$\Delta\mathcal{B} = 2$: A State of the Field, and Looking Forward

A brief overview of theoretical and experimental physics opportunities from the participants of
The Amherst Center for Fundamental Interactions Workshop
Theoretical Innovations for Future Experiments Regarding Baryon Number Violation, Part 1
In Coordination with the Snowmass Rare Processes and Precision Frontier

Ken Andersen[1], K.S. Babu[2], Stefan Baessler[3], Joshua Barrow[*4,5], Zurab Berezhiani[6,7], Christian Bohm[8], Gustaaf Brooijmans[9], Leah Broussard[†1], Vince Cianciolo[1], Christopher Crawford[10], Marcel Demarteau[1], P.S. Bhupal Dev[11], Jordy de Vries[‡12,13], Alexey Fomin[14], Nadia Fomin[4], Matthew Frost[1], Susan Gardner[10], Sudhakantha Girmohanta[15], Elena Golubeva[16], Leendert Hayen[17], Julian Heeck[3], Yuri Kamyshkov[4], Georgia Karagiorgi[9], Ed Kearns[18], Bingwei Long[19], David McKeen[20], Bernhard Meirose[8], David Milstead[8], Rabindra N. Mohapatra[21], Robert W. Pattie, Jr.[22], Brad Plaster[10], Jean-Marc Richard[23], Daniel J. Salvat[24], Valentina Santoro[25], Anatoli Serebrov[14], Robert Shrock[15], W. M. Snow[24], C.M. Swank[26], Zhaowen Tang[27], James Ternullo II[4], Louis Varriano[28], Michael Wagman[§5], Linyan Wan[18], James D. Wells[29], Wanchun Wei[26], and A. R. Young[17]

[1]Oak Ridge National Laboratory
[2]Oklahoma State University
[3]University of Virginia
[4]The University of Tennessee at Knoxville
[5]Fermi National Accelerator Laboratory
[6]University of L'Aquila
[7]Gran Sasso National Laboratory
[8]Stockholm University
[9]Columbia University
[10]University of Kentucky
[11]Washington University, St. Louis
[12]University of Massachusetts, Amherst, MA 01003, USA
[13]RIKEN BNL Research Center, Brookhaven National Laboratory, Upton, NY 11973-5000, USA
[14]NRC "Kurchatov Institute" - PNPI
[15]Stony Brook University
[16]Institute for Nuclear Research, Moscow
[17]North Carolina State University
[18]Boston University
[19]Sichuan University
[20]TRIUMF
[21]University of Maryland
[22]East Tennessee State University
[23]Université de Lyon & IN2P3
[24]Indiana University
[25]The European Spallation Source
[26]California Institute of Technology
[27]Los Alamos National Laboratory
[28]University of Chicago
[29]University of Michigan, Ann Arbor

August 31st, 2020

Suggested Snowmass Topical Groups:

- (RF4) Rare Processes and Precision Frontier: Baryon and Lepton Number Violating Processes
- (RF3) Rare Processes and Precision Frontier: Small Experiments
- (RF6) Rare Processes and Precision Frontier: Dark Sectors
- (NF3) Neutrino Frontier: Beyond the Standard Model
- (NF10) Neutrino Frontier: Neutrino Detectors

Abstract

The origin of the matter-antimatter asymmetry apparently obligates the laws of physics to include some mechanism of baryon number ($\mathcal{B}$) violation. Searches for interactions violating $\mathcal{B}$ and baryon-minus-lepton number ($\mathcal{B}-\mathcal{L}$) represent a rich and underutilized opportunity. These are complementary to the existing, broad program of searches for $\mathcal{L}$-violating modes such as neutrinoless double β-decay which could provide deeper understandings of the plausibility of leptogenesis, or $\mathcal{B}$-violating, ($\mathcal{B}-\mathcal{L}$)-conserving processes such as proton decay. In particular, a low-scale, post-sphaleron violation mechanism of ($\mathcal{B}-\mathcal{L}$) could provide a *testable* form of baryogenesis. Though theoretically compelling, searches for such ($\mathcal{B}-\mathcal{L}$)-violating processes like $\Delta\mathcal{B}=2$ dinucleon decay and $n\to\bar{n}$ remain relatively underexplored experimentally compared to other rare processes. By taking advantage of upcoming facilities such as the Deep Underground Neutrino Experiment and the European Spallation Source, this gap can be addressed with new intranuclear and free searches for neutron transformations with very high sensitivity, perhaps greater than three orders of magnitude higher than previous experimental searches. Recent theoretical and experimental advances and sensitivities of next-generation searches for neutron transformations were detailed as part of the Amherst Center for Fundamental Interactions Workshop, "Theoretical Innovations for Future Experiments Regarding Baryon Number Violation," directly coordinated with the Rare Processes and Precision Measurements Frontier.

* jbarrow3@vols.utk.edu; also at Fermilab
† broussardlj@ornl.gov
‡ jdevries@umass.edu
§ mwagman@fnal.gov

The Amherst Center for Fundamental Interactions Workshop, "Theoretical Innovations for Future Experiments Regarding Baryon Number Violation," held virtually August 3^{rd}–7^{th}, 2020, brought to light several key opportunities and requirements to address the origin of the baryon asymmetry in the universe (BAU) by searching for neutron-antineutron transformations ($n \to \bar{n}$). Observation of $n \to \bar{n}$[1–3] would be clear evidence for baryon number ($\mathcal{B}$) violation (BNV), one of the three Sakharov conditions[4] that has yet to be experimentally confirmed, and which together can explain the dynamical generation of the BAU. To avoid "washing out" by Standard Model (SM) sphalerons, ($\mathcal{B} - \mathcal{L}$)-violation is a prerequisite for any pre-existing $\mathcal{B}$ or $\mathcal{L}$ asymmetry to dynamically develop and survive; the latter is the case in classic leptogenesis. With the effective impossibility of a definitive, "on shell" test for classic leptogenesis, similar to the confirmations of the $W^{\pm}$, Z^0, and Higgs, other potentially observable baryogenesis alternatives become attractive to consider. Since $\Delta(\mathcal{B} - \mathcal{L}) \neq 0$ for $n \to \bar{n}$ (and more generally $\Delta\mathcal{B} = 2$ dinucleon decays), the fundamental physics behind $n \to \bar{n}$ may well underlie the origin of the $\mathcal{B}$-asymmetry surviving until our current epoch. This contrasts with the ephemeral $\mathcal{B}$-asymmetry generated in grand unified theories via $\Delta(\mathcal{B} - \mathcal{L}) = 0$ processes, which can be diluted by sphaleron effects.

Many beyond SM (BSM) theories of baryogenesis predict $n \to \bar{n}$ in an observable range. An example is the compelling[5] post-sphaleron baryogenesis (PSB) model[6–8] where baryogenesis occurs after the electroweak phase transition, predicting an upper limit on the $n \to \bar{n}$ oscillation period $\tau_{n\bar{n}}$ which may be within reach of forthcoming experiments. More generally, "Majorana baryogenesis"[9–11], effective at low energy scales, can also lead to observable $n \to \bar{n}$. These mediating Majorana fermions could be the gluinos or neutralinos of supersymmetric models with R-parity violation, or can be involved in neutrino (ν) mass generation[12]. In some cases, if certain colored scalars remain light at the TeV scale[13], GUT scale BNV interactions can lead to successful baryogenesis and observable $n \to \bar{n}$. It has been shown that $n \to \bar{n}$ can also result in models where baryogenesis proceeds through the related process of particle-antiparticle oscillations of heavy flavor baryons[14;15]. This possibility points towards new physics at the scale of a few TeV, and its ingredients (heavy neutral fermions and colored scalars) could be within the reach of the Large Hadron Collider (LHC).

In a low-energy effective field theory (EFT) analysis, the leading operators contributing to proton (and bound n) decay are four-fermion operators, which have dimension $d = 6$, and hence coefficients of the form $1/M_{Nd}^2$, where M_{Nd} denotes the mass scale characterizing the physics responsible for nucleon decay. However, these operators conserve ($\mathcal{B} - \mathcal{L}$), and are thus not useful for understanding the BAU. In contrast, $n \to \bar{n}$ is mediated by six-quark operators, which have $d = 9$, and so have coefficients of order $1/M_{n\bar{n}}^5$. If $M_{Nd} \simeq M_{n\bar{n}}$, then one might naively conclude that nucleon decay would be more important than $n \to \bar{n}$ as a manifestation of BNV. However, there are models in which the opposite is the case, where instead nucleon decay is absent or highly suppressed while $n \to \bar{n}$ remains the dominant manifestation of BNV[1;2;16–19].

It is known that $n \to \bar{n}$ can occur naturally at observable rates in a model with a left-right-symmetric gauge group $G_{LRS} = \mathrm{SU}(3)_c \times \mathrm{SU}(2)_L \times \mathrm{SU}(2)_R \times \mathrm{U}(1)_{B-L}$[1;20;21]. Here, $\mathcal{B}$ and $\mathcal{L}$ are connected via the ($\mathcal{B} - \mathcal{L}$) gauge generator, and the breaking of $\mathcal{L}$ leads to Majorana ν's via the seesaw mechanism. This, in turn, can lead naturally to $n \to \bar{n}$ in a quark-lepton unified theory, while proton decay is absent in minimal versions of such models.

Another class of models with $n \to \bar{n}$ are those with extra spatial dimensions, where SM fermions can retain localized wave functions within these extra dimensions[22–24]. In such models, it is trivial to suppress nucleon decays well below experimental limits by separating the wave function centers of quarks and leptons sufficiently. $n \to \bar{n}$ transitions are not suppressed because the six-quark operators do not involve leptons. In these cases, $n \to \bar{n}$ oscillations can occur at rates comparable to existing experimental limits[22–24], and there are many explicit model examples[1;22;23] in which nucleon decay is absent or highly suppressed. Thus, $n \to \bar{n}$ would remain the primary manifestation of BNV for forseeable terrestrial experiments. Other examples of models without proton decay but with $n \to \bar{n}$ have been discussed in[25–28].

The question of the origin of the BAU may be related to that of the nature of dark matter, such as via a cogenesis between ordinary and dark sectors[29]. Mirror matter, a type of hypothetical dark sector constituted by cold atomic or baryonic matter originating from a sterile parallel SM′ gauge sector (a replica of our active SM sector), is a viable dark matter candidate[30;31]. Such a sector may provide another experimental portal onto $n \to \bar{n}$ physics, as well as motivate synergistic R&D initiatives. $\Delta(\mathcal{B} - \mathcal{L}) = 1$ interactions between SM and SM′ sectors may be at the origin of ordinary (active) and mirror (sterile) ν mixing[32] or neutron–mirror neutron mixing, leading to neutron–mirror neutron transitions ($n \to n'$)[33;34]. In the early universe, such mixing can co-generate both ordinary and mirror $\mathcal{B}$ asymmetries[29;35] giving a common origin to the observed baryonic and dark matter fractions of the universe, $\Omega_{\mathrm{DM}}/\Omega_{\mathrm{B}} \simeq 5$[30;36]. In contrast to $n \to \bar{n}$, $n \to n'$ could be a fast process with an oscillation period of seconds, and thus contain rich astrophysical implications, e.g. for ultra-high energy cosmic rays[37;38]. Some deviations from the null-hypothesis have been reported in $n \to n'$ disappearance searches using ultracold neutrons (UCN)[39;40]. The phenomena of $n \to \bar{n}$ ($\Delta\mathcal{B} = 2$) and $n \to n'$ ($\Delta\mathcal{B} = 1$) can be interrelated in unified theoretical frameworks, becoming parts of one common picture[41]. It can also provide a novel mechanism of $n \to \overline{n}$ via an $n \to n' \to \overline{n}$ shortcut[42], whose effect can be ten orders of magnitude larger than the one induced by direct $n \to \bar{n}$ mixing.

Predictions for $\tau_{n\bar{n}}$ and dinucleon decay rates start with quark-level amplitudes for $\Delta\mathcal{B} = 2$ six-quark operators, which are then matched to the hadronic level by calculations combining lattice QCD and chiral effective field theory (χEFT). Depending on the quark-level operator, different hadronic operators are induced. Typically, the most important are one-body $n \to \bar{n}$ operators, giving rise to both $n \to \bar{n}$ as well as dinucleon decays at leading order in χEFT[43;44]. The $n \to \bar{n}$ transition matrix elements of these operators have recently been calculated in exploratory lattice QCD calculations which directly connect the low-energy $n \to \bar{n}$ oscillation period to the parameters of BSM theories of ($\mathcal{B} - \mathcal{L}$)-violation[45;46]. In χEFT, $n \to \bar{n}$ is described by a Majorana n mass whose coupling can be fixed by matching to lattice QCD results. The same coupling can be used to calculate the deuteron lifetime at leading order in χEFT, but at higher-order there are additional contributions from two-body operators encoding the strength of $\Delta\mathcal{B} = 2$ nuclear interactions. The presence of these relatively unexplored interactions currently gives rise to uncertainties in determinations of BNV decays of nuclei. With improvements in the hadronic and nuclear theory, this difference could instead be turned into a feature for eventually discriminating between different BSM explanations of $(\mathcal{B}-\mathcal{L})$-violation after observing *both* free and bound $n \to \bar{n}$ in experiments. Capitalizing on recent progress in lattice QCD calculations of nuclear matrix elements[47;48] and *ab initio* nuclear theory calculations[49;50] which include high-order nucleon-nucleon and nucleon-antinucleon chiral interactions, the lifetimes of some heavier nuclei of experimental interest, such as ^{16}O, could be reliably calculated using similar EFT methods, relying on controlled approximations to the SM to compute the required nuclear matrix elements. BSM physics parameters can be related to the lifetimes of even heavier nuclei using well-known existing nuclear models[51–53], themselves offering excellent phenomenologies to be probed.

Future facilities will provide compelling and complementary opportunities to further explore both BNV and dark sector candidates using free n's alongside more traditional intranuclear searches for $n \to \bar{n}$ and dinucleon decays. Searches for free and intranuclear $n \to \bar{n}$ are both needed to determine the source(s) of BSM physics. The European Spallation Source (ESS), currently under construction, will be the world's most powerful pulsed source of cold n's. Current and future large underground detectors such as Super-Kamiokande (SK), the Deep Underground Neutrino Experiment (DUNE)[54], and Hyper-Kamiokande (HK)[55] offer substantial increases in mass, exposure, and reconstruction capabilities, and thus higher sensitivities to rare processes. Existing US-based Basic Energy Science facilities, including but not limited to the Spallation Neutron Source (SNS) and High Flux Isotope Reactor (HFIR) at ORNL[56], can be leveraged for research and development for complementary science on short time scales, and are also interesting possibilities to consider with their planned future upgrades. Examples include an optimized future 100 MW HFIR and the planned Second Target Station at the SNS.

The last free $n \to \bar{n}$ search using cold n's was performed in $\sim$1990 at the Institut Laue-Langevin (ILL)[57], achieving a lower limit of $\tau_{n\bar{n}} \sim 10^8$ s. In the intervening period, there has been substantial progress in both development of advanced n optics and annihilation-generated particle detection capabilities. By taking advantage of the current state of the art at future n sources, an improvement in sensitivity of $\gtrsim 1000\times$ILL[3;58–60] becomes possible, reaching $\tau_{n\bar{n}} \sim 10^{9-10}$ s[61–63]. The most promising opportunity for a future free $n \to \bar{n}$ search comes from an ambitious proposal by the NNBAR Collaboration[3;62] at the ESS. The ESS has included an important design accommodation for NNBAR to achieve the high n intensities needed for this search, the Large Beam Port (LBP), which has now been constructed. Optimization of the cold source for NNBAR is underway via the €3M Horizon2020 HighNESS project[60;62]. As the ESS is expected to run at 5 MW operation after $\gtrsim 2030$, a staged program accessing the physics questions of dark sectors through sterile n' searches such as $n \to n'$, $n \to n' \to n$[56] and $n \to n' \to \bar{n}$ has been developed, taking advantage of the existing n scattering facilities at ORNL, and continuing with an optimized experimental setup on the lower intensity fundamental physics ANNI beamline[64] as part of the HIBEAM program[62].

Another proposed approach to the free search for $n \to \bar{n}$ utilizes a material trap for the long-term storage of ultracold neutrons. With a UCN source production of 10^8 n/s, the increase of the experimental sensitivity can be about 10-40$\times$ILL, and so reaching $\tau_{n\bar{n}} \sim 10^{8-9}$ s, depending on the model of n reflection from the material trap walls[65–70]. The sensitivity of the experiment with UCN is lower than in the baseline NNBAR beam experiment at the ESS; however, realization of the experiment with UCN is less expensive and much more compact. In addition, this approach presents an important opportunity to perform a free search in an independent experiment using a very different methodology.

In similarity to free n searches, observable rates for intranuclear dinucleon processes, including $n \to \bar{n}$, show great complementary experimental reach across large underground experiments such as SK[71;72], DUNE[54], and HK[55]. SK has produced the world's best lower limit, $\tau_{n\bar{n}} > 2.7 \times 10^8$ s[71]. Prodigious amounts of n's in these large mass detectors provide the capacity to overcome expected intranuclear suppression of $n \to \bar{n}$ rates[43;53], though irreducible atmospheric ν backgrounds seem to persist at great cost to signal efficiency[72]. Similarly, when comparing to background, intranuclear final state interactions of annihilation-generated mesons can lead to some uncertainty surrounding the region of interest when investigating reconstructed total momentum and total invariant mass[53;71;72]. Better modeling of the annihilation location, process, transport, and differences across many nuclear model configurations are all currently being investigated. Given the special expected topological aspects of $\bar{n}$ annihilation within nuclei, there has been much progress to date in applications of deep learning and other automated analysis techniques such as boosted decision trees to the separation of these rare process signals from background. When converting through the traditional intranuclear suppression factor formalism[51;53], intranuclear searches are expected to probe $\tau_{n\bar{n}} \gtrsim 10^{8-9}$ s.

TeV-scale colored scalars responsible for dinucleon decay, $n \to \bar{n}$, and low-scale baryogenesis can be searched for at the LHC via dijet resonances. Current LHC limits on heavy scalar diquarks are already very stringent: $M_{qq} \gtrsim 7.5$ TeV[73]. This could be further improved at the future HL-LHC, and provide a complementary probe of $\Delta\mathcal{B} = 2$ processes. In the context of a given model with specific flavor structures, such as PSB[8], the LHC limit could be somewhat relaxed, especially if there is a sizable branching ratio to final state quarks involving the third generation. These channels, like tj and tb, are directly relevant for $n \to \bar{n}$ and should be searched for in future dijet analyses; such future collider constraints are expected to close portions of interesting parameter space to future free $n \to \bar{n}$ searches. A future 100 TeV collider could in principle probe the *entire* allowed parameter space of compelling PSB models.

By taking advantage of recent theoretical and experimental advances and next-generation facilities, searches for $n \to \bar{n}$ can be performed with significantly improved sensitivity compared to previous limits, and with great complementarity to future collider-based searches. To capitalize on these opportunities, scientific investment is needed in next decade to explore new ideas and directions which can improve the viability and sensitivity of these searches. $\Delta\mathcal{B} = 2$ searches serve an important and complementary role to searches for neutrinoless double β-decay and proton decay, and these efforts will address an important gap in the worldwide program to understand the baryon asymmetry of the universe.

References

[1] R. N. Mohapatra and R. Marshak, Phys. Rev. Lett. **44**, 1316 (1980), [Erratum: Phys.Rev.Lett. 44, 1643 (1980)].

[2] S. Glashow, NATO Sci. Ser. B **61**, 687 (1980).

[3] I. Phillips, D.G. *et al.*, Phys. Rept. **612**, 1 (2016), 1410.1100.

[4] A. Sakharov, Sov. Phys. Usp. **34**, 392 (1991).

[5] A. Nelson, CP Violation, Baryon violation, RPV in SUSY, Mesino Oscillations, and Baryogenesis, 2017, Slide 4: http://www.int.washington.edu/talks/WorkShops/int_17_69W/People/Nelson_A/Nelson.pdf.

[6] K. Babu, R. Mohapatra, and S. Nasri, Phys. Rev. Lett. **97**, 131301 (2006), hep-ph/0606144.

[7] K. Babu, P. S. B. Dev, and R. Mohapatra, Phys. Rev. D **79**, 015017 (2009), 0811.3411.

[8] K. Babu, P. S. B. Dev, E. C. Fortes, and R. Mohapatra, Phys. Rev. D **87**, 115019 (2013), 1303.6918.

[9] C. Cheung and K. Ishiwata, Phys. Rev. D **88**, 017901 (2013), 1304.0468.

[10] I. Baldes, N. F. Bell, A. Millar, K. Petraki, and R. R. Volkas, JCAP **11**, 041 (2014), 1410.0108.

[11] C. Grojean, B. Shakya, J. D. Wells, and Z. Zhang, Phys. Rev. Lett. **121**, 171801 (2018), 1806.00011.

[12] P. S. B. Dev and R. N. Mohapatra, Phys. Rev. D **92**, 016007 (2015), 1504.07196.

[13] K. Babu and R. Mohapatra, Phys. Lett. B **715**, 328 (2012), 1206.5701.

[14] D. McKeen and A. E. Nelson, Phys. Rev. D **94**, 076002 (2016), 1512.05359.

[15] K. Aitken, D. McKeen, T. Neder, and A. E. Nelson, Phys. Rev. D **96**, 075009 (2017), 1708.01259.

[16] L. Chang and N. Chang, Phys. Lett. B **92**, 103 (1980).

[17] T.-K. Kuo and S. Love, Phys. Rev. Lett. **45**, 93 (1980).

[18] R. Cowsik and S. Nussinov, Phys. Lett. B **101**, 237 (1981).

[19] S. Rao and R. Shrock, Phys. Lett. B **116**, 238 (1982).

[20] R. Mohapatra and J. C. Pati, Phys. Rev. D **11**, 2558 (1975).

[21] G. Senjanovic and R. N. Mohapatra, Phys. Rev. D **12**, 1502 (1975).

[22] S. Nussinov and R. Shrock, Phys. Rev. Lett. **88**, 171601 (2002), hep-ph/0112337.

[23] S. Girmohanta and R. Shrock, Phys. Rev. D **101**, 015017 (2020), 1911.05102.

[24] S. Girmohanta and R. Shrock, Phys. Rev. D **101**, 095012 (2020), 2003.14185.

[25] S. Rao and R. E. Shrock, Nucl. Phys. B **232**, 143 (1984).

[26] J. M. Arnold, B. Fornal, and M. B. Wise, Phys. Rev. D **87**, 075004 (2013), 1212.4556.

[27] R. Allahverdi, P. S. B. Dev, and B. Dutta, Phys. Lett. B **779**, 262 (2018), 1712.02713.

[28] S. Gardner and X. Yan, Phys. Lett. B **790**, 421 (2019), 1808.05288.

[29] Z. Berezhiani, Int. J. Mod. Phys. A **33**, 1844034 (2018).

[30] Z. Berezhiani, Int. J. Mod. Phys. **A19**, 3775 (2004), hep-ph/0312335.

[31] Z. Berezhiani, D. Comelli, and F. L. Villante, Phys. Lett. **B503**, 362 (2001), hep-ph/0008105.

[32] Z. Berezhiani, A. Dolgov, and R. Mohapatra, Phys. Lett. B **375**, 26 (1996), hep-ph/9511221.

[33] Z. Berezhiani and L. Bento, Phys. Rev. Lett. **96**, 081801 (2006), hep-ph/0507031.

[34] Z. Berezhiani, Eur. Phys. J. **C64**, 421 (2009), 0804.2088.

[35] L. Bento and Z. Berezhiani, Phys. Rev. Lett. **87**, 231304 (2001), hep-ph/0107281.

[36] Z. Berezhiani, Eur. Phys. J. ST **163**, 271 (2008).

[37] Z. Berezhiani and L. Bento, Phys. Lett. B **635**, 253 (2006), hep-ph/0602227.

[38] Z. Berezhiani and A. Gazizov, Eur. Phys. J. **C72**, 2111 (2012), 1109.3725.

[39] Z. Berezhiani and F. Nesti, Eur. Phys. J. C **72**, 1974 (2012), 1203.1035.

[40] Z. Berezhiani *et al.*, Eur. Phys. J. C **78**, 717 (2018), 1712.05761.

[41] Z. Berezhiani, Eur. Phys. J. C **76**, 705 (2016), 1507.05478.

[42] Z. Berezhiani, (2020), 2002.05609.

[43] F. Oosterhof, B. Long, J. de Vries, R. Timmermans, and U. van Kolck, Phys. Rev. Lett. **122**, 172501 (2019), 1902.05342.

[44] J. Haidenbauer and U.-G. Meißner, Chin. Phys. C **44**, 033101 (2020), 1910.14423.

[45] E. Rinaldi *et al.*, Phys. Rev. Lett. **122**, 162001 (2019), 1809.00246.

[46] E. Rinaldi *et al.*, Phys. Rev. D **99**, 074510 (2019), 1901.07519.

[47] USQCD, W. Detmold *et al.*, Eur. Phys. J. A **55**, 193 (2019), 1904.09512.

[48] Z. Davoudi *et al.*, (2020), 2008.11160.

[49] H.-W. Hammer, S. König, and U. van Kolck, Rev. Mod. Phys. **92**, 025004 (2020), 1906.12122.

[50] S. Gandolfi, D. Lonardoni, A. Lovato, and M. Piarulli, Front. Phys. **8**, 117 (2020), 2001.01374.

[51] C. Dover, A. Gal, and J. Richard, Phys. Rev. C **31**, 1423 (1985).

[52] E. Friedman and A. Gal, Phys. Rev. D **78**, 016002 (2008), 0803.3696.

[53] J. L. Barrow, E. S. Golubeva, E. Paryev, and J.-M. Richard, Phys. Rev. D **101**, 036008 (2020), 1906.02833.

[54] DUNE, B. Abi *et al.*, (2020), 2002.03005.

[55] Hyper-Kamiokande, K. Abe *et al.*, (2018), 1805.04163.

[56] L. Broussard *et al.*, EPJ Web Conf. **219**, 07002 (2019), 1912.08264.

[57] M. Baldo-Ceolin *et al.*, Z. Phys. C **63**, 409 (1994).

[58] M. J. f. t. N. C. Frost, (2016), 1607.07271.

[59] E. Klinkby and T. Soldner, Fundamental physics possibilities at the European Spallation Source, in *VI European Conference on Neutron Scattering (ECNS2015)*, 2016.

[60] V. Santoro *et al.*, Journal of Neutron Research **Pre-press**, 1 (2020), 2002.03883.

[61] V. Nesvizhevsky, V. Gudkov, K. Protasov, W. Snow, and A. Voronin, Phys. Lett. B **803**, 135357 (2020).

[62] A. Addazi *et al.*, (2020), 2006.04907.

[63] V. Gudkov, V. Nesvizhevsky, K. Protasov, W. Snow, and A. Voronin, Phys. Lett. B **808**, 135636 (2020), 1912.06730.

[64] T. Soldner *et al.*, EPJ Web Conf. **219**, 10003 (2019), 1811.11692.

[65] A. Serebrov, A. Fomin, and Y. Kamyshkov, Tech. Phys. Lett. **42**, 99 (2016).

[66] A. Fomin, A. Serebrov, O. Zherebtsov, E. Leonova, and M. Chaikovskii, J. Phys. Conf. Ser. **798**, 012115 (2017).

[67] A. Fomin, PoS **INPC2016**, 189 (2017).

[68] A. Fomin *et al.*, KnE Energ. Phys. **3**, 109 (2018).

[69] A. Fomin *et al.*, J. Phys. Conf. Ser. **1390**, 012133 (2019).

[70] A. Fomin *et al.*, EPJ Web Conf. **219**, 07003 (2019).

[71] Super-Kamiokande, K. Abe *et al.*, Phys. Rev. D **91**, 072006 (2015), 1109.4227.

[72] L. Wan, Neutron-antineutron oscillation search at Super-Kamiokande, 2020, Link here, and video here.

[73] CMS, A. M. Sirunyan *et al.*, JHEP **05**, 033 (2020), 1911.03947.