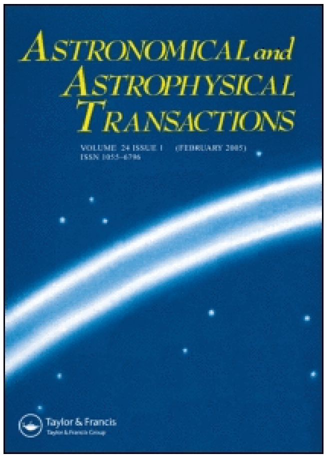

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GAMMA LINES NUCLEI ^{6,7}Li, ^{7}Be FROM ACCRETING MATERIAL ON THE NEUTRON STAR

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The possibility of the observation of gamma lines from nuclei ^{6,7}Li, ^{7}Be, produced at the accreting material on a neutron star is discussed. The $\alpha\alpha$ collisions were considered. These lines with $E \sim 0.429$; 0.478; 3.56 MeV probably may be observed by an instrument with sensitivity better than $\sim 10^{-5}$ phot/cm^2 sec from X-ray sources with normal chemical abundance.

KEY WORDS Accretion, neutron stars, gamma lines.

INTRODUCTION

The accretion of gas on a neutron star must be accompanied by intensive gamma radiation because of, production of π^0, $\pi^{\pm}$ mesons, and by nuclear and thermonuclear reactions in the star atmosphere. The created gamma-ray telescopes (SIGMA and GRO's QSSE), and projected ones (GGAPP, and INTEGRAL/NEE) provide the sensitivity from 10^{-3} to $2 \div 3 \times 10^{-6}$ phot/cm^2 sec in energy range 0.1–5 MeV. This will be able to detect some of the discussed γ lines. This will be a unique possibility to look in the atmosphere of accreting neutron stars, and to get new information about accretion streams, and even information about the nuclear equation of state. This problem was discussed for the first time by Schvartsman (1970), and later by Bisnovatyi-Kogan *et al.* (1980), Bildsten (1990), and others (see, for example, abstracts "γ line Astrophysics" Paris, Saclay, Dec. 10–13, 1990 of the symposium).

We would shortly like to discuss the possibility of the observation of γ lines from radiative decay of excited nuclei in reaction $\alpha \rightarrow \alpha$ from accreting neutron stars. When this paper was almost finished we learned about the discussion of this question by Guessoum *et al.*, in the abovementioned abstracts.

2. GAMMA RAYS FROM EXCITED NUCLEI ^{6,7}Li*, ^{7}Be*

The gravitational energy of accreting material is

$$\sim 140\left(\frac{M_*}{M_\odot}\right)\left(\frac{10\,\mathrm{km}}{R_*}\right)\ \mathrm{MeV/nucl} \tag{1}$$

and its fall is accompanied by various nuclear reactions.

In this paper we examine the process of radiation of excited nuclei for nuclear reactions of the next type:

$$\alpha + \alpha \rightarrow \begin{cases} {}^{6}\mathrm{Li}^{*} + \mathrm{p} + \mathrm{n} \\ {}^{7}\mathrm{Li}^{*} + \mathrm{p} \\ {}^{7}\mathrm{Be}^{*} + \mathrm{n} \end{cases} \tag{2}$$

The spectrum of lower excited states of ^{6,7}Li, ^{7}Be is shown in Figure 1. Levels $(7/2)^{-}$ in ^{7}Be and ^{7}Li generally decay into channels (α, ^{3}He) and (α, t) and their contribution to gamma emission is very small. Similarly, the level 3^{+} (2.186 MeV) of ^{6}Li will decay to the partial channel (α, d) and its contribution will also be very small. The decay of level 0^{+} into a particle channel is strongly forbidden by the conservation of isospin, and therefore this level will contribute to γ radiation. Hence, only γ lines with $E = 0.478$; 0.429 and 3.56 MeV can radiate in reactions (2). To calculate the luminosity of the considered γ lines, it is necessary, firstly, to know the cross section of appearance of excited states in reactions, (2) and secondly, it is necessary to have the macroscopic model of the material accreting on the neutron star. The cross section of reactions (2), when summed over relevant levels of nuclei ^{6,7}Li, ^{7}Be, was measured experimentally in the region of energies of colliding α particles with $E = 60$ MeV to 200 MeV (Woo *et al.*, 1985). The cross section of reactions (α, ^{7}Li) and (α, ^{7}Be), in this region of energies, is decreased exponentially with the energy. The cross section of the reaction (α, ^{6}Li), is approximately constant to 140 MeV, and then it is also exponentially decreased. Since the thresholds of reactions (α, ^{7}Li), (α, ^{7}Be), (α, ^{6}Li) is high enough (17.2, 18.9, 24.5 MeV), therefore, one can consider that the energy limit of colliding α particles, when they are able to produce the reaction (2), is in region 35–40 MeV. We have defined the cross section in the region 40–60 MeV by prolongation of the curves of paper (Woo *et al.*, 1985). The important question is the relation of probabilities of the ground and excited states of nuclei ^{6,7}Li, ^{7}Be. Taking into account the semiquantitative character of our calculation, we suppose that populations of ground, and first excited states in nuclei ^{7}Li, ^{7}Be,

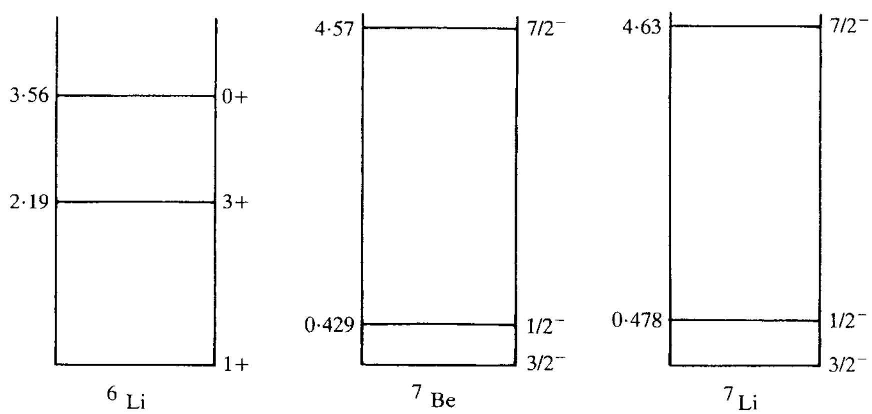

Figure 1

are equal. We believe that in ^{6}Li, populations of all third states are also equal. As we know the stopping of accreting material takes place in the polar column of a neutron star. We also suppose that the stopping is pure Coulomb. The energy E (MeV/nucl) of α particle on the depth y (g/cm^2) from the boundary of atmosphere is given by a relation:

$$y = 13(\text{g/cm}^2)\left[\left(\frac{E_0}{140\ \text{MeV/nucl}}\right)^2 - \left(\frac{E}{140\ \text{MeV/nucl}}\right)^2\right]\left(\frac{10}{\ln\Lambda}\right) \tag{3}$$

where E_0 is the initial energy of α particle (MeV/nucl), $\ln\Lambda$ is the Coulomb logarithm. The total length of the stopping y_0 is found from (3), for $E = 0$. The number Q of γ-quanta per one projectile α-particle is given by a formula:

$$Q = \int_0^{y_0} F(y)n(y)\sigma(y)\,dy \tag{4}$$

where $F(y)$ is the flux of α-particles at depth y (when $y = 0$ $F(0) = 1$), $n(y)$ is the density of α-particles in the stopping medium, σ is the cross section of the production of the nuclei, ^{6,7}Li, ^{7}Be, in excited states. Neglecting the absorption of α-particle, and by the change of the density of stopping material, one can produce:

$$\begin{aligned} Q &= \frac{X_\alpha}{A_\alpha}\frac{1}{m_p}\int_0^{y_0}\sigma(y)\,dy \\ &= \frac{X_\alpha}{A_\alpha}\frac{1}{m_p}\int_0^{E_0}\sigma(E)E\,dE\,\frac{1}{154\ln\Lambda} \end{aligned} \tag{5}$$

where X_α is the weight concentration of α particles (when there is a normal abundance $X_\alpha = 0.3$), A_α is the atomic weight of α particle, m_p is the mass of the proton. The value Q for ^{7}Li, for example, is $\sim 1.75\times10^{-3}$. The luminosity in γ lines may be calculated by the formula:

$$L_\gamma = \frac{X_\alpha}{A_\alpha}\frac{Q\dot{M}}{m_p} = \left(\frac{X_\alpha}{A_\alpha}Q\right)\left(\frac{\hbar\omega}{E_p}\right)L_x. \tag{6}$$

here, $\dot{M}$ is the velocity of accretion, and L_x is the luminosity of source in X-ray region. The flux of γ quanta on the Earth after normalization on the flux from the brightest X-ray source Sco X-1 is:

$$\begin{gathered} F_\gamma\left(\frac{\text{phot}}{\text{cm}^2\text{sec}}\right) = \left(\frac{1}{2}\div\frac{1}{3}\right)\times10^{-5}X_\alpha\left(\frac{F_X}{F_X(\text{Sco X-1})}\right) \\ F_\gamma^{\max}\sim(0.3\text{–}0.5)\times10^{-5}. \end{gathered} \tag{7}$$

The opacity of the atmosphere of the accreting neutron star is defined by the Compton scattering, and processes of creation of electron-positron pairs in the nuclear field. As it is shown by Bisnovatyi-Kogan *et al.* (1980), for energy photons ≤ 5 MeV that is for $\gamma = E_\gamma/m_ec^2 \leq 10$, the Compton effect will be the main source of opacity.

Let us consider the form of column of accreting material and its depth taking into account only Compton scattering. For the filled polar column (Lipunov,

1987) the depth may be calculated by the formula:

$$\tau_{\parallel} = \int_{R_*}^{\infty} \frac{X_\alpha \sigma \rho}{A_\alpha m_p} dR = \frac{X_\alpha}{A_\alpha} \left(\frac{L_x}{L_{Ed}}\right)\left(\frac{\sigma}{\sigma_T}\right)\left(\frac{c}{v_{ff}}\right) \frac{4\sqrt{2}}{\theta^2} \tag{8}$$

$$\tau_{\perp} = \frac{X_\alpha}{A_\alpha} \sigma \frac{\rho}{m_p} \theta R_x = \tau_{\parallel} \theta \tag{9}$$

where σ_T is the Thomson section, $L_{Ed} = 4\pi G m_p M_* c/\sigma_T$ is the Eddington luminosity, $\theta = 0.1\,\dot{M}_{18}^{1/7} M_*^{1/14} \mu_{30}^{-2/7} R_6^{1/2}$ is the angle of opening of the polar column, μ_{30} is the dipole moment of the neutron star. For an unfilled polar column, (Basko, Sunyaev, 1976) the depth may be calculated by the formula:

$$\tau_{\perp} = \approx \tau_{\perp}(\text{filling})\left(\frac{a}{d}\right) \tag{10}$$

where d is the radius of column, a is the width of wall, $\tau_{\perp}$ may amount to ~ 0.5. From the kinematics of $\alpha\alpha$ reactions, it follows that the relation $\Delta E/E$ is approximately equal to $\sim 1/50$ in the transversal direction to the column, and $\sim 1/10$ in the direction parallel to column. These lines must be naturally shifted by the gravitational field ($\varphi/c^2 \sim 0.023$–0.41).

CONCLUSION

The future gamma-ray spectrometers with a sensitivity better than $\sim 10^{-5}$ ph/cm^2 sec, can detect γ lines from excited nuclei of lithium and beryllium, with energy $\sim$3.56 MeV (^{6}Li), 0.478 MeV (^{7}Li), 0.429 MeV (^{7}Be) from an accreting neutron star, even with normal chemical abundance. If the concentration of α particles is higher than the normal abundance, it is probable to detect these lines by instrument GRO QSSE.

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