Supernova Preshock Neutronization Burst as a Probe of Non-Standard Neutrino Interactions

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ABSTRACT

Core-collapse supernova (CCSN) provides a unique astrophysical site for studying neutrino-matter interactions. Prior to the shock-breakout neutrino burst during the collapse of the iron core, a preshock $\nu_e$ burst arises from the electron capture of nuclei and it is sensitive to the low-energy coherent elastic neutrino-nucleus scattering (CE$\nu$NS) which dominates the neutrino opacity. Since the CE$\nu$NS depends strongly on the non-standard neutrino interactions (NSI) which are completely beyond the standard model and yet to be determined, the detection of the preshock burst thus provides a clean way to extract the NSI information. Within the spherically symmetric general-relativistic hydrodynamic simulation for the CCSN, we investigate the NSI effects on the preshock burst. We find that the NSI can maximally enhance the peak luminosity of the preshock burst almost by a factor of three, reaching a value comparable with that of the shock-breakout burst. Future detection of the preshock burst will have critical implications on astrophysics, neutrino physics and physics beyond the standard model.

1. INTRODUCTION

Neutrinos interact feebly with ordinary matter (Wolfenstein 1999). Nonetheless, they play a critical role in a core-collapse supernova (CCSN), which marks the death of massive stars with mass $\gtrsim 8 \, M_\odot$ and leaves behind a compact remnant (see Woosley et al. 2002; Janka 2012; Burrows & Vartanyan 2021, for reviews). In a CCSN, most ($\sim 99\%$) of the released gravitational potential energy ($\sim 10^{53}$ erg) of the progenitor star is ultimately liberated through neutrino emission within a $\sim 10$ s burst. Neutrinos from CCSNe can thus carry invaluable information on both CCSN and neutrino physics (Koshiba 2003).

Meanwhile, the discovery of neutrino oscillations (Fukuda et al. 1998; Ahmad et al. 2002) indicates neutrinos are massive and lepton flavors are mixed, providing solid experimental evidence of physics beyond the Standard Model (SM). Current and upcoming neutrino experiments can measure subdominant neutrino oscillation effects that are expected to give information on the yet-unknown neutrino parameters and the non-standard interactions (NSI) between neutrinos and matter (Wolfenstein 1978; Ohlsson 2013; Farzan & Tórtola 2018; Bhupal Dev et al. 2019). Note that the NSI are completely originated from new physics beyond the SM and not an expected consequence of existing theories or neutrino oscillations. The NSI can modify the production, propagation and detection of neutrinos and thus may crucially affect the interpretation of the relevant experimental data. While the oscillation experiments can put important constraints on the NSI parameters, non-oscillation data (e.g., from neutrino scattering experiments) is needed to break the possible degeneracy of the neutrino parameters allowed by oscillation data alone (Coloma et al. 2017). Indeed, the deep inelastic neutrino scattering experiments (e.g., CHARM (Dorenbosch et al. 1986) and NuTeV (Zeller et al. 2002)) can help to break degeneracy but the constraints apply only if the NSI are generated by mediators not much lighter than the electroweak scale. For light mediators (Denton et al. 2018), the degeneracy can only be broken through combining with results on coherent elastic neutrino-nucleus scattering (CE$\nu$NS), which was predicted in the 1970’s (Freedman 1974) but observed only recently by the COHERENT Collaboration (Akimov et al. 2017, 2021).

Indeed, a global fit to neutrino oscillation and CE$\nu$NS data indicates that the degeneracy of neutrino parameters is significantly disfavored for a wider range of NSI models (Farzan & Tórtola 2018; Esteban et al. 2018; Coloma et al. 2020). Although significant progress has
been made on constraining the NSI parameters by analyzing data on neutrino oscillations, deep inelastic neutrino scattering and CEνNS, some NSI parameters are still not well constrained. In particular, the vector-like quark-νe neutral current (NC) couplings, $\varepsilon^{\nu V}_{ee}$ and $\varepsilon^{dV}_{ee}$, are the least experimentally constrained (Farzan & Tórtola 2018; Esteban et al. 2018; Coloma et al. 2020), preserving parameter space large enough for causing sizeable modifications on the CEνNS cross sections. Compared to the case of charged current (CC) NSI, it is a much more daunting task to constrain NC NSI due to the experimental and theoretical difficulties. Because of the frequent CEνNS in a CCSN, the CCSN can thus provide an ideal site for constraining the NC NSI parameters. Recently, Suliga & Tamborra (2021) estimate the NSI effects on neutrino-nucleon scattering in the post-bounce SN core within the diffusion time criterion wherein the neutrinos cannot be trapped for too long. In this work, we show that the neutrino burst from the preshock neutronization in a CCSN can be used as a novel and clean probe of the NC NSI parameters $\varepsilon^{\nu V}_{ee}$ and $\varepsilon^{dV}_{ee}$.

2. PRESHOCK NEUTRONIZATION BURST

Modern CCSN models (O’Connor et al. 2018) have commonly predicted the existence of the so-called neutronization neutrino burst with a peak luminosity $\sim 4 \times 10^{53}$ erg s$^{-1}$, which emerges during the first ~ 25 ms after the core bounce as a result of sudden breakout of a flood of neutrons freshly produced in shock-heated matter (and some νe produced previously that have diffused to the neutrinosphere) when the bounce shock penetrates the neutrinosphere and reaches the neutrino-transparent regime at sufficiently low densities. This shock-breakout burst mainly comprises νe from electron captures on free protons in the shock-heated matter.

Prior to the shock-breakout burst, there exists a smaller burst due to νe produced from the preshock neutronization of the collapsing core (Liebendörfer et al. 2003; Kachelrieß et al. 2005; Wallace et al. 2016; O’Connor et al. 2018). This preshock burst emerges as a result of the competition between the νe emission due to electron captures on nuclei during the early neutronization stage of core collapse and the νe trapping due to the opacity enhancement as the density and temperature of the core increase. Although the preshock burst is weaker than the shock-breakout burst, it generally has weaker model dependence in the CCSN simulations since it only involves the relatively simpler dynamics in the early stage of the CCSN. In particular, the preshock burst is expected to strongly depend on the CEνNS cross sections which essentially control the neutrino opacity in the preshock stage (Bruenn & Mezzacappa 1997), and thus to provide a clean probe of the NC NSI parameters $\varepsilon^{\nu V}_{ee}$ and $\varepsilon^{dV}_{ee}$. It should be noted that the NC interactions change the neutrino opacity without directly changing the neutrino production rate which is mainly determined by the CC electron capture processes (Sullivan et al. 2016; Langanke et al. 2021).

3. NSI EFFECTS ON NEUTRINO-NUCLEUS SCATTERING

Following the spirit of effective four-fermion couplings in low-energy weak interactions, the NC NSI Lagrangian can be typically formulated as (Ohiolson 2013; Farzan & Tórtola 2018; Bhupal Dev et al. 2019)

$$\mathcal{L}_{\text{NSI}} = -2\sqrt{2}G_F \varepsilon^{fX}_{\alpha\beta} \left(\bar{\nu}_\alpha \gamma^\mu P_L \nu_\beta\right) \left(\bar{f} \gamma_\mu P_X f\right),$$

where $G_F$ is the Fermi constant, $\varepsilon^{fX}_{\alpha\beta}$ denote the NSI parameters with $\varepsilon^{fX}_{\alpha\beta} \sim 1$ corresponding to a NSI strength comparable to that of SM weak interactions, $f \in \{\epsilon, \mu, \tau\}$ represent neutrino flavors, $P_L$ is the matter field, and $P_X$ with $X = L(R)$ represents the left(right) chirality projection operator. The NSI parameters are flavor diagonal for $\alpha = \beta$, while the lepton flavor is violated and the NSI become flavor-changing for $\alpha \neq \beta$. Here we mainly focus on the flavor-diagonal NC vectorial NSI couplings of $\nu_e$ to the light quarks, i.e.,

$$\varepsilon^{fV}_{ee} = \varepsilon^{fL}_{ee} + \varepsilon^{fR}_{ee}; f \in \{u, d\},$$

since they have relatively larger parameter space with $\varepsilon^{uV}_{ee}(\varepsilon^{dV}_{ee}) \in [0.0, 0.5]$ while the amplitude of other NSI parameters has been tightly constrained to be $\lesssim 0.1$ (Farzan & Tórtola 2018; Esteban et al. 2018; Coloma et al. 2020). Note the SNO results (Aharmim et al. 2008) agree well with the prediction of standard solar model, suggesting a small NSI axial interactions and thus $\varepsilon^{fL}_{ee} \approx \varepsilon^{fR}_{ee}$. With $\varepsilon^{u(d)} = \varepsilon^{u(d)V}_{ee}$, the effective NSI couplings to nucleons can thus be obtained as

$$\varepsilon^p = 2\varepsilon^u + \varepsilon^d,$$

$$\varepsilon^n = \varepsilon^u + 2\varepsilon^d.$$
are irrelevant to the NC NSI parameters $\varepsilon^u$ and $\varepsilon^d$. For simplicity, we neglect the weak magnetism corrections for anti-neutrinos (Horowitz 2002) since here we mainly focus on the neutronization burst in the early stage of CCSN, which mainly involves $\nu_e$. In such a case, the cross section modification is rather straightforward, namely, we only need to replace the NC vector couplings $g^p_V = 1/2 - 2\sin^2\theta_W$ and $g^n_V = -1/2$ in the SM, respectively, by $g^p'_{V}$ and $g^n'_{V}$ as

$$g^p'_{V} = g^p_{V} + \varepsilon^p, \quad g^n'_{V} = g^n_{V} + \varepsilon^n. \quad (4)$$

Correspondingly, the cross section expression is modified by replacing the weak charge of nucleus $Q_W = -2(Zg^p_{V} +Ng^n_{V})$ by $Q'_W$ as

$$Q'_W = Q_W + Q^\text{NSI}_W, \quad Q^\text{NSI}_W = -2(Z\varepsilon^p + N\varepsilon^n). \quad (5)$$

The ratio of the neutrino-nucleus cross sections with and without NSI can be expressed as $\sigma_{\text{SM+NSI}}/\sigma_{\text{SM}} = Q'^2_W/Q^2_W$ (Burrows et al. 2006) if we neglect the corrections from $C_{\text{FF}}$ and $C_{\text{LOS}}$. To examine the NSI effects on neutrino-nucleus scattering, we plot in Fig. 1 the ratio $\sigma_{\text{SM+NSI}}/\sigma_{\text{SM}}$ as a function of $\varepsilon^d (\varepsilon^u = 0)$ or $\varepsilon^u (\varepsilon^d = 0)$ for several typical nuclei, i.e., $^{12}\text{C}$, $^{56}\text{Fe}$ and $^{208}\text{Pb}$, as well as protons (p) and neutrons (n). One sees that the neutrino-nucleus cross sections can be drastically suppressed and even vanish around a certain value of $\varepsilon^d (\varepsilon^u)$ depending on the isospin of the nucleus. This is due to the fact that the effective weak charge $Q'_W$ may vanish for a certain value of $\varepsilon^d (\varepsilon^u)$ satisfying the relation $Y_p(g^p_{V} + 2\varepsilon^u + \varepsilon^d) + (1 - Y_p)(g^n_{V} + \varepsilon^u + 2\varepsilon^d) = 0$, where $Y_p = Z/A$ is the proton fraction of the nucleus. One can easily find $Q'_W = 0$ when $\varepsilon^u + \varepsilon^d = 0.159$ for nuclei with $N = Z$ (e.g., $^{12}\text{C}$), and for more neutron-rich nuclei (e.g., $^{56}\text{Fe}$, $^{208}\text{Pb}$) with smaller $Y_p$, $Q'_W = 0$ generally leads to larger $\varepsilon^d (\varepsilon^u)$, as shown in Fig. 1. On the other hand, the neutrino-p(n) cross section exhibits relatively weak sensitivity to $\varepsilon^d$ or $\varepsilon^u$. These features will lead to a number of interesting consequences on the neutrino burst in CCSN.

4. NSI EFFECTS ON NEUTRINO BURST

SN core collapse and bounce are simulated using the spherically-symmetric general-relativistic hydrodynamic code GR1D (O’Connor & Ott 2010; O’Connor 2015). As a default of the CCSN simulation, we adopt the 15 $M_\odot$ solar-metallicity progenitor star (s15s7b2) from Woosley & Weaver (1995), and the SFHo equation of state (EOS) from Steiner et al. (2013) is used to describe the physics of stellar matter. Fig. 2 shows the time evolution of all-flavor neutrino number and energy luminosities in the initial two stages of CCSN, i.e., the infall phase and neutronization burst, with $\varepsilon^u = 0, 0.1, 0.2, 0.3, 0.4, 0.5$ ($\varepsilon^d = 0$). The later two stages of accretion phase and Kelvin-Helmholtz cooling phase are not shown for simplicity since our main focus is the preshock burst.
For all the $\varepsilon^u$ values considered here, it is clearly seen from Fig. 2 that the luminosity displays two peaks, i.e., the smaller one around the bounce and the larger one after the bounce, respectively corresponding to the preshock burst and the shock-breakout burst. In particular, we note (although not shown here) that the preshock burst essentially consists of only $\nu_e$, and the shock-breakout burst (around the peak) is also dominated by $\nu_e$ with $\lesssim 15\%$ heavy-flavor (anti-)neutrinos and tiny ($\lesssim 1\%$) $\bar{\nu}_e$. In addition, the average $\nu_e$ energy of the preshock burst is $\sim 10$ MeV. For the shock-breakout burst, the average energy is $\sim 14$ MeV for $\nu_e$, $\sim 15$ MeV for heavy-flavor (anti-)neutrinos and $\sim 10$ MeV for $\bar{\nu}_e$. These general features have been also observed in various modern CCSN simulations (O’Connor et al. 2018).

The most interesting feature illustrated in Fig. 2 is the NSI effects on the two bursts, i.e., while the variation of the peak luminosity for the shock-breakout burst with $\varepsilon^u$ is a little complicated and relatively weak ($\lesssim 10\%$), the corresponding variation for the preshock burst is rather straightforward and very drastic. For the latter, the peak luminosity first increases with $\varepsilon^u$ varying from 0 to 0.2, and then decreases as $\varepsilon^u$ changes from 0.2 to 0.5. Such a variation is mainly due to the NSI effects on the neutrino-nucleus scattering. As shown in Fig. 1, increasing $\varepsilon^u$ from 0 to 0.2 will reduce drastically the neutrino-nucleus cross section and even make it vanish at $\varepsilon^u \sim 0.2$, and the cross section enhances again as $\varepsilon^u$ increases from 0.2 to 0.5. During the early neutronization stage of CCSN, the $\nu_e$, $e^-$ and nuclei are dominant and the CE$\nu$NS decisively controls the neutrino opacity (Bruenn & Mezzacappa 1997). The suppression on neutrino-nucleus scattering will increase neutrino’s mean free path and thus enhance the neutrino emission. Quantitatively, it is remarkable to see from Fig. 2 that the peak number (energy) luminosity of the preshock burst can reach to $\sim 2.1 \times 10^{58}$ s$^{-1}$ ($\sim 3.9 \times 10^{53}$ erg s$^{-1}$) for $\varepsilon^u = 0.2$, which is significantly larger than and almost three times of the corresponding value of without NSI [i.e., $\sim 0.86 \times 10^{58}$ s$^{-1}$ ($\sim 1.3 \times 10^{53}$ erg s$^{-1}$)] for $\varepsilon^u = 0$, and it even becomes comparable to the corresponding result of the shock-breakout burst [i.e., $\sim 2.5 \times 10^{58}$ s$^{-1}$ ($\sim 6.0 \times 10^{53}$ erg s$^{-1}$)].

It is interesting to see that the peak luminosity of the shock-breakout burst does not much depend on the NSI, and this is understandable since the shock-breakout burst neutrinos are mainly produced through electron captures on free protons in the shock-heated matter and escape in the neutrino-transparent regime at sufficiently low densities where the neutrino-nucleus scattering is less important. The neutrino-nucleon scattering in the shock-heated matter may give rise to opacity and thus influence the neutrino emission of the shock-breakout burst, but the NSI effects are relatively weak as shown in Fig. 1 (a). Moreover, the preshock burst may also slightly influence the shock-breakout burst since the former affects the $\nu_e$’s distribution behind the neutrinosphere. Furthermore, modern CCSN simulations (O’Connor et al. 2018) indicate some sensitivity of the shock-breakout burst height and shape to the details of the neutrino transport, while the preshock burst is relatively robust due to the much simpler dynamics involved. Therefore, our results suggest that the preshock burst of CCSN should be a clean probe of the NSI.

To examine the robustness of the preshock burst as a probe of $\varepsilon^d$, we show in Fig. 3 the peak number luminosity of the preshock burst as a function of $\varepsilon^d$ ($\varepsilon^u = 0$) and $\varepsilon^u$ ($\varepsilon^d = 0$) using three different EOSs, i.e., the default SFHo EOS, the LS220 EOS from Lattimer & Swesty (1991) with nuclear matter incompressibility $K_0 = 220$ MeV and Shen EOS from Shen et al. (2011). One sees that the difference of low density ($\lesssim 10^{12}$ g/cm$^3$) stellar matter EOS for the three EOSs since the preshock burst mainly involves stellar matter with density up to the neutrino trapping value ($\sim 10^{12}$ g/cm$^3$). Indeed, using the Lattimer and Swesty EOSs (Lattimer & Swesty 1991) with $K_0 = 180$ MeV and 375 MeV which give very different EOS around and above nuclear density ($\gtrsim 10^{14}$ g/cm$^3$) but same low density EOS, we find the resulting peak number luminosities are almost the same as that with $K_0 = 220$ MeV. In addition, one sees from Fig. 3 that
the $\epsilon^f$ maximizing the peak number luminosity is larger than that minimizing the $\nu_e$-$^{56}$Fe cross section as shown in Fig. 1, and this is mainly because the $^{56}$Fe nuclei in the collapsing core are transformed to more neutron-rich nuclei due to electron captures and thus larger $\epsilon^f$ is needed to minimize the $\nu_e$-nucleus cross sections as discussed previously.

We also note the preshock burst only weakly depends on the progenitor mass, consistent with the earlier findings (Takahashi et al. 2003; Kachelrieß et al. 2005; Wallace et al. 2016). Nevertheless, the progenitor property can be constrained with multimessenger signals (Mukhopadhyay et al. 2020; O’Connor & Ott 2013; Warren et al. 2020; Segerlund et al. 2021; Barker et al. 2021) once the source is detected. Moreover, the more realistic three-dimensional (3D) simulations (Nagakura et al. 2021) give very similar predictions on the neutronization burst during the early stage of CCSN as the one-dimensional (1D) simulations adopted here, further justifying the robustness of the preshock burst as a probe of $\epsilon^f$. In addition, the non-standard neutrino self interactions (NSI) are not considered here. Although the NSI may significantly modify the neutrino flavor transformation and thus influence the neutrino spectra (Dighe & Sen 2018; Yang & Kneller 2018; Lei et al. 2020), they are not expected to cause sizeable modification on our results unless the NSI neutrino-neutrino coupling $g_\nu$ can be significantly larger than the NSI neutrino-quark coupling $g_q$ (e.g., $g_\nu \gtrsim 90g_q$). This is because the NSI only have minor impact on the neutrino opacity due to the small $\nu_e$ fraction and cross section compared to those of nuclei in the early collapsing core. It will be interesting to see the NSI effects on the preshock burst when the $g_\nu$ is extremely large (e.g., $g_\nu \gtrsim 90g_q$).

In Fig. 3, we consider only two extreme cases by independently varying $\epsilon^d$ ($\epsilon^u = 0$) or $\epsilon^u$ ($\epsilon^d = 0$), and the results with simultaneous variation of $\epsilon^d$ and $\epsilon^u$ should be between the corresponding results of the two extreme cases. Moreover, due to the quadratic dependence of the CE$\nu$NS cross section on the weak charge, there inevitably exists $\epsilon^f$ degeneracy for a fixed peak luminosity of the preshock burst. In particular, Fig. 3 displays degeneracy for $\epsilon^f = 0$ and $\epsilon^f \sim 0.4$. The combined analysis of neutrino oscillation and CE$\nu$NS experiments perhaps can break the degeneracy. As pointed out in (Farzan & Tórtola 2018), $\epsilon^d \simeq 0.3$ is more favored than $\epsilon^d = 0$ at a level of $2\sigma$ in analyses of solar neutrino experiments. Recently, the COHERENT collaboration report their new measurement of CE$\nu$NS on Argon, excluding the parameter region around $\epsilon^f \sim 0.2$ with 90% C.L. (Akimov et al. 2021). Nevertheless, the peak luminosity of the preshock burst still keeps great sensitivity to the NSI in the remaining parameter space.

It is instructive to have a discussion on the experimental detection of the preshock burst. Although the neutrino oscillation should not lead to magnific modiﬁcations to the core collapse dynamics (Chakraborty et al. 2011; Dasgupta et al. 2012; Stapleford et al. 2020), it will largely distort the $\nu_e$ emission pattern in terrestrial detectors. Hence, it is better to use all-flavor detection to depict the temporal structure of the preshock burst. Recently, Raj (2020) shows the feasibility of detecting neutrino number luminosity from a failed CCSN using large-scale DM detectors, from which we note the detection of the preshock burst is possible if a source is located within $\sim 1$ kpc. Luckily, such pre-supernova stars are somewhat not too rare in our galaxy, and a list of 31 candidates within 1 kpc, including the famous Betelgeuse, is rendered in Mukhopadhyay et al. (2020). In addition, the $\epsilon^f$ reduces the detection rate of the detectors made of nuclei but has no effects on the neutrino-electron cross sections and even enhances the neutrino-p cross sections, and therefore the detectors made of protons or electrons should be ideal choice. As an example, we estimate the detection potential of $\epsilon^u$ by the Hyper-Kamiokande (Abe et al. 2018) via the electron scattering channel. Using the nsntools (Migenda et al. 2021) code to simulate the detector response for the preshock burst from a 1 kpc CCSN, we find the event count per 1 ms can reach $\mathcal{O}(10^2)$ around the preshock burst peak. By assuming $\chi^2 = \sum (N_{\text{SM}} - N_{\text{NSI}})^2/\sigma_{\text{stat}}^2$, we find the discovery region of $\epsilon^u$ with $3\sigma$ is $[0.015, 0.388] \bigoplus [0.415, 0.5]$ for no neutrino oscillation and $[0.033(0.023), 0.373(0.380)] \bigoplus [0.438(0.424), 0.5]$ for the oscillation scenario with normal (inverted) neutrino-mass ordering. Furthermore, it is important to note that the flavor-blind measurement via the elastic neutrino-p scattering, e.g., in JUNO (An et al. 2016), can avoid the influence of oscillation and even break the degeneracy at $\epsilon^f \sim 0.4$ due to the NSI enhancement of neutrino-p cross sections as shown in Fig. 1 (a). Such detection configuration of JUNO is yet to be added in nsntools.

Finally, we note that the enhancement of neutrino emission in the preshock burst can reduce the central electron fraction $Y_e$ of the CCSN, e.g., the central $Y_e$ after the bounce is reduced from 0.281 to 0.247 as $\epsilon^u$ varies from 0 to 0.2. This reduction of $Y_e$ may influence the later neutrino flavor evolution, explosion dynamics and nucleosynthesis (Kajino et al. 2019; Cowan et al. 2021) of the CCSN. Reliable predictions on these topics are beyond the 1D simulations, and it will be extremely interesting to explore them within the more realistic 3D simulations (Nagakura et al. 2021). In addition, it is...
worth noting that the detection of the preshock burst may provide a clean way to extract neutrino oscillation information and determine the neutrino-mass hierarchies (Takahashi et al. 2003; Kachelrieß et al. 2005; Wallace et al. 2016).

5. CONCLUSION

We have demonstrated that the preshock neutrino burst in CCSN can serve as a clean probe of the largely unknown NSI parameters $\varepsilon_{\nu e}^{V}$ and $\varepsilon_{e\nu}^{V}$. In particular, our results indicate that the NSI can enhance the peak luminosity of the preshock burst almost by a factor of three and make the luminosity comparable to that of the shock-breakout burst, which will have critical implications on the explosion dynamics of CCSN. Future detection of the preshock burst will open a new window to extract information on the CCSN, the NSI, the neutrino oscillation, and the neutrino-mass hierarchies.

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Software: GR1D (O’Connor & Ott 2010; O’Connor 2015), NuLib (O’Connor 2015), sntools (Migenda et al. 2021).

REFERENCES

Abe, K., Abe, K., Aihara, H., et al. 2018, arXiv e-prints, arXiv:1805.04163. https://arxiv.org/abs/1805.04163
Aharmim, B., Ahmed, S. N., Amsbaugh, J. F., et al. 2008, PhRvL, 101, 111301, doi: 10.1103/PhysRevLett.101.111301
Ahmed, Q. R., Allen, R. C., Andersen, T. C., et al. 2002, PhRvL, 89, 011301, doi: 10.1103/PhysRevLett.89.011301
Akimov, D., Albert, J. B., An, P., et al. 2017, Science, 357, 1123, doi: 10.1126/science.aao0990
—. 2021, PhRvL, 126, 012002, doi: 10.1103/PhysRevLett.126.012002
An, F., An, G., An, Q., et al. 2016, Journal of Physics G Nuclear Physics, 43, 030401, doi: 10.1088/0954-3899/43/3/030401
Barker, B. L., Harris, C. E., Warren, M. L., O’Connor, E. P., & Couch, S. M. 2021, arXiv e-prints, arXiv:2102.01118. https://arxiv.org/abs/2102.01118
Bhupal Dev, P., et al. 2019, SciPost Phys. Proc., 1, doi: 10.21468/SciPostPhysProc.2.001
Brueckner, O. M., & Mezzacappa, A. 1997, PhRvD, 56, 7529, doi: 10.1103/PhysRevD.56.7529
Burrows, A., Reddy, S., & Thompson, T. A. 2006, NuPhA, 777, 356, doi: 10.1016/j.nuclphysa.2004.06.012
Burrows, A., & Vartanyan, D. 2021, Nature, 589, 29, doi: 10.1038/s41586-020-03059-w
Chakraborty, S., Fischer, T., Mirizzi, A., Saviano, N., & Tomãs, R. 2011, PhRvL, 107, 151101, doi: 10.1103/PhysRevLett.107.151101
Coloma, P., Denton, P. B., Gonzalez-Garcia, M. C., Maltoni, M., & Schwetz, T. 2017, Journal of High Energy Physics, 2017, 116, doi: 10.1007/JHEP04(2017)116
Coloma, P., Esteban, I., Gonzalez-Garcia, M. C., & Maltoni, M. 2020, Journal of High Energy Physics, 2020, 23, doi: 10.1007/JHEP02(2020)023
Cowan, J. J., Sneden, C., Lawler, J. E., et al. 2021, Reviews of Modern Physics, 93, 015002, doi: 10.1103/RevModPhys.93.015002
Dasgupta, B., O’Connor, E. P., & Ott, C. D. 2012, PhRvD, 85, 065008, doi: 10.1103/PhysRevD.85.065008
Denton, P. B., Farzan, Y., & Shoemaker, I. M. 2018, Journal of High Energy Physics, 07, 037, doi: 10.1007/JHEP07(2018)037
Dighe, A., & Sen, M. 2018, PhRvD, 97, 043011, doi: 10.1103/PhysRevD.97.043011
Dorenbosch, J., Allaby, J. V., Amaldi, U., et al. 1986, Physics Letters B, 180, 303, doi: 10.1016/0370-2693(86)90315-1
Esteban, I., Gonzalez-Garcia, M. C., Maltoni, M., Martinez-Soler, I., & Salvado, J. 2018, Journal of High Energy Physics, 2018, 180, doi: 10.1007/JHEP08(2018)180
Farzan, Y., & Tórtola, M. 2018, Frontiers in Physics, 6, 10, doi: 10.3389/fphy.2018.00010
Freedman, D. Z. 1974, PhRvD, 9, 1389, doi: 10.1103/PhysRevD.9.1389
Fukuda, Y., Hayakawa, T., Ichihara, E., et al. 1998, PhRvL, 81, 1562, doi: 10.1103/PhysRevLett.81.1562
Horowitz, C. J. 2002, PhRvD, 65, 043001, doi: 10.1103/PhysRevD.65.043001
Janka, H.-T. 2012, Annual Review of Nuclear and Particle Science, 62, 407, doi: 10.1146/annurev-nucl-102711-094901
Kachelrieß, M., Tomàs, R., Buras, R., et al. 2005, PhRvD, 71, 063003, doi: 10.1103/PhysRevD.71.063003
