I TEP-27-94

Fermilab Library
0 1160 0037130 4

INSTITUTE OF THEORETICAL
AND EXPERIMENTAL PHYSICS

ITEP-27-94

I.V.Panov

CROSS-SECTIONS OF NEUTRINO CAPTURE BY HEAVY NUCLEI IN R-PROCESS REGION

MOSCOW 1994

FERMILAB
JUN 28 1994
LIBRARY

УДК 523. М-16

CROSS-SECTIONS OF NEUTRINO CAPTURE BY HEAVY NUCLEI IN R-PROCESS REGION: Preprint ITEP 27-94/

I.V.Panov - M., 1994 - 12p.

Huge neutrino impulse during collapse of a massive star can accelerate the formation of heavy elements in rapid nucleosynthesis. To take into consideration the change of yields of new forming elements due to neutrino capture by nuclei it is necessary to know the cross-section values of this process. In this work the behaviour of computed neutrino capture cross-sections are studied in dependance of neutron excess value, beta-decay strength function model and neutrino spectrum. The light neutron excess dependance is explained. The evaluation of the role of beta-decay strength function model and neutrino spectrum approximation is made. There was shown that to get a better agreement between calculations and experiment it is necessary to include the neutrino capture by nuclei of ^{16}O into consideration. The results can be accomplished in explosive nucleosynthesis and experiments of neutrino detection.

Fig. - 4, ref. - 22.

© Институт теоретической и экспериментальной физики, 1994

It is well known that the heavy nuclei behind iron peak were formed in nature predominantly in the reactions of neutron capture [1,2]. The Analysis of solar abundance curve shows the heavy nuclei were formed in two different nucleosynthesis processes under neutron flux. The first one is so called s-process. It takes place when beta-decay rates $\lambda_\beta \gg \lambda_{n\gamma}$ (the neutron density $n_n \sim 10^{16}$ cm^{-3}). The other one is so called r-process. It used to be under high neutron density and involves very neutron-rich nuclei ($\lambda_\beta \ll \lambda_{n\gamma}$).

The most probable site of rapid nucleosynthesis is Supernovae explosion [2,3,5]. But the details of heavy elements formation are not known up to now and, by all means, the reactions with only neutrons are not sufficient to solve all the questions of r-process problem. Of course, the reactions with charged particles should be taken into account either. Some attempts to include the reactions of interaction with protons and α-particles into consideration of r-process have already made [6, 7] as well as the evaluation of the effect of neutrino scattering upon the nuclei [17]. But duration time of r-process $\sim$ characteristic time of neutrino exposure and except above mentioned effects the direct neutrino-induced change of the nuclear charge in neutrino-nuclei reactions makes significant influence upon the yields of elements during nucleosynthesis [8].

To prognose the cross-section values of neutrino capture by neutron rich nuclei $\sigma_\nu(E)$ there was used the approach [18] based upon the beta-decay

strength function. This approach defines the cross-section of neutrino capture taking into account the excitation states of daughter nucleus including very energetic states, such as giant Gamov-Teller resonance. This fact is very important in astrophysics, where reactions used to be under the temperatures of some units of 10^9 K. So:

$$\sigma(E_{\nu_e}) = \frac{g_A^2}{\pi c^3 h^4} \int_0^{E_{\nu_e}-Q} S_\beta(E) E_e p_e F(E_e, Z)\, dE\,, \qquad (1)$$

where $E = E_{\nu_e} - E_e - Q + m_e c^2$, and

$S_\beta(E)$ is strength function of β-decay;

$F(E_e, Z)$ is the Fermi function, Z being the charge of daughter nucleus.

Averaging cross-section (1) over normalized neutrino energy spectrum ($\int_0^\infty f_{\nu_e}(E_{\nu_e})\, dE_{\nu_e} = 1$) [16]:

$$f_{\nu_e}(E_{\nu_e}) \cong \frac{\pi}{c^2 h^3} \cdot \frac{Exp[-\alpha(E_{\nu_e}/kT_0)^2]}{1 + exp(E_{\nu_e}/kT_0)} \cdot E_{\nu_e}^2\,, \qquad (2)$$

we can got the values of $< \sigma_{\nu_e} >$ for every nuclear species. α and T_0 are the parameters of ν_e -spectrum approximation.

The knowledge of $< \sigma_{\nu_e} >$ gives the opportunity to compute the rates of neutrino-capture:

$$\lambda_\nu = N_i < \sigma_{\nu_e} > q_{\nu_e} \frac{L_{b_\nu}(t)}{< E_{\nu_e} > 4\pi r^2}\,, \qquad (3)$$

where

L_{b_ν} is the total (bolometric) neutrino luminosity [15];

q_{ν_e} stands for the fraction of energy emitted via electron neutrinos;

$< E_{\nu_e} >$ is the mean energy of ν_e, and r is the distance of irradiated matter from the center of a star.

The values of $< \sigma_{\nu_e} >$ varies mainly within $(0.2\text{–}20)\times 10^{-40}$ cm^2 for A and Z under consideration.

Earlier there was supposed [9] the value of σ_ν had to increase with $(N-Z)$. To solve this question quantitatively as well as to define the influence of the model of strength function upon the cross-section value there were used two microscopic models of beta-decay strength function, based upon the finite Fermi–system theory by Migdal (FFST) [20]. In FFST to construct the beta-decay strength function $S_\beta(E)$ it is need to solve the equation for effective field in nucleus:

$$V_\beta(r) = V_0(r) + \sum F^\omega(r, r_1) L(r_1, r_2, \omega) V(r_2)\,, \qquad (4)$$

where external field $V_0 = e_q \frac{g_A}{g_V} \sigma\tau$, F^ω – effective nuclon-nuclon interaction.

In the framework of quasi-classical approach to description of collective isobaric states [10, 11] the equation for effective field (2) transforms into:

$$V(r) = V^\omega(r) + \frac{g_0' 4\pi d\rho}{d\mu \sum R^+_{\lambda_1}(r) R_{\lambda_2}(r) \beta_{\lambda_1\lambda_2} A_{\lambda_1\lambda_2} V_{\lambda_2\lambda_1(r)}} \qquad (5)$$

and was solved without taking into account l-forbidden parts and parameterization of angular parts and M^2 were defined through the resume $\chi_{\lambda_1\lambda_2}$ of the field $V^\omega_{\lambda_1\lambda_2}|_{\omega=\omega_s}$ (Model-I):

$$M_s^2 = \sum_{\lambda_1\lambda_2} \chi_{\lambda_1\lambda_2} A_{\lambda_1\lambda_2} V_{\lambda_2\lambda_1}(\omega)\,. \qquad (6)$$

Calculations according Model I were performed with Breit-Wigner form of resonances: $M^2 \sim \Gamma/[(E_i - E)^2 + \Gamma^2]$, but with different dependance resonance width from energy: $\Gamma = \alpha E^2$ and $\Gamma = \alpha E_i^2$ (fig.3,4). Parameter $\alpha \sim 1/\epsilon_F$.

For comparison, we compute σ_ν for some nuclei, using Model-II [12] in which the equations (4) were solved numerically but the propagator $L(r_1, r_2, \omega)$ [13] was calculated ignoring the effects of slot variation in external field [14].

The Gamow-Teller strength function determinates the response of a nucleus to the charge-exchange external field V_0, is given by the formula:

$$S_{GT}(\omega) = \frac{2J+1}{4\pi}\left(\int e_q V_0(r)\rho_{tr}(r;\omega)\,dr\right)^2, \qquad (7)$$

where transition density of nuclear excitation with ω_s frequency is defined in FFST as

$$\rho_{tr}(r;\omega_s) = C \cdot Im \int L(r,r';\omega_s)V(r';\omega_s)\,dr, \qquad (8)$$

and normalization constant C is determined by the value of a matrix element of transition from basic to excited state:

$$M^2_{0\to s} = (2J+1)\left(\int dr e_q V_0(r)\rho_{tr}(r,\omega_s)\right)^2 = \int_{\Delta\omega} S(\omega)d\omega, \qquad (9)$$

$\Delta\omega$ is an interval where the concrete $S(\omega)$ maximum is exhausted;

All the calculations were made with the sum rule: $\int_0^{E_m} S_\beta(E)dE = e_q^2 \cdot 3(N-Z)$, where $E_m = 30$ MeV, $e_q = 0.8$.

For testing the calculations of σ_ν the cross-section of neutrino capture for $^{71}Ga + \nu_e \to e^- +^{71} Ge$ reaction was computed. For reactor spectrum σ_ν on ^{71}Ga is equal to $40 \div 100 \cdot 10^{-45}$ cm^2 and depends from quenching and type of energetic dependence resonances widths and is in a good agreement with previous results [18].

In a case of neutrino from reactor spectrum the g.s. and low lying excitations bring in the main contribution in the value of neutrino capture cross-section σ_ν (figure 1). For stiff neutrino spectrum of supernovae [16] the Gamov-Teller resonance gives the main part into the cross-section values and $\sigma_\nu(^{71}Ga) \cong 6 \cdot 10^{-41}$.

As $M^2 \sim (N-Z)$, it was natural to suppose [9] that σ_ν rises according to the increase of $(N-Z)$. But real situation according to present calculations is not so simple. First, the contribution of low lying so called "pygmy resonances", especially situated in the region of $5 \div 10$ MeV makes the dependence

σ_ν of M^2 more complicated. In fig.1 the reduced transition probabilities for different Rb-isotopes are presented. Second, because of the increasing of GTR–position by energy with (N - Z) the distance between maximum of neutrino spectrum (see fig.1,2) and GTR energy increases either. And as a result the dependence of σ_ν value upon (N - Z) is weaker its dependence upon the parameters of GT-resonance and presence of pygmy-resonances.

In fig.2 the dependence of ν-spectrum on parameters α and T_0 is shown. The light changes of these parameters are lead to significant variations of σ_ν values (fig.3).

In fig.4 the dependence σ_ν on $(N-Z)$ and the influence of strength function model, parameterization of resonances and form of neutrino spectrum upon the σ_ν of Rb-isotopes are shown.

On the base of these calculations we can conclude that both the type of resonance parameterization and model of β-decay strength function show rather weak influence upon the value of σ_ν. The form of neutrino spectrum gives the strongest contribution into the neutrino capture cross-section value.

These calculations of σ_ν values are two times higher than evaluations of σ_ν, used in [8]. That means that the neutrino pulse from supernovae have to change the yields of heavy elements in rapid nucleosynthesis more significantly. Further calculations in the framework of kinetic model can give us more exact knowledge of neutrino capture consequences upon the yields of elements in rapid nucleosynthesis.

In the calculations the flux of antineutrino was not taken into account – the $\sigma_{\bar{\nu}_e}$– values of these nuclei are one or one and a half order of magnitude lower then σ_{ν_e} because of the differences in structure of β^- and β^+ strength functions and energy threshold for neutron-rich nuclei. By all means, it is necessary to take into account in calculations the process of neutrino capture by nuclei for detecting neutrino pulse from supernovae:

$$1)\ \nu_e + {}^{16}O \rightarrow {}^{16}F + e^- \rightarrow \beta^+ - decay\ of\ {}^{16}F \rightarrow {}^{16}O + e^+ + \nu_e,$$
$$2)\ \tilde{\nu}_e + {}^{16}O \rightarrow {}^{16}N + e^+ \rightarrow \beta^- - decay\ of\ {}^{16}N \rightarrow {}^{16}O + e^- + \tilde{\nu}_e\ ; \qquad (10)$$

Though both of these reactions have a rather high threshold: 16.4 MeV in a first case and 10.8 Mev [21] in a second one, thank to high energetic tail of ν-spectrum the contribution of these reactions into registration would not be small and the systematic decrease of calculated events of neutrino capture [4] may be eliminated by taking into account of these reactions. Rough evaluations in a first case result in some percents increasing of neutrino counting and better fitting the experiment curve [4]. Further more exact calculations would give the evaluation of the effect value in this case.

In conclusion I acknoledge the collaboration with Yu.S.Lyutostansky at early phase of this work [9] and would like to express my deep gratitude for useful discussions to I.N.Borzov and D.K.Nadyozhin.

This work was supported in part by the Russian Foundation of Fundamental Research, grants No. 93-02-3632 and No. 93-02-17114.

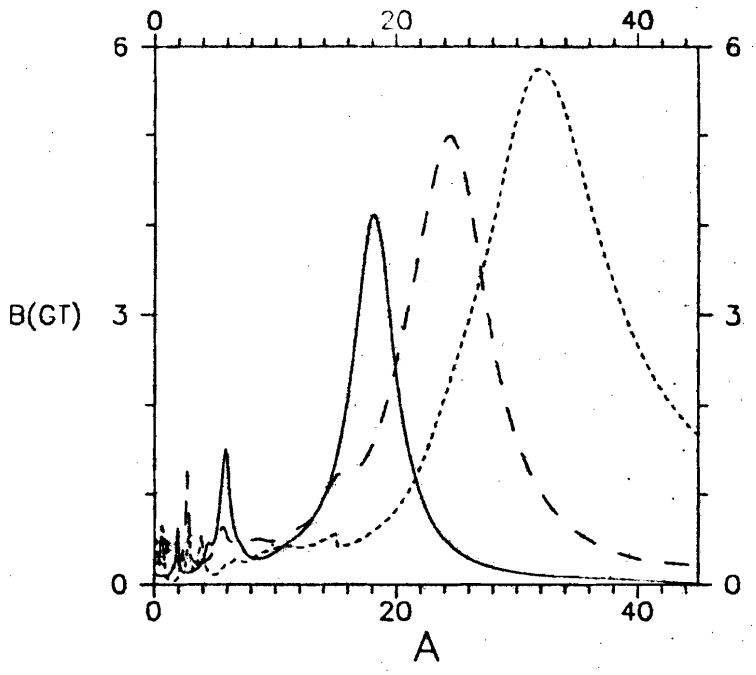

Fig.1. Reduced transition probabilities B_{GT} of beta-decay for rubidium isotopes.

——— A= 89
— — A=105
------ A=121

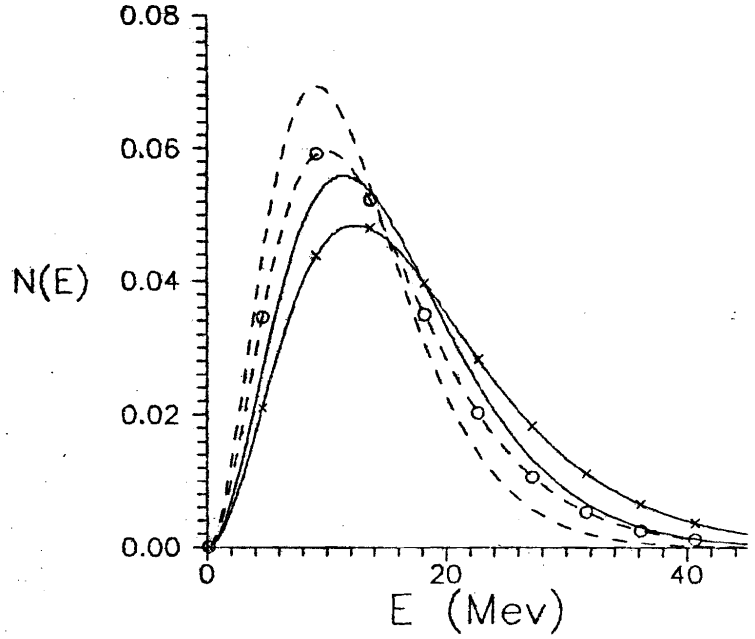

Fig.2. The dependence of normalized neutrino spectrum from parameters T_0 and α.

——— T=5.6 α=0.024
– – – T=4.5 α=0.024
oooooo T=4.5 α=0
xxxxxx T=5.6 α=0

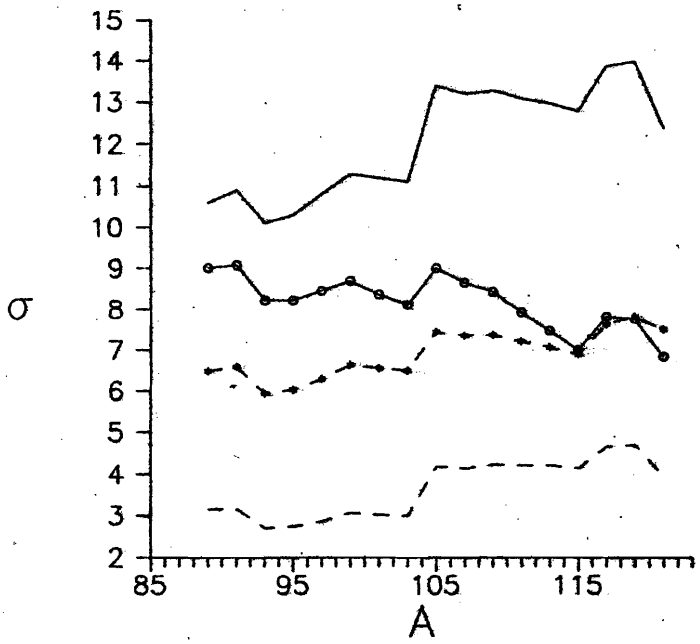

Fig.3. Dependence of neutrino capture cross-section (in 10^{-41} cm^2) from parameters T_0, α, Γ for odd Rb isotopes.

⟷⟷⟷	T_0=5.6	α=0.024	$\Gamma=f(E_i)$
———	T_0=5.6	α=0	$\Gamma=f(E_i)$
o-o-o-o-o	T_0=5.6	α=0	$\Gamma=f(E)$
– – –	T_0=4.5	α=0.024	$\Gamma=f(E_i)$

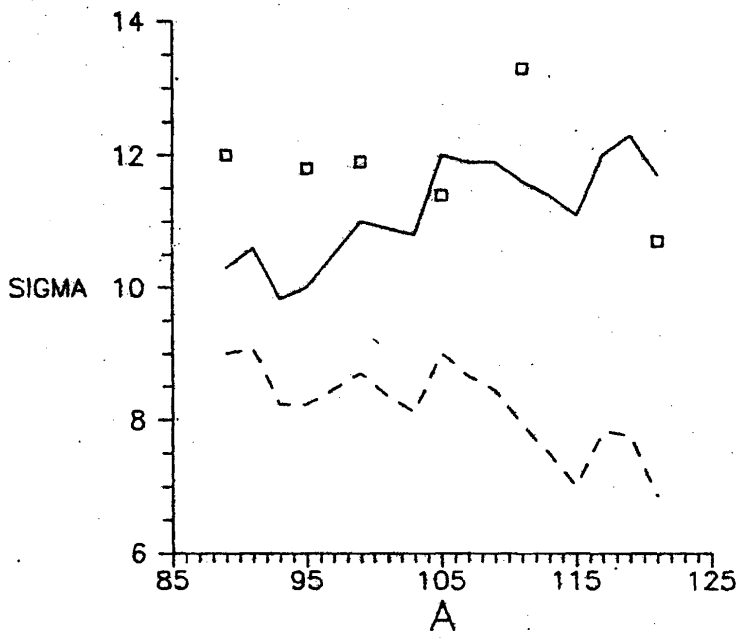

Fig. 4. Neutrino capture cross-sections σ_ν of odd Rb isotopes (in 10^{-41} cm^2), T_0=5.6, α=0.

– – – Model–I, $\Gamma=f(E)$

——— Model–I, $\Gamma=f(E_i)$

□□□□□ Model–II

REFERENCES

1. G.R. Burbidge, E.M. Burbidge, W.A. Fowler, F. Hoyle. Synthesis of the elements in stars. // Rev. Mod. Phys. 1957, v.29, p.547.

2. W. Hillebrandt. The rapid neutron-capture process and the synthesis of heavy and neutron-rich elements. // Space Sci. Rev. 1978, v.21, p.639.

3. J.J. Cowan, F.-K. Thielemann, J.W. Truran. The R-process and Nucleochronology. // Phys. Reports, 1991, v.208, p.269.

4. V.S.Imshennik, D.K.Nadyozhin. Supernova 1987A in the Large Magellanic Cloud: Observations and Theory. // Sov. J. Success of Physical Sciences, 1988,v.156, p.561.

5. B.S. Meyer, G.J. Mathews, W.M. Howard, S.E. Woosley, R.D. Hoffman. r-process nucleosynthesis in the high-entropy supernova bubble. // Astrophysical J. 1992, v.399, p. 656.

6. S.E. Woosley, R.D. Hoffman. The α-process and the r-process. // Astrophys. J. 1992, v.395, p.202.

7. V.M. Chechetkin, D.A. Ptitsyn. On the nucleosynthesis beyond the iron peak in supernovae. // Sov. Astron. Lett. (USA). Translated of Pis'ma Astron. Zh.(USSR) 1982, v.8, No.10, p.600.

8. The influence of neutrino flux upon the nucleosynthesis of heavy nuclei. D.K. Nadyozhin, I.V. Panov. // In: The Proceedings of the III International Symposium on Weak and Electromagnetic Interactions in Nuclei (WEIN-92), Dubna, Russia, 1993, p.479.

9. Yu.S. Lyutostansky, I.V. Panov. Heavy element formation during explosive nucleosynthesis. // In: Proceedings of Int. School "Low Energy Weak Interactions", Dubna, Russia, 1991, p. 148.

10. Yu.V.Gaponov, Yu.S.Lyutostansky. Microscopic theory of Gamov-Teller resonance and isobaric collective 1^+ states for spherical nuclei. // Fiz. Elem. Chastits Atom. Yadra, 1981, v.12, p.1324 (Sov. J. Part. Nuclei 1982, v.12, p.528).

11. V.G.Aleksankin, Yu.S. Lyutostansky, I.V. Panov. Half-lives periods for nuclei far from stability line and structure of beta-decay strength function. // Sov.J.Nucl.Phys. (USA) 1981, v.34, No.6, p.1451.

12. I.N. Borzov, S.A. Fajans. Particle-hole propagator in continuum. Preprint FEI-1128. Obninsk, 1981.

13. I.N. Borzov, S.A. Fajans, E.L. Trykov. Gamow-Teller strength functions of stable and neutron deficient nuclei. // Sov. J. Nucl. Phys. 1990, v.52, p.985.

14. I.N. Borzov, S.A. Fajans, Yu.S. Lyutostansky, I.V. Panov. Simple microscopic model for beta-decay strength functions and delayed neutron emission probabilities. // In: Proc. of 6 Int.Conf. on nuclei far from stability + 9 Int. Conf. on atomic masses and fundamental constants. 19-24 July 1992, Bernkastel-Kues, Germany, p.PE22.

15. D.K. Nadyozhin. The neutrino radiation for a hot neutron star formation and the envelope outburst problem. // Astrophys. Space Sci. 1978, v.53, p. 131.

16. D.K. Nadyozhin, I.V. Otroshchenko. Electron neutrino and antineutrino spectra associated with the process of neutron star formation. // Sov. Aston. 1980, v.57, No.1, p.78.

17. R.I. Epstein, S.A. Colgate, W.C. Haxton. Neutrino-induced r-process nucleosynthesis. // Phys. Rev. Letters, 1988, v. 61, p. 2038.

18. A.A. Borovoy, Yu.S. Lyutostansky, I.V. Panov, S.H. Hakimov, N.B. Shul'gina. The strength function of germanium 71 and the problem of $\nu_e - \nu_s$ oscillations. // JETP Lett. (USA), 1988, v.48, p. 565.

19. Yu.S. Lyutostansky, I.V. Panov. Half-lives of neutron-rich nuclei and evaluation of astrophysical r-process duration. Preprint ITEP No. 32, Moscow, 1988.

20. A.B. Migdal. Theory of Finite Fermi Systems and the properties of Atomic Nuclei. // Interscience Pub., New York, 1967.

21. E.R. Hill, H.V. Groote, K. Takahashi. // CERN-report. CERN-76-13. 1976. P. 142.

22. P.Vogel et.al. Reactor antineutrino spectra and their application to antineutrino-induced reactions. // Phys. Rev. C. 1981, v.24, p.1543.

И.В.Панов

Сечения захвата нейтрино тяжелыми нейтроно-избыточными ядрами.

Подписано к печати 22.03.94 Формат 60x90 I/I6 Офсетн.печ.
Усл.-печ.л.0,75 Уч.-изд.л. 0,5 Тираж I75 экз. Заказ 27.
Индекс 3649

Отпечатано в ИТЭФ, II7259, Москва, Б.Черемушкинская,25