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Neutrino process for nuclei involved in r-process nucleosynthesis: cross section to nuclei with A< 30

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In this work we have studied weak processes such $\beta-$decay and neutrino capture that are very important for the r-process. This process takes place far from the $\beta-$stability line, that means in a region where data are very scarce experimentally. In order to study the nucleosynthesis of elements heavier than iron it is necessary to know the cross sections of neutrino-nucleus processes for these nuclei. We have fitted results obtained by Gross Theory of Beta Decay (GTBD) applied to neutrino-nucleus cross sections. We used a four degree polynomial dependence of the cross section with the incident neutrino energy in fitting Gross Theory theoretical results. This dependence allows us to systematically calculate the neutrino–nucleus cross sections for a large group of nuclei, such as those needed in the r-process (more than 4000 nuclei). Our fitting and interpolation procedures are shown to be in a good agreement and the GTBD cross sections are successfully reproduced.

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1. Introduction

Nuclear elements abundance in the universe are promoted by different astrophysics sites. The nuclear reactions re-arranges the basic constituents of atomic nuclei using different allowed configurations, where particle captures and photon nuclei emission are important mechanisms [1]. In addition when neutrinos flux are present they are also captured and emitted by $\beta-$decay of the involved nuclei. But the process of adding neutrons will lead to neutron-rich isotopes that will decay towards a more stable isotopes, releasing energy and particles [3].

In order to explain the abundances of heavy elements a few process were proposed but in this work we are only interested in the r-process (rapid neutron capture), that is the natural way to create most of heavy elements, once for neutrons we does not have Coulomb barrier making neutrons easier to capture than protons. The r-process can occurs under explosive conditions as well as in neutron star fusion process (merging of neutron star) [2], where large neutron fluxes can be released during short time scales (much faster than beta decay). This situation creates a very unstable neutron rich isotopes close to the neutron drip line. At some point the probability of beta decay will be greater than additional neutron capture.

It is well know that the r-process is a primary process independent of the star metallicity degree. It is necessary to have a very intense neutron fluxes to make neutron capture possible by seed nuclei. Until now is not completely know the astrophysics sites where this process take place, previous work associated with core collapse supernova explosions [4], however presently other assumptions are available in the literature as source of r-process occurrence. More recently the observation of the kilonova [2] has confirm places like Binary Neutron Star mergers (BNS) as possible site [5, 6]. This binary system consist of two neutron stars losing energy and angular momentum through the emission of gravitational waves until merges. We are particularly interested in this site once a large amount of free neutrons are available to build-up the heaviest elements and the possibility of multimensseger astronomy.

We can say that all elements havier than iron has a component of abundance generated by the r-process. But when temperature decreases some reactions slow down and the abundance of each isotope will also depend on the β-decays, neutrino captures and photodisintegrations. In order to study the formation of heavy elements it is necessary to calculate the competitive rate of this nuclear reactions. For β-decay and neutrino capture we will use the Gross Theory for Beta Decay (TGBD) proposed by Takahashi and Yamada [7]. It is essentially a parametric model, which attempted to combine the single-particle and statistical arguments in a phenomenological way. Nowdays, differents versions of GTBD have been used like GT2 and Semi-Gross Theory [8, 9]. Between the improvements we can remark the addition of forbidden transitions and the inclusion of pairing effects which is very important to describe neutrino-nucleus reactions in a more realistic way.

The computational work of the GTBD is much simpler than others microscopic models like RPA and Shell model. Also the capability of reproduce the experimental half lives by GTBD and to extrapolate to those nuclei far way from the β-stability line is quite satisfactory. This half-lives predictions depend strongly on the mass model used. In order to obtain a good approximation for the mass values of those nuclei close to the neutron drip-line we will apply the machine learning technique [10], that has been used recently in a several nuclear calculations.

2. The gross theory for beta decay and neutrino capture

The GTBD permit us to evaluate the total decay rate for allowed transitions

$$\lambda_\beta = \frac{G_F^2}{2\pi^3}\int_{-Q_\beta}^{0} dE[g_V^2|\mathcal{M}_F(E)|^2 + g_A^2|\mathcal{M}_{GT}(E)|^2]f(-E), \tag{1}$$

where $G_F = (3.034545 \pm 0.00006) \times 10^{-12}$ and $f(E)$ are, respectively, the weak coupling constant and the Fermi integral. $g_V = 1$ and $g_A = -1$ are the vector and axial-vector effective coupling constants. The argument of the matrix element (E) is the transition energy measured from the parent ground state

$$E_\beta = E_e + E_\nu = -E > 0.$$

$f(-E)$ is the integral, given by

$$f(-E) = \int_1^{-E+1} (-E + 1 - E_e)^2 E_e\sqrt{E_e^2 - 1} \times F(Z, E_e)dE_e, \tag{2}$$

$F(Z, E_e)$ is the Fermi function that takes account the coulomb interaction between the electron and daughter nucleus. In this work we use the Fermi function proposed by Takahashi and Yamada [7]. The Q_β value is the difference between neutral atomic masses of parent and daughter nuclei, given by

$$Q_\beta = M(A, Z) - M(A, Z + 1) = B(A, Z + 1) - B(A, Z) + m(nH) \tag{3}$$

with $B(A, Z)$ and $B(A, Z + 1)$ being the corresponding nuclear binding energies, and $m(nH) = m_n - m(^1H) = m_n - m_p - m_e = 0.782$ MeV. For those β-stables nuclei there are experimental data available in [12], but to those nuclei far away from the β-stability line we have to employ an empirical mass formula [13]. We also are looking to improve this values using the machine learning technique, recent studies obtained great results in the improvement of the beta and alpha mass difference [10, 14].

The squares of the Fermi (F) and Gamow-Teller (GT) matrix elements are given by

$$|\mathcal{M}_X(E)|^2 = \int_{\mathcal{E}_{min}}^{\mathcal{E}_{max}} D_X(E, \mathcal{E})W(E, \mathcal{E})\frac{dN_1}{d\mathcal{E}}d\mathcal{E}, \tag{4}$$

where $\mathcal{E}_{min}$ is the lowest single-particle energy of the parent nucleus and $\mathcal{E}_{max}$ is the energy of the highest occupied state. The state density can be written by

$$\frac{dN_1}{d\mathcal{E}} = N_1\left[1 - \left(1 - \frac{Q + E}{\mathcal{E}_F}\right)^{\frac{3}{2}}\right], \tag{5}$$

where N_1 is the neutron number of the father nucleus and $\mathcal{E}_F$ is the Fermi energy. The weight function $W(E, \epsilon)$ is defined in the interval $0 \leq W(E, \epsilon) \leq 1$ and takes into account the Pauli blocking. The energy distribution function $D_\Omega(E, \epsilon)$ measures the probability that a nucleon with single-particle energy undergoes a β-transition. We have neglected the ϵ-dependence and assumed that all nucleons have the same decay probability, so $D_X(E, \epsilon) \equiv D_X(E)$. That can be a Gaussian

$$D_X(E) = \frac{1}{\sqrt{2\pi}\sigma_X}\exp\left[\frac{-(E - E_X)^2}{2\sigma_X^2}\right], \tag{6}$$

where E_X is the resonance energy and σ_X the standard deviation. The Fermi and Gammow-Teller resonance are

$$E_F = \pm(1.44ZA^{-1/3} - 0.7825) \quad \text{MeV} \tag{7}$$

$$E_{GT} = E_F + \delta, \qquad \delta = 26A^{-1/3} - 18.5(N-Z)/A \quad \text{MeV}. \tag{8}$$

The standard desviations are

$$\begin{aligned} \sigma_F &= 0.157ZA^{-1/3}\text{MeV}, \\ \sigma_{GT} &= \sqrt{\sigma_F^2 + \sigma_N^2}, \end{aligned} \tag{9}$$

with σ_N being a setting parameter which comes from the energy propagation produced by the forces dependent of the nuclear spin. In their work Samana et al., proposed an improvement in the minimization method compared to the original TGBD work [15]

$$\chi^2 = \sum_{n=1}^{N_0} \left[\frac{\log\left(\tau_{1/2}^{cal}(n)/\tau_{1/2}^{exp}(n)\right)}{\Delta \log\left(\tau_{1/2}^{exp}(n)\right)} \right]^2, \tag{10}$$

onde $\Delta \log\left(\tau_{1/2}^{exp}(n)\right) = |\log[\tau_{1/2}^{exp}(n) + \delta\tau_{1/2}^{exp}(n)] - \log[\tau_{1/2}(n)]|$.

One of the most important process in the nucleosynthesis of heavy elements is the neutrino capture. The neutrino cross section σ_ν for allowed transitions reads

$$\sigma(E_\nu) = \frac{G^2}{\pi} \int_0^{E_\nu - m_e} p_e E_e F(Z+1, E_e)[g_V^2|\mathcal{M}_F(E)|^2 + g_A^2|\mathcal{M}_{GT}(E)|^2]dE. \tag{11}$$

3. Results for the neutrino capture cross sections (fitted in the region A<30)

In order to study the r-process we need to obtain the neutrino cross section for those nuclei far way from the beta stability line that we do not have any experimental data. In this way, Barbero et al. proposed an expression to systematically calculate the neutrino-nucleus cross section for a large number of nuclei [16].

$$\sigma(E_\nu) = \sum_{i=0}^{4} \mathcal{D}_i(A,Z)E_\nu^i, \tag{12}$$

where $\mathcal{D}_i(A,Z)$ are a function of the mass and atomic numbers, given by

$$\mathcal{D}_i(A,Z) = \sum_{m=1}^{4}\sum_{n=0}^{4} d_{nm}^{(i)} Z^n \alpha_m(A). \tag{13}$$

For the dependence with A was inspired by the adjustment of coefficientes in the liquid drop model. We have $\alpha_1(A) = A$, $\alpha_2(A) = A^{2/3}$, $\alpha_3(A) = A^{-1/3}$ and $\alpha_4(A) = A^{-1}$.

In table (1) is shown the $d_{nm}^{(i)}$ coefficients derived from the interpolation between the fourth order polynomial adjustment of the cross sections from our GTBD model and the neutrino energy. With this coefficients we can obtain our original cross sections and extrapolate for neighborhood nuclei. The neutrino-nucleus cross section evaluated with our GTBD model are compared with the

i	0	1	2	3	4
d^i_{01}	2.6504	0.9410	4.2958×10^{-2}	-1.1244×10^{-5}	-6.1025×10^{-10}
d^i_{02}	-4.7901	-2.1260	-7.0830×10^{-2}	-1.7109×10^{-5}	-4.2481×10^{-9}
d^i_{11}	6.3811×10^{-2}	7.1228×10^{-2}	2.6180×10^{-3}	-5.5074×10^{-7}	-1.5627×10^{-9}
d^i_{12}	-0.1814	-0.1693	-7.7739×10^{-3}	3.3177×10^{-6}	-2.8410×10^{-9}
d^i_{21}	1.7291×10^{-3}	4.5213×10^{-3}	1.2939×10^{-4}	-8.5625×10^{-9}	-3.5893×10^{-12}
d^i_{22}	-9.4967×10^{-3}	-1.2526×10^{-2}	-5.7365×10^{-4}	1.2205×10^{-6}	-7.9304×10^{-10}
d^i_{31}	2.9003×10^{-5}	2.3441×10^{-4}	7.0156×10^{-6}	-5.2311×10^{-9}	-2.7659×10^{-12}
d^i_{32}	-5.8203×10^{-4}	-9.1441×10^{-4}	-3.2248×10^{-5}	5.9803×10^{-9}	-1.2081×10^{-11}
d^i_{41}	-1.9324×10^{-6}	8.3064×10^{-6}	5.0249×10^{-7}	-6.4370×10^{-10}	-8.8650×10^{-14}
d^i_{42}	-3.8794×10^{-5}	-6.9434×10^{-5}	-1.4018×10^{-6}	-1.1529×10^{-9}	-3.4066×10^{-13}

Table 1: Coefficients $d^{(i)}_{nm}$ (in units of 10^{-42} cm^2) for the even-even set of nuclei decaying by β^-.

cross section obtained by eq. (12) in figure (1). It can be seen that our cross sections are successfully reproduced. This gives us confidence to study those nuclei far away from the beta stability line. We hope in the near future to extend our calculations for a set of 965 nuclear species in the mass region $A < 220$ which are essential for the r-process.

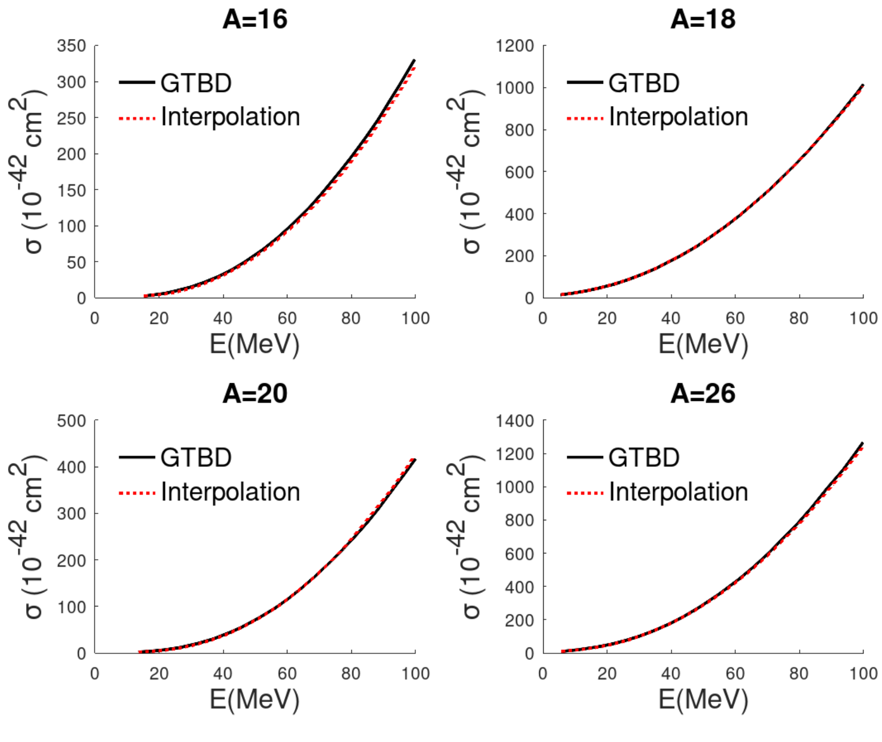

Figure 1: Cross-section as a function of the neutrino energy for β^- decay.

References

[1] R. Diehl, D.H. Hartmann and N. Prantzos, Astrophysics with Radioactive Isotopes (Springer, Switzerland, 2018), p. 16

[2] Nanae Domoto et al 2021 ApJ 913 26.

[3] S. Nikas, Nucleosynthesis on the aftermath of neutron star mergers: The creation of the first r-process peak PhD thesis (PhD thesis, TU Darmstadt, 2021).

[4] G. Wallerstein, I. J. Iben, P. Parker, A. M. Boesgaard, G. M. Hale, A. E. Champagne, C. A. Barnes, F. Käppeler, V. V. Smith, R. D. Hoffman, F. X. Timmes, C. Sneden, R. N. Boyd, B. S. Meyer and D. L. Lambert, Rev. Mod. Phys. , vol. 69, no. 4, pp. 995-1084, 1997.

[5] M. Arnould, S. Goriely and K. Takahashi, "The r-process of stellar nucleosynthesis: Astrophysics and nuclear physics achievements and mysteries," Phys.Rept., vol. 450, pp. 97-213, 2007.

[6] M. Kotska, N. Koning, Z. Shand, R. Ouyed and P. Jaikumar, "r-Java 2.0: the astrophysics," Astron. Astrophys., 2014.

[7] Takahashi K and Yamada M 1969 Prog. Theor. Phys. 41 1470.

[8] T. Kondoh, T. Tachibana, M. Yamada, Progress of Theoretical Physics, Volume 74, Issue 4, October 1985, Pages 708–724.

[9] T. Tachibana, M. Yamada, Y. Yoshida, Progress of Theoretical Physics, Volume 84, Issue 4, October 1990, Pages 641–657.

[10] Z. M. Niu et al., Phys. Rev. C **99**, 064307 (2019).

[11] M.B. Aufderheide, I. Fushiki, S.E. Woosley, D.H. Hartmann, Astr. Jour. Suppl. 91, 389 (1994).

[12] https://www.nndc.bnl.gov/nudat3/

[13] Tachibana T, Uno M, Yamada M and Yamada S 1988 At. Data Nucl. Data Tables 39 251.

[14] U. Rodríguez et al 2019 J. Phys. G: Nucl. Part. Phys.

[15] A.R. Samana, C. Barbero, S.B. Duarte, A.J. Dimarco, F. Krmpotic, New Jour. Phys. 10, 1 (2008).

[16] Barbero, C.A., dos Santos, M.C. and Samana, A.R. Systematic Calculation of Neutrino–Nucleus Cross Section Available for Astrophysical Applications. Braz J Phys 50, 331–345 (2020).