patrignani, J. A. Peacock, M. Pennington, S. T. Petcov, V. A. Petrov, E. Pianori, A. Piepke, A. Pomarol, A. Quadt, J. Rademacker, G. Raffelt, B. N. Ratcliff, P. Richardson, A. Ringwald, S. Roesler, S. Rolli, A. Romaniouk, L. J. Rosenberg, J. L. Rosner, G. Rybka, R. A. Ryutin, C. T. Sachrajda, Y. Sakai, G. P. Salam, S. Sarkar, F. Sauli, O. Schneider, K. Scholberg, A. J. Schwartz, D. Scott, V. Sharma, S. R. Sharpe, T. Shutt, M. Silari, T. Sjöstrand,

P. Skands, T. Skwarnicki, J. G. Smith, G. F. Smoot, S. Spanier, H. Spieler, C. Spiering, A. Stahl, S. L. Stone, T. Sumiyoshi, M. J. Syphers, K. Terashi, J. Terning, U. Thoma, R. S. Thorne, L. Tiator, M. Titov, N. P. Tkachenko, N. A. Törnqvist, D. R. Tovey, G. Valencia, R. Van de Water, N. Varelas, G. Venanzoni, L. Verde, M. G. Vincter, P. Vogel, A. Vogt, S. P. Wakely, W. Walkowiak, C. W. Walter, D. Wands, D. R. Ward, M. O. Wascko, G. Weiglein, D. H. Weinberg, E. J. Weinberg, M. White, L. R. Wiencke, S. Willocq, C. G. Wohl, J. Womersley, C. L. Woody, R. L. Workman, W.-M. Yao, G. P. Zeller, O. V. Zenin, R.-Y. Zhu, S.-L. Zhu, F. Zimmermann, P. A. Zyla, J. Anderson, L. Fuller, V. S. Lugovsky, and P. Schaffner. Review of Particle Physics. *Physical Review D*, 98(3):030001, aug 2018. URL: https://doi.org/10.1103/PhysRevD.98.030001https://link.aps.org/doi/10.1103/PhysRevD.98.030001, doi:10.1103/PhysRevD.98.030001.

[19] Ya. B. Zeldovich. Storage of cold neutrons. *JETP*, 36(6):1952–1953, 1959.

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