IL NUOVO CIMENTO **45 C** (2022) 8
DOI 10.1393/ncc/i2022-22008-9

Colloquia: SoUP 2021

EstrellaNueva: A tool to study neutrinos from supernovae

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received 4 November 2021

Summary. — The study of neutrinos is a great experimental challenge due to their small cross section of interaction. For this reason, the efforts of several international scientific collaborations have focused on the design and construction of detectors with several tons of active material. At the same time, a community of researchers is dedicated to simulate the supernovae neutrino flux. EstrellaNueva is a code written in Python, that offers a link between supernova simulations and the expected observed signal in the detectors, allowing to calculate the expected event rate, taking into account the simulated supernova flux, the cross section of the interaction channel, and the experimental characteristics of the detector. The aim of this work is to present the status of the EstrellaNueva code, showing the theoretical frame and the interaction channels that are currently implemented.

1. – Introduction

A supernova (SN) emits about 3×10^{53} erg of energy in the form of neutrinos of all species, representing 99% of the total emitted energy. The emission of neutrinos is considered quasi-thermal at the neutrino-sphere (sphere where it is considered that neutrinos can travel without diffusing with the SN matter due to their small interaction cross sections but still deep inside the SN) and the primary flux is parametrized by the following expression as a function of neutrino energy E and SN time t (the elapsed time taking the origin at the core bounce) [1],

$$\begin{aligned} F^0_\nu(E,t) =& \mathcal{L}_\nu(t)\frac{\left(1+\beta_\nu(t)\right)^{1+\beta_\nu(t)}}{\Gamma\left(1+\beta_\nu(t)\right)}\frac{E^{\beta_\nu(t)}}{\left(\left\langle E_\nu\right\rangle(t)\right)^{\beta_\nu(t)+2}}\times \\ & \exp\left[-\left(\beta_\nu(t)+1\right)\frac{E}{\left\langle E_\nu\right\rangle(t)}\right], \end{aligned} \tag{1}$$

(*) E-mail: `oiglez@estudiantes.fisica.unam.mx` where $\mathcal{L}_\nu$ is the luminosity, $\langle E_\nu \rangle$ the neutrino mean energy, and β_ν is the so-called energy-shape parameter. These quantities are referred to the neutrino species $\nu = (\nu_e, \nu_\mu, \nu_\tau, \bar{\nu}_e, \bar{\nu}_\mu, \bar{\nu}_\tau)$. The energy-shape parameter is given by

$$\beta_\nu(t) = \frac{2\left(\langle E_\nu \rangle(t)\right)^2 - \langle E_\nu^2 \rangle(t)}{\langle E_\nu^2 \rangle(t) - \left(\langle E_\nu \rangle(t)\right)^2}, \tag{2}$$

and it quantifies how close is the neutrino spectrum to the black-body spectrum as a function of time [1]. Using the neutrino flux emitted by the SN, F_ν, it is possible to calculate the number of interactions. The number of interactions per unit time and unit energy is

$$\frac{d^2 N_\nu}{dEdt}(E,t) = \frac{N_t}{4\pi d^2}\sigma_\nu(E) F_\nu(E,t), \tag{3}$$

where d is the distance to the SN, N_t the number of target particles in the active volume of the detector, and σ_ν is the total cross section as a function of the neutrino energy for a given interaction channel. Integrating eq. (3), the interaction rates with respect to E and t are

$$\frac{dN_\nu}{dE}(E) = \int_{t_0}^{t_{end}} dt \left[\frac{d^2 N_\nu}{dEdt}(E,t)\right], \tag{4}$$

and

$$\frac{dN_\nu}{dt}(t) = \int_0^\infty dE \left[\frac{d^2 N_\nu}{dEdt}(E,t)\right], \tag{5}$$

respectively.

In the case of $\nu - x \to \nu - x$ elastic scattering, where x means electron, proton, or nucleus for coherent elastic neutrino-nucleus scattering (CEνNS), it is possible to compute the interaction rate with respect to the recoil particle energy T. In this case, the number of interactions per unit time, unit energy and unit recoil energy is given by

$$\frac{d^3 N_\nu}{dEdTdt}(E,T,t) = \frac{N_t}{4\pi d^2}\frac{d\sigma_\nu}{dT}(E,T) F_\nu(E,t), \tag{6}$$

where $\frac{d\sigma_\nu}{dT}$ is the differential cross section with respect to T, which is related to the total cross section as follows:

$$\sigma_\nu(E) = \int_0^{T_{max}(E)} \frac{d\sigma_\nu}{dT}(E,T)dT, \tag{7}$$

where

$$T_{max}(E) = \frac{2E^2}{2E+m}, \tag{8}$$

and m is the mass of particle x. From eq. (6), the interaction rate with respect to T is obtained as follows,

$$\frac{dN_\nu}{dT}(T) = \int_{t_0}^{t_{end}} dt \int_{E_{min}(T)}^{\infty} dE \left[\frac{d^3N_\nu}{dEdTdt}(E,T,t)\right], \tag{9}$$

where

$$E_{min}(T) = \frac{T+\sqrt{T(T+2m)}}{2}. \tag{10}$$

Finally, the total number of interactions is

$$N_\nu = \int_0^\infty dE \left[\frac{dN_\nu}{dE}(E)\right] = \int_{t_0}^{t_{end}} dt \left[\frac{dN_\nu}{dt}(t)\right] = \int_0^\infty dT \left[\frac{dN_\nu}{dT}(T)\right]. \tag{11}$$

The above description shows the implemented theoretical frame.

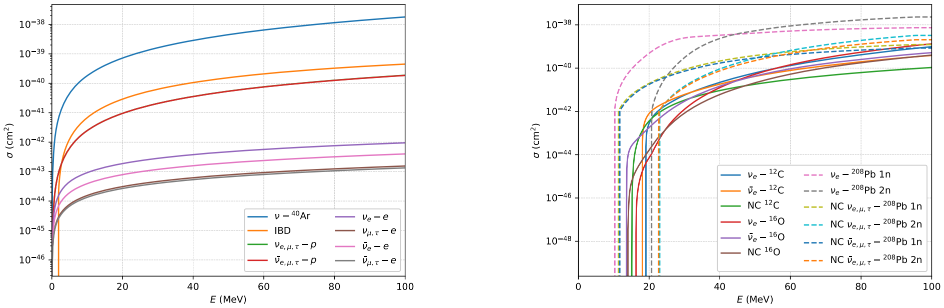
This work is organized as follows: sect. **2** is dedicated to present the cross sections of the detection channels implemented in the EstrellaNueva code and sect. **3** shows an example of some of the interaction rates that can be computed. Finally, sect. **4** presents the conclusions.

2. – Detection channels

The EstrellaNueva code has implemented the cross section of the principal detection channels for materials used in current and future neutrino detectors, such as water, argon, xenon, lead, and mineral liquid scintillators. The detection channels are: neutrino-electron ($\nu - e$) elastic scattering [2], neutrino-proton ($\nu - p$) elastic scattering [3], inverse beta decay (IBD) [3], CEνNS [4], and the interactions with ^{12}C, ^{16}O, and ^{208}Pb. The last three were taken from the SNOwGLoBES [5] repository in the form of data files and the rest were implemented analytically. In the case of CEνNS, the form factor of the nucleus $F(q^2)$ is assumed equal to 1, which means that the transfered momentum q is considered very small ($q^2 \to 0$), as a first approximation. In future updates of the code, the functional dependence of $F(q^2)$ will be taken into account with a more accurate approximation for supernovae (SNe) neutrino energies. These cross sections depend on the mass and atomic number of the target nucleus. Figure 1 shows the cross sections implemented in EstrellaNueva, where the cross section for CEνNS in ^{40}Ar is also shown.

3. – Interaction rates

The EstrellaNueva code was specifically designed for complementing the simulations made by various SN simulation groups, estimating the event rate expected in neutrino detectors. The Garching group [6] uses the PROMETHEUS-VERTEX code [1, 6] to simulate the time dependence of the flux parameters at the neutrino-sphere. Then, without taking into account the effects of neutrino oscillations in the SN matter, as a first approximation, it is possible to calculate the interaction rate assuming that the neutrino flux emitted by the SN is equal to the primary flux at the neutrino-sphere ($F_\nu = F_\nu^0$). As an example, model ls220_s15.0 is used, which corresponds to a progenitor of mass



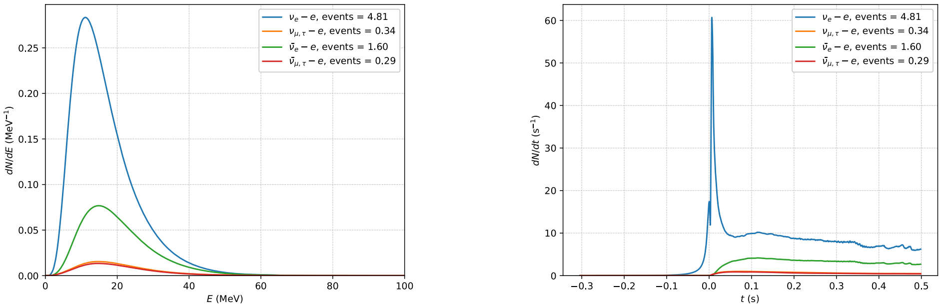
(a) (b)

Fig. 1. – Cross sections as function of the neutrino energy. (a) $\nu - {}^{40}$Ar refers to CEνNS in ^{40}Ar. In the case of interactions with protons, the cross sections for neutrinos and antineutrinos are superimposed. (b) NC are neutral current interactions, while the rest are charge current interactions (CC). In the case of interactions with ^{208}Pb, (1n) and (2n) are interactions resulting in one and two neutrons, respectively. See [5] for references.

$M = 15.0 M_\odot$ ($M_\odot$ is the mass of the Sun) and was simulated by the Garching group using the equation of state of Lattimer and Swesty [7], with a nuclear incompressibility of 220 MeV. Setting a distance of 10 kpc to the SN, the detector material as LAB (Linear Alkylbenzene), and the detector mass equal to 1 kton, the interaction rates for $\nu - e$ elastic scattering are obtained and shown in figs. 2 and 3 (a). Similar curves can be obtained for CEνNS. Figure 3 (b) shows the CEνNS rate with respect to T in 1 kton of argon.

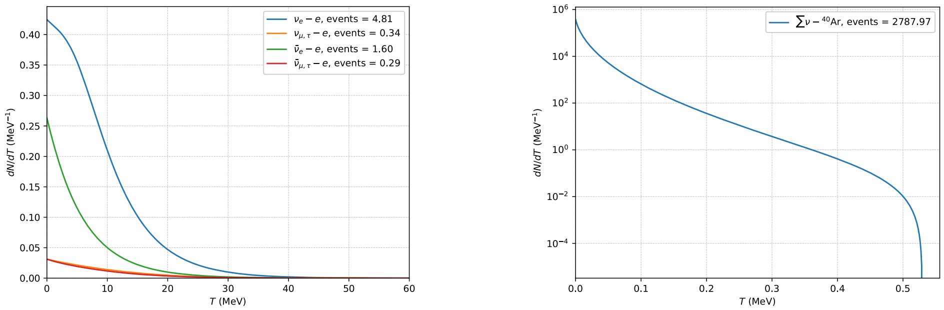
4. – Conclusions

The EstrellaNueva code provides a useful user-friendly tool to study the neutrino and SN properties, simulating the expected number of events in neutrino detectors. Several



(a) (b)

Fig. 2. – (a) Interaction rates for $\nu - e$ elastic scattering with respect to the neutrino energy E. The total number of events for each channel are also shown. (b) Interaction rates for $\nu - e$ elastic scattering with respect to the SN time t. The total number of events for each channel are also shown.



(a) (b)

Fig. 3. – (a) Interaction rates for $\nu - e$ elastic scattering with respect to the recoil electron energy T. The total number of events for each channel are also shown. (b) Interaction rate for CEνNS in 1 kton of ^{40}Ar with respect to the recoil nucleus energy T. The total number of events is also shown.

detection channels are currently implemented, such as neutrino-electron and neutrino-proton elastic scattering, inverse beta decay, coherent elastic neutrino-nucleus scattering, and the interactions with ^{12}C, ^{16}O, and ^{208}Pb. The next steps include implementing the neutrino oscillations in SNe, the quenching factor for neutrino-proton elastic scattering, a more accurate approximation for the nuclear form factor considering a functional dependence with the transfered momentum to the nucleus, and the option to include experimental characteristics such as the resolution and the efficiency of the detector.

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This work is supported by the projects CONACYT CB-2017-2018/A1- S-8960 and DGAPA UNAM grant PAPIIT-IN108020. The authors wish to thank J. Rumleskie, J. Tseng, and the SNO+ Collaboration, as well as Eduardo Peinado, Leon M. G. de la Vega, and L. J. Flores for helpful discussions.

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