A novel approach for the study of CEvNS.

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We propose the use of isotopically highly enriched detectors for the precise study of coherent-elastic neutrino-nucleus scattering (CEvNS). CEvNS has been measured for the first time in CsI and recently confirmed with a liquid argon detector. It is expected that several new experimental setups will measure this process with increasing accuracy. Taking Ge detectors as a working example, we demonstrate that a combination of different isotopes is an excellent option to probe, for instance, the dominant quadratic dependence on the number of neutrons, $N$, that is predicted by the theoretical models. This is only an example, but the scheme has much more general applicability. Experiments based on the new approach can make a simultaneous differential CEvNS measurements with detectors of different isotopic composition. Particular combination of observables could be used to cancel systematic errors.

Very low energy neutrinos, such as those generated in reactors or pion decay at rest sources (\(\pi\) DAR), provide a new means of testing the Standard Model (SM) and its possible extensions. Precise measurements are required to understand the nature of the neutrino, to elucidate the phenomena that give rise to its unique properties and to determine its impact on the evolution of the Universe. After more than forty years of being proposed \cite{1}, the coherent elastic neutrino nucleus-scattering (CEvNS) was observed for the first time in 2017 by the COHERENT collaboration \cite{2,3} through a CsI detector located at the Spallation
Neutron Source (SNS) at Oak Ridge National Laboratory (ORNL). This process has also been confirmed by the same collaboration by using a liquid argon detector [4, 5].

A precise measurement of CEvNS is of interest for many fields such as nuclear physics, particle physics and applications. Just to mention some examples, CEvNS can help to extract detailed information about the nuclear radius for different target materials [6–9] as well as to constrain parameters which describe physics beyond the SM such as non-standard interactions [10–12], light mediators [13], neutrino magnetic moments [14, 15] or sterile neutrinos [16–18]. An application of considerable interest of reactor antineutrino detection using CEvNS is in nuclear security [19]. We propose a novel approach for the precise study of CEvNS; namely, the use of isotopically highly enriched detectors. We discuss Ge as a concrete example to show feasibility, but the proposed technique of using isotopically enriched material has much more general applicability. A detector based on multi-isotope detectors would have a particular combination of observables providing a fast unambiguous signature of antineutrino detection.

It was noticed, since the first theoretical proposal of CEvNS by Freedman [1], that its corresponding cross section has a quadratic dependence on the number of neutrons due to its coherent character. This enhancement makes the process very attractive both experimentally and theoretically [10]. The large cross section makes it the dominant process at low energies and opens a new detection channel that can give new independent physical information. Despite this advantage, the heavy mass of the nucleus implies the detection of a very low energy recoil and makes the measurement an experimental challenge. Nuclear recoil signals at low energies are not well calibrated and the ability to observe CEvNS from a reactor flux is very dependent on low energy quenching factors. These are not well known and their uncertainties are considerable. Significant progress has been made recently to better understand the associated systematic effects [20]. Long experiments might require corrections due to small drifts or for nonlinearities in the signal digitizer. Besides, as the process is testing a new energy region, it is natural that theoretical uncertainties will appear. That is the case, for instance, of the mean neutron radius of the target nuclei, for which, usually, only theoretical predictions exist. As a first step to test physics beyond the SM, the variables under discussion have to be well determined.

In this letter we propose a general experimental method to improve the CEvNS accuracy by using an array of detectors of the same element but different isotopes. The use
of such an array will help to diminish different systematic errors (from flux uncertainties, for instance) and to mitigate the dependence on form factors, allowing a better knowledge of the cross section and making it an even better tool for testing new physics. Currently, there are several proposals either ongoing or planned to measure CEvNS with a stopped-pion neutrino source or with reactor antineutrinos using different target materials such as CONNIE using Si-based CCDs [21, 22]; COHERENT [23], CONUS [24], νGEN [25], and TEXONO [26], using ionization-based Ge semiconductors; and MINER [27], NuCLEUS [28], and RICOCHET [29] using cryogenic detectors (Si, Zn, Ge). The proposed technique discussed here could be applied to any of these technologies, but to illustrate the idea, we will only consider the germanium case. The process of isotopically enriching germanium is a well-developed technology that has provided highly-enriched $^{76}\text{Ge}$ for detectors used in the search for neutrinoless double beta decay [30, 31]. Furthermore, isotopically modified Ge detectors depleted in $^{76}\text{Ge}$ have been produced and showed identical performance as those produced previously from natural germanium material [32, 33]. Mitigation or cancelation of the effect of systematic uncertainties is a crucial issue in many fields of Physics. The high purity that can be achieved in Ge detectors and the possibility of producing identical detectors that differ only in the number of neutrons provides a unique laboratory for the study of the CEvNS interaction.

For definiteness, we concentrate in the use of such an array of Ge detectors to study the $N^2$ CEvNS dependence, but it is important to remark that there is a wide margin to drastically improve several observables with this type of array. Furthermore, it will be shown that the differential nuclear recoil spectra have a non-trivial relative shape between the different isotopes. Its understanding will also help to inform the $N$ dependence of CEvNS and other observables, by conveniently choosing the appropriate region of energy. We will show that this setup of three different germanium detectors can probe this rule with a precision that may not be matched by other experiments. As with any CEvNS experiment, these measurements are inevitably affected by systematic uncertainties that mainly result, for instance, from quenching and form factors. However, in this particular case, the system of coupled detectors shares the same systematic effects and the correlations help to make a cleaner statement about the relative value of the cross sections.
FIG. 1: Differential event rate in terms of the nuclear recoil for two different isotopes ($^{70}$Ge and $^{76}$Ge) exposed to a stopped-pion neutrino source (left) or a reactor flux (right). As discussed in the text, we can see that for higher energies the lighter $^{70}$Ge has higher predicted rates per keV in both cases.

Within the SM, the explicit form of the CEvNS cross section is

$$\left( \frac{d\sigma}{dT} \right)_{\text{coh}}^{\text{SM}} = \frac{G_F^2 M}{\pi} \left[ 1 - \frac{MT}{2E_{\nu}^2} \right] \left[ Z g_p^V F_Z(q^2) + N g_n^V F_N(q^2) \right]^2$$

with $M$ the mass of the nucleus, $E_{\nu}$ the incident neutrino energy, and $F_X$ the nuclear form factors, with $X = Z, N$ for protons and neutrons, respectively. The factors $g_p^V = 1/2 - 2\sin^2\theta_W$ and $g_n^V = 1/2$ are the weak coupling constants. Notice that $g_p^V << g_n^V$ and, in consequence, the main dependence in this formula goes as $N^2$.

A precise confirmation of the $N^2$ dependence is challenging. The uncertainties coming from very different detectors with different exposure to the flux makes this task non-trivial. It is well known that germanium ($Z = 32$) has five stable natural isotopes: $^{70}$Ge, $^{72}$Ge, $^{73}$Ge, $^{74}$Ge, and $^{76}$Ge, implying a difference of up to 15% in the number of neutrons. The $N^2$ dependence will provide a significant variation in the number of CEvNS events per isotope. The use of three enriched detectors, $^{70}$Ge, $^{73}$Ge, and $^{76}$Ge, under simultaneous exposure time would solve the issue of dealing with different systematic uncertainties.

It is important to notice the behavior of the nuclear recoil energy spectra due to the neutron number. We would expect that the main difference between any two isotopes should be dominated by the variation between the squares of the corresponding number of neutrons for each isotope. However, the different masses of the isotopes also play an
important role, especially at the high energy tail of the recoil energy spectrum. We can illustrate this by considering two different isotopes, having \( N_1 \) and \( N_2 \) neutrons and a mass given approximately by \((Z + N_i)m_N\) with \( m_N \) the mass of an average nucleon. Taking only leading terms, the difference between their cross sections will be, approximately,

\[
\delta = \frac{d\sigma(N_2)}{dT} - \frac{d\sigma(N_1)}{dT} = \frac{G_F m_N}{\pi} \left( a(N_1, N_2, Z) - b(N_1, N_2, Z) \frac{m_N T}{2 E_\nu^2} \right)
\]

with

\[
a(N_1, N_2, Z) = g_n^2 \left( Z(N_2^2 - N_1^2) + (N_2^3 - N_1^3) \right)
\]

\[
b(N_1, N_2, Z) = g_n^2 \left( Z^2(N_2^2 - N_1^2) + 2Z(N_2^3 - N_1^3) + (N_2^4 - N_1^4) \right).
\]

For the case of \(^{70}\text{Ge}\) and \(^{76}\text{Ge}\), we will have \(a/b \simeq 0.01\), which means that the difference, \(\delta\), will vanish for \(T = 0.02 E_\nu^2/m_N\). For an average reactor antineutrino flux of \(E_\nu = 6\,\text{MeV}\) this happens around \(T = 0.7\,\text{keV}\), while for a \(\pi\) DAR source with average energy of \(E_\nu \simeq 40\,\text{MeV}\), the same situation arises at \(T \approx 32\,\text{keV}\). The more appealing result is that \(\delta\) will be negative for recoil energies above these values, that is, despite our expectation of a higher number of events for heavier isotopes, this is not the case in the tail of the recoil spectrum, an odd feature that could help to test the predicted CEvNS cross section. This is illustrated in Fig. [1] for reactor and \(\pi\)-DAR neutrinos, where we show the expected differential rate for two different isotopes after integrating over the incoming neutrino energy on each case.

To study the response of the proposed array of three Ge isotopes, we will start by defining the expected number of events, given by the convolution of the differential cross section, \(d\sigma/dT\), and the neutrino flux, \(\phi(E)\), that is:

\[
N^{\text{theo}} = N_D \int_T A(T) dT \int_{E_{\text{min}}}^{E_{\text{max}}} dE \phi(E) \frac{d\sigma}{dT},
\]

with \(N_D\) the number of target nuclei within the detector and \(A(T)\) an acceptance function.

We will start by considering a neutrino flux from a stopped-pion neutrino source; specifically one with the characteristics of the SNS at ORNL. In such case the total incident neutrino flux is given by three different contributions which result from the decay of pions.
and muons. We can use the total number of events predicted by Eq. (4) to test the characteristic \( N^2 \) dependence in the cross section of CEvNS. To do so, we replace the \( N \) factor in Eq. (1) by a variable, \( N' \), which will test how much an experimental measurement deviates from the \( N^2 \) dependence. Just like the number of neutrons, this factor will be different for each nucleus, and we can express:

\[
N_{\text{theo}} = N'^2 \left( g_{n}^2 N_D \frac{G_F^2 M}{\pi} \int_T A(T) dT \int_{E_{\text{min}}}^{E_{\text{max}}} dE \left[ 1 - \frac{MT}{2E_{\nu}^2} \right] \phi(E) F_N^2(q^2) \right) + N' \left( Z g_{p}^2 N_D \frac{G_F^2 M}{\pi} \int_T A(T) dT \int_{E_{\text{min}}}^{E_{\text{max}}} dE \left[ 1 - \frac{MT}{2E_{\nu}^2} \right] \phi(E) F_Z(q^2) F_N(q^2) \right) + Z^2 g_{p}^2 N_D \frac{G_F^2 M}{\pi} \int_T A(T) dT \int_{E_{\text{min}}}^{E_{\text{max}}} dE \left[ 1 - \frac{MT}{2E_{\nu}^2} \right] \phi(E) F_Z^2(q^2)
\]

The first term in Eq. (5) explicitly shows the dominant quadratic dependence on the number of neutrons for \( N' = N \). A \( N^2 \) rule would be absolute if \( g_{p}^2 \ll g_{n}^2 \) so that the second and third terms would be negligible. Indeed, this is close to the real case since \( g_{p}^2 / g_{n}^2 \approx 0.05 \); in all our computations we consider the complete expression of Eq. (5). We have explicitly checked that our results for the limiting case \( g_{p}^2 \to 0 \) are qualitatively similar. To test the sensitivity to the \( N^2 \) rule we perform a \( \chi^2 \) analysis following the covariant matrix approach, that is, we minimize the squared function:

\[
\chi^2 = \sum_{ij} (\Delta_i^{\text{theo}} - \Delta_i^{\text{exp}}) [\sigma_{ij}]^{-1} (\Delta_j^{\text{theo}} - \Delta_j^{\text{exp}}),
\]

where \( \sigma_{ij} \) is the covariant matrix and \( \Delta_i^{\text{exp}} \) the ‘experimental’ measurement, that we assume as the SM prediction. The indices \( i, j \) run over the observables tested during the analysis, which in this case depends on the number of detectors in the array.

We consider an experimental array of three different germanium isotopes located at the same distance from the neutrino source and taking data under identical conditions. Under these conditions, the detectors will be exposed to the same neutrino flux, regardless of any variations through the running time and there will be correlations among the systematic uncertainties which, as we will see, will be useful to test the \( N^2 \) dependence. We will consider only 10 kg of material for each of the three isotopes: \( ^{70}\text{Ge} \), \( ^{73}\text{Ge} \), and \( ^{76}\text{Ge} \). We consider a time of exposure of one year, a Helm distribution for protons and neutrons, and
FIG. 2: Expected measurement of the $N$ dependence in the case of different Germanium detectors within the same experimental setup. We assume that the three detectors, with equal mass, will be exposed to the same $\pi$-DAR SNS neutrino beam (see the text for details), that the systematic errors will be correlated, and we consider events from 5 up to 30 keV. The magenta and blue regions correspond, respectively, to the results of $^{76}\text{Ge}$ vs $^{73}\text{Ge}$ and $^{70}\text{Ge}$ vs $^{76}\text{Ge}$ at a 90 % C.L. when marginalizing over the missing detector.

an acceptance function equal to a step function. The covariance matrix is a $3 \times 3$ matrix with nonzero elements outside the diagonal due to the correlation between the detectors. Denoting by $A$ and $B$ the most significant sources of errors within the experiment, with $\sigma^A$ and $\sigma^B$ their corresponding uncertainties, we have:

$$
\sigma^2 = \begin{pmatrix}
\sigma_{70}^{\text{stat}} + \sigma_{70}^A + \sigma_{70}^B & \sigma_{70}^A \sigma_{73}^A + \sigma_{70}^B \sigma_{73}^B & \sigma_{70}^A \sigma_{76} + \sigma_{70}^B \sigma_{76}^B \\
\sigma_{70}^A \sigma_{73}^A + \sigma_{70}^B \sigma_{73}^B & \sigma_{73}^{\text{stat}} + \sigma_{73}^A + \sigma_{73}^B & \sigma_{73}^A \sigma_{76} + \sigma_{73}^B \sigma_{76}^B \\
\sigma_{70}^A \sigma_{76} + \sigma_{70}^B \sigma_{76}^B & \sigma_{73}^A \sigma_{76} + \sigma_{73}^B \sigma_{76}^B & \sigma_{76}^{\text{stat}} + \sigma_{76}^A + \sigma_{76}^B
\end{pmatrix}.
$$

(7)

This notation allows us to generalize the matrix elements for experiments with different neutrino sources and detection technologies. As a particular example for $\pi$-DAR source, we consider a 10 kg detector for each isotope, exposed to similar experimental conditions as those of the SNS [34]. We take the quenching factor ($A = \text{QF}$) and form factor ($B = \text{FF}$) effects as the main contributions to systematic uncertainties under a conservative case where each of these contributions have an impact of 5% in the total number of events. As the experimental array consists of three detectors, the $\chi^2$ function in Eq. (6) depends on three parameters, giving a volume as an allowed region for the number
of neutrons in each isotope, \(N'\). Two projections are shown in Fig. (2) at a 90% C.L. For instance, the magenta region shows the simultaneously allowed \(N'\) values for \(^{73}\text{Ge}\) and \(^{76}\text{Ge}\) when marginalizing the information about \(^{70}\text{Ge}\). As we can see, the expected region forms an ellipse that restricts the values of \(N'\) to lie in correlation to one another according to the \(N^2\) rule. A similar analysis is shown in blue for \(^{70}\text{Ge}\) and \(^{76}\text{Ge}\). It is important to notice that the expectation in this case is that the different detectors will show the expected proportionality of the three different cross sections.

We also consider the case of the same detector array, exposed now to a reactor antineutrino flux \([35–37]\). In this case, the flux from the reactor will be composed of only electron antineutrinos, and we take the main contributions for systematic errors from quenching factors (\(A = \text{QF}\)) and the neutrino flux itself (\(B = \text{NF}\)). Again we, consider these contributions to have an impact of 5% in the total number of events. For our computations we assume a neutrino flux of \(1 \times 10^{13} \, \nu/cm^2/s\) (a typical flux for several CEvNS experiments \([24]\)), a one year data taking and a mass of 10 kg for each detector. The incoming flux will be higher in this case, although the nuclear recoil energy threshold is more demanding. Despite this, if a 1keV recoil-energy threshold level can be reached, it is expected that this set of detectors can test the \(N^2\) rule with good significance.

This is illustrated in the left panel of Fig. (3). This figure illustrates the regions where we expect to have a measurement of the number of events when comparing the data from different detectors by pairs again marginalizing the information of the third detector, and considering the same previously discussed correlation. Indeed, if the \(N^2\) rule holds, the different measurements in the germanium detectors will be correlated. It is possible to see that the sensitivity would be enough to clearly distinguish different pairs of measured events. For comparison, the dashed line in the same panel shows the result of the expected measured number of events for the pair \(^{70}\text{Ge}, \, ^{76}\text{Ge}\) in the case where we do not have any correlations. It is clear that the effect of correlation is of the highest importance \(^1\).

As we have mentioned, we were expecting that measuring the tail of the spectrum will imply a rate of events where the lightest isotope will measure more events than the heavier one. This is the case in the left panel of Fig. (3). If the detector technology can go down in

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\(^1\) For this reactor example, the error in the antineutrino flux spectrum will also be a correlated error. However, it is expected that the error will be of the order of 2%; having no impact in comparison with other expected systematics.
FIG. 3: Expected number of events for the three different Ge detectors exposed to a reactor antineutrino flux. We show in the left panel the result of integrating on the large recoil energy of the spectrum from 1 to 2 keV. The central panel considers a recoil energy range from 0.7 to 1 keV. Finally, the right panel shows the correlation of the expected number of events between different detectors, for the recoil energy range from 0.4 to 0.8 keV. It can be seen that the event rate between the detectors is inverted on opposite sides of the spectrum (the blue and magenta ellipses get interchanged). For comparison, the uncorrelated case for the $^{70}$Ge vs $^{76}$Ge pair is also shown in the left panel.

In summary we present a novel approach for precision measurements of CEvNS. There are no major obstacles for constructing and operating a multi-isotope Ge detector array based on current technology. Moreover, other nuclei can also be used, such as silicon or nickel. We have shown that measuring CEvNS from the same neutrino source at the same time with several isotopically enriched detectors will improve the accuracy of the measurement. We have illustrated this idea with a well motivated array based on three different germanium isotopes and applied to the concrete example of confirming the $N^2$ rule. Besides current technology detectors, the same technique can be applied to other technologies that allow a lower energy thresholds as in the case of bolometers. After the first detection of CEvNS at the SNS, the next generation of experiments will aim for precision measurements. Despite
several years and a worldwide effort, detection of CEvNS at a reactor has not been observed. Neutrino fluxes and quenching factors remain as considerable sources of uncertainty. The proposal discussed here will help to achieve the necessary accuracy to disentangle different contributions from nuclear and particle physics such as the neutron charge distribution and the weak mixing angle value. It will also help to keep the different systematics under control and provide a clear signature of antineutrino detection.

This work was performed under the auspices of the U.S. Department of Energy by Oak Ridge National Laboratory under Contract No. DE-AC05- 00OR22725. This work has been supported by CONACyT under grant A1-S-23238.

[1] D. Z. Freedman, Phys. Rev. D 9, 1389 (1974). doi:10.1103/PhysRevD.9.1389
[2] D. Akimov et al. [COHERENT Collaboration], Science 357, no. 6356, 1123 (2017) doi:10.1126/science.aa0990 [arXiv:1708.01294 [nucl-ex]].
[3] D. Akimov et al. [COHERENT Collaboration], doi:10.5281/zenodo.1228631 [arXiv:1804.09459 [nucl-ex]].
[4] D. Akimov et al. [COHERENT Collaboration], Phys. Rev. D 100, no. 11, 115020 (2019) doi:10.1103/PhysRevD.100.115020 [arXiv:1909.05913 [hep-ex]].
[5] D. Akimov et al. [COHERENT], [arXiv:2003.10630 [nucl-ex]].
[6] M. Cadeddu, C. Giunti, Y. F. Li and Y. Y. Zhang, Phys. Rev. Lett. 120 (2018) no.7, 072501 doi:10.1103/PhysRevLett.120.072501 [arXiv:1710.02730 [hep-ph]].
[7] D. K. Papoulias, T. S. Kosmas, R. Sahu, V. K. B. Kota and M. Hota, Phys. Lett. B 800 (2020), 135133 doi:10.1016/j.physletb.2019.135133 [arXiv:1903.03722 [hep-ph]].
[8] D. Aristizabal Sierra, J. Liao and D. Marfatia, JHEP 06 (2019), 141 doi:10.1007/JHEP06(2019)141 [arXiv:1902.07398 [hep-ph]].
[9] P. Coloma, I. Esteban, M. C. Gonzalez-Garcia and J. Menendez, JHEP 08 (2020) no.08, 030 doi:10.1007/JHEP08(2020)030 [arXiv:2006.08624 [hep-ph]].
[10] J. Barranco, O. G. Miranda and T. I. Rashba, JHEP 12 (2005), 021 doi:10.1088/1126-6708/2005/12/021 [arXiv:hep-ph/0508299 [hep-ph]].
[11] K. Scholberg, a stopped-pion neutrino source,” Phys. Rev. D 73 (2006), 033005 doi:10.1103/PhysRevD.73.033005 [arXiv:hep-ex/0511042 [hep-ex]].
[12] J. Billard, J. Johnston and B. J. Kavanagh, JCAP 11 (2018), 016 doi:10.1088/1475-7516/2018/11/016 arXiv:1805.01798 [hep-ph].

[13] Y. Farzan, M. Lindner, W. Rodejohann and X. J. Xu, JHEP 05 (2018), 066 doi:10.1007/JHEP05(2018)066 arXiv:1802.05171 [hep-ph].

[14] H. T. Wong, Nucl. Phys. B Proc. Suppl. 138 (2005), 333-336 doi:10.1016/j.nuclphysbps.2004.11.076 arXiv:hep-ex/0311001 [hep-ex].

[15] O. G. Miranda, D. K. Papoulias, M. Tórtola and J. W. F. Valle, JHEP 07 (2019), 103 doi:10.1007/JHEP07(2019)103 arXiv:1905.03750 [hep-ph].

[16] B. Dutta, Y. Gao, R. Mahapatra, N. Mirabolfathi, L. E. Strigari and J. W. Walker, Phys. Rev. D 94 (2016) no.9, 093002 doi:10.1103/PhysRevD.94.093002 arXiv:1511.02834 [hep-ph].

[17] B. C. Cañas, E. A. Garcés, O. G. Miranda and A. Parada, Phys. Lett. B 776 (2018), 451-456 doi:10.1016/j.physletb.2017.11.074 arXiv:1708.09518 [hep-ph].

[18] O. G. Miranda, D. K. Papoulias, O. Sanders, M. Tórtola and J. W. F. Valle, arXiv:2008.02759 [hep-ph].

[19] M. Bowen and P. Huber, arXiv:2005.10907 [physics.ins-det].

[20] J. I. Collar, A. R. L. Kavner and C. M. Lewis, Phys. Rev. D 100, no.3, 033003 (2019) doi:10.1103/PhysRevD.100.033003 arXiv:1907.04828 [nucl-ex].

[21] A. Aguilar-Arevalo et al. [CONNIE Collaboration], JINST 11, no. 07, P07024 (2016) doi:10.1088/1748-0221/11/07/P07024 arXiv:1604.01343 [physics.ins-det].

[22] A. Aguilar-Arevalo et al. [CONNIE Collaboration], Phys. Rev. D 100, no. 9, 092005 (2019) doi:10.1103/PhysRevD.100.092005 arXiv:1906.02200 [physics.ins-det].

[23] D. Akimov et al. [COHERENT Collaboration], arXiv:1803.09183 [physics.ins-det].

[24] M. Lindner, W. Rodejohann and X. J. Xu, JHEP 1703, 097 (2017) doi:10.1007/JHEP03(2017)097 arXiv:1612.04150 [hep-ph].

[25] V. Belov et al., J. Instrum. 10, P12011 (2015).

[26] H. T. Wong, H. B. Li, J. Li, Q. Yue and Z. Y. Zhou, J. Phys. Conf. Ser. 39 (2006), 266-268 doi:10.1088/1742-6596/39/1/064 arXiv:hep-ex/0511001 [hep-ex].

[27] G. Agnolet et al. [MINER], Nucl. Instrum. Meth. A 853 (2017), 53-60 doi:10.1016/j.nima.2017.02.024 arXiv:1609.02066 [physics.ins-det].

[28] G. Angloher et al. [NUCLEUS], Eur. Phys. J. C 79 (2019) no.12, 1018 doi:10.1140/epjc/s10052-019-7454-4 arXiv:1905.10258 [physics.ins-det].
[29] J. Billard, et al. J. Phys. G 44 (2017) no.10, 105101 doi:10.1088/1361-6471/aa83d0
arXiv:1612.09035 [physics.ins-det]].

[30] M. Gunther, et al. [Heidelberg-Moscow Collaboration], Phys. Rev. D 55, 54-67 (1997)
doi:10.1103/PhysRevD.55.54

[31] K. P. Gradwohl, O. Moras, J. Janicskó-Csáthy, S. Schönert and R. R. Sumathi,
arXiv:2009.07585 [physics.ins-det]].

[32] D. Budjas, et al. JINST 8, P04018 (2013) doi:10.1088/1748-0221/8/04/P04018
arXiv:1303.6768 [physics.ins-det]].

[33] M. Agostini et al. Nucl. Phys. B Proc. Suppl. 229-232, 489-489 (2012)
doi:10.1016/j.nuclphysbps.2012.09.126

[34] D. Akimov et al. [COHERENT], arXiv:1509.08702 [physics.ins-det]].

[35] P. Huber and T. Schwetz, Phys. Rev. D 70 (2004), 053011 doi:10.1103/PhysRevD.70.053011
arXiv:hep-ph/0407026 [hep-ph]].

[36] G. Mention, M. Fechner, T. Lasserre, T. A. Mueller, D. Lhuillier, M. Cribier and A. Le-
tourneau, Phys. Rev. D 83 (2011), 073006 doi:10.1103/PhysRevD.83.073006 [arXiv:1101.2755
[hep-ex]].

[37] V. I. Kopeikin, L. A. Mikaelyan and V. V. Sinev, Phys. Atom. Nucl. 60 (1997), 172-176