Astronomical and Astrophysical Transactions (*AApTr*), 2023, Vol. 34, Issue 1, pp. 27–34,
ISSN 1055-6796, Photocopying permitted by license only, ©Cambridge Scientific Publishers

The spectroscopy of possible γ-ray background in the white dwarf atmosphere

D.N. Doikov[1,*], M.D. Doikov[2]

[1] *Odesa National Maritime University, 34 Mechnikov Str., Odesa, 650024, Ukraine*
[2] *Plovdiv University "Paisii Hilendarski", Faculty of Physics and Engineering Technology, Tzar Asen Str., 4000 Plovdiv, Bulgaria*

Received 22 June, 2023

The interaction between accretions flows and the surface of white dwarfs (WD) in the same regimes may produce continuous γ-ray flows. After proton–nuclear and α-particle–nuclear collisions, part of the gravitation and magnetic energy transforms into a nuclear radiation transition. We calculated and selected cross sections and compared them with the characteristic specific binding energies of nucleons in the considered projective nuclear. Together with γ-lines after the nuclear transformation, we may observe the resulting γ-spectra. Here, neutron evaporation channels are also calculated and conclusions are drawn about the probable formation of isotopes that produce positrons during decays.

Keywords: CV star system, γ-ray spectroscopy, perovskite detector, background γ-ray spectra in AM Her type polar

1 Introduction

The increased sensitivity of γ-ray detection was made possible thanks to a new generation of semiconductors that have been constructed from heavy elements with large atomic numbers. In chemical classification, these are so named perovskite crystals. Specifically in our case, these are CsPbBr3 semiconductor crystals with mean atomic weight 57.35 a.u. In the first step, we plan our experimental activity in the energy range from 0.01 to 10 MeV. This is a hard X-ray and soft γ-ray quanta. In common cases, these radiation flows initiate three basic processes leading to an internal photo effect: Compton scattering, atomic photo-effect, and production of electron–positron pairs and accompanied by Auger electron injection conductivity zone and the effects of fluorescence. All these phenomena lead to the creation of adding free electron conductivity and current impulses. The last work of Doikov (2022) presented and described equipment for the simultaneous detection of the rapid processes of formation

*Email: dmitro.doikov@gmail.com

by optic and hard radiation quanta in cataclysmic variable stars (CVs). For the real detection of the considered rapid processes the conception of monitoring detection systems with the extraction of useful signals has been proposed. Resolution and relaxation nanosecond times τ_{rel} dimension in peroxide crystals leads to the creation of useful signals with a coefficient of efficiency 27–45%. The potential difference inside the crystal cut before applying it to the input of the interface is chosen to be within 0.5–1 kV. In most cases, minimal cooling is required.

2 Astrophysical aspects. Selection of research objects

A polar is a special type of Cataclysmic Variable (CV) and among CVs there is a group of binary star systems with a strong magnetic field known as AM Herculis type star. Polars are more suitable for the approbation of the developed equipment intended for monitoring γ-radiation according to several criteria. The main part of the accretion flows from companion stars are collected into magnetic columns of white dwarfs (WDs). This matter inside the column simultaneously accelerates and contracts and collides with the surface of the star at the magnetic poles. The energy resource obtained by the falling gas in the gravitational and magnetic fields inside the magnetic column is sufficient to accelerate the temperature at its base to 10^7–10^9 degrees. Moreover, the gravitational field only accelerates the gas, while the magnetic field creates a strong compression in the transverse direction. From the fifty-year history of observations of Polars, their main characteristics and their evolution in time have been refined. In Section 2 we select the physical parameters of the magnetic column and will calculate only the spectroscopic which is important in considering the problem of γ-ray sources in polar. We take energy losses due to soft X-ray, ultraviolet, and synchrotron radiation beyond the scope of consideration and give arguments in favor of the fact that we believe that the given resources of gravitational and magnetic energy are sufficient to also start thermonuclear reactions. For reliable registration of thermonuclear precursors, we need to learn how to register the background hard X-ray and soft γ-radiation of nuclear origin, emanating from hot magnetic spots during quiet periods between optical outbursts of polar. We estimate the time scales of explosive thermonuclear combustion and select characteristic lines that are sensitive to the processes under consideration.

To plan to monitor possible γ-radiation from the hot spots of WDs included in CVs we will estimate the fall energy in a hard external magnetic field. Let $B_{WD} \approx 10^3$ T; the hot spots radius is $R \approx 2 \cdot 10^5$ m. Mass of the WD is $M_{WD} \approx 0.6 M_{\odot}, R_{WD} \approx 6 \cdot 10^6$ m. The mass loss from close star is $\dot{M} = 10^{-11}\, M_{\odot}$. The nonregular 3–4 flares per year are usually observed in the optical spectra of polar AM Her. The above parameters of the polar make it possible to carry out preliminary calculations of the possible background γ-spectrum of the magnetic poles of the WD. Let us express in terms of a relation connecting the thermodynamic properties of a white dwarf and the combined action of intense gravitational and magnetic fields.

$$P = \frac{B_{WD}^2}{2\mu_0} + \frac{\rho V^2}{2}, \tag{1}$$

where ρ is the density of accretion gas in the bottom part of the magnetic column, $\mu_0 = 4\pi \cdot 10^{-7}$ Hn/m is the magnetic constant. After substitution of the physical

parameters, the result is that both terms have 10^{13}–10^{14} Pa. The conservation of magnetic flows Φ_{WD} in the upper point of the caption $\Phi_{WD}(S)$ of companion's gases and in the bottom part of the magnetic column $\Phi_{WD}(S_0)$ leads to the relation:

$$B_{WD}^{UP} \cdot S = B_{WD}^{0} \cdot S_0. \tag{2}$$

The latter relationship is an important indication that the likelihood of flare activity increases as magnetic tubes narrow. The magnetic pressure, the magnetic force, and the work of the magnetic field act across the field and only imply the heating of the falling gas. For the thermalization of the directed motion of the incident gas and the work of the magnetic field force to compress the incident gas at the base of the magnetics column to lead to the background γ-radiation, thermal motion velocities are limited. From (1) and (2), $V_{th} \approx (3\text{–}4)\cdot 10^6$ m/s. Then the achievement of the desired thermal velocities is possible only with a tenfold decrease in the volume of the magnetic column occupied by the gas. The simplest solution to this problem is to postulate the form of a magnetic column not in the form of a conventional cylindrical tube, but in the form of a pointed cone-shaped structure at the bottom. Such forms are often adopted for pulsars and black holes. They are called funnels. You can build arguments in reverse order. Registration of the background γ-radiation confirms the cone-shaped structure of the magnetic tubes of the pillars near the surface of the WD. Having made sure that the thermal energies are sufficient for the formation of gamma radiation, let us consider thermonuclear processes that could give us the background γ-spectrum necessary for the planned registration. For the objects we are considering in this article, we can distinguish three main channels of thermonuclear transformations producing gamma quanta. In the next section, we will discuss them in more detail.

3 Accelerators, projectivity, and targets into polar magnetic columns

Accelerators. These are polar magnetic columns with $B_{WD} \approx 10^3$ T in hard gravitational fields generated from WD with surface acceleration $g \approx (10^6\text{–}10^7)$ m/s^2. The combined action of the magnetic and gravitation fields can lead to sporadic thermonuclear reactions. We selected the following type of these reactions.

Projectivities. These are the reactions of the formation and rapid decay of the unstable proton excess isotope. In these cases, we have in the form of projectivity hydrogen and helium from accretion flows. In other exotic cases, we have the possibilities to include C–N–O elements from companion stars. Mainly, in the bottom part of the column H and He atoms transform into accelerated energetic particles protons, and α-particles that took part in the considered reactions. Depending on the chemical composition of WD atmospheres and other nearby surface layers we presented cross-sections for nuclear reaction links.

Targets. The targets in the bottom part of the column are mainly atoms of H, ${}^{3}_{2}$He, ${}^{4}_{2}$He, ${}^{12}_{6}$C, ${}^{13}_{6}$C, ${}^{14}_{7}$N, ${}^{16}_{8}$O. The polar spectra consist of lines of C, N, Fe and Mg elements. We do not exclude the consistency of solar abundances in projectivities' flows. The presence of possible nuclear emission lines in γ-spectra from the hot shapes in magnetics poles will allow us to attribute them to the chemical composition

of WD. That is to consider them a target. After collision with projective proton and α-particles the targets form hard X-ray and soft γ-ray emission spectra. The importance of registering such a spectrum is that it must always accompany the accretion of matter. In common definition, a target is the nuclei with relatively small mean kinetic energy.

4 Continuous induced γ-radiation

4.1 Proton and α-particle collisions with WD atmospheres

In the paper by Doikov et al., 2019, which was devoted to AGN positron spectroscopy, a mechanism was proposed for replenishing the continuous γ-spectrum. In the course of the reactions of thermonuclear cycles, the collision of structural nuclei (starting from helium) with protons and other nuclei is not always inelastic in nature. There are also radiative transitions in structural cores caused by quasi-elastic collisions. In WD atmospheres, such structural cores include ${}^{4}_{2}\mathrm{He}$, ${}^{12}_{6}\mathrm{C}$, ${}^{14}_{7}\mathrm{N}$, ${}^{16}_{8}\mathrm{O}$ which we will call target nuclei. The chemical elements in the incident flow will be called projectile particles, denoting them, respectively, p, α (He), C, O. The total cross sections of reactions leading to the formation of γ-quanta and neutrons evaporation will be given in millibarns.

The continuous induced γ-radiation holds for a wide range of accreting WD and pulsars in binary star systems. As can be seen from Figs 1–3, induced radiation has its characteristic structure. Moreover, such an emission spectrum is slightly distorted by radiation transfer in the atmosphere of a WD because and formed on the WD surface. To achieve sufficient energies of the accreting gas, the compression of the incident jet should be taken into account. To do this, near the magnetic poles, we should assume a conical structure of the magnetic tube. Then we should expect an increase in the kinetic energy of the flow with a simultaneous increase in its temperature. Refinement

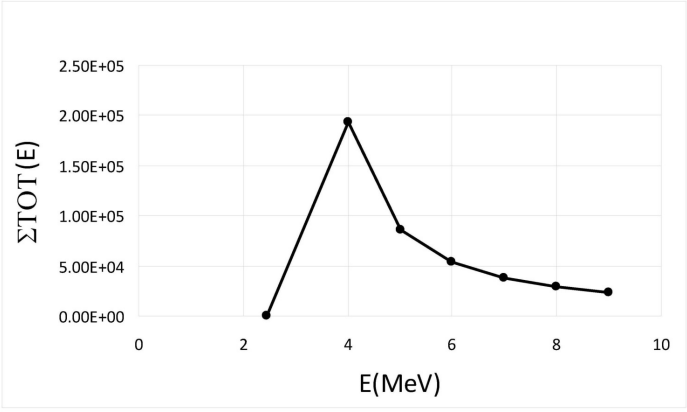


Figure 1 Dependence of total cross section ΣTOT(E) in mbn (10^{-27} cm^2) from proton energies E (MeV) with the reaction channel $p + {}^{4}_{2}He \rightarrow \gamma + ...$ The point of intersection of the E axis with the graph is the reaction threshold energy $\mathrm{E}_b \approx 2.462$ MeV.

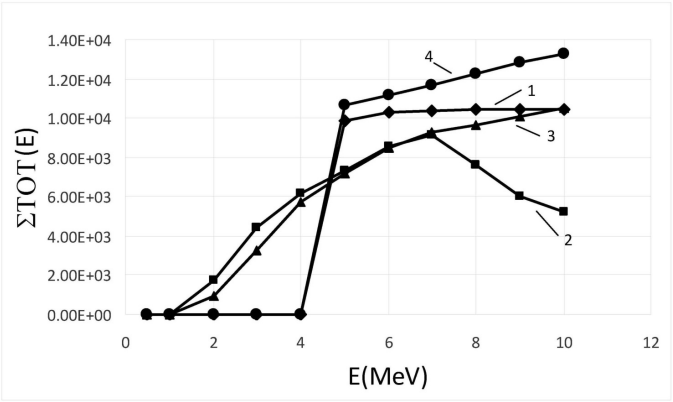


Figure 2 The total cross section ΣTOT(E) of γ-emission in mbn (10^{-27} cm^2) from energies E (MeV): 1, $p + {}^{12}_{6}\,C \rightarrow \gamma + ...$; 2, $p + {}^{13}_{6}\,C \rightarrow \gamma + ...$; 3, $p + {}^{14}_{7}\,N \rightarrow \gamma + ...$; 4, $p + {}^{16}_{8}\,O \rightarrow \gamma + ...$.

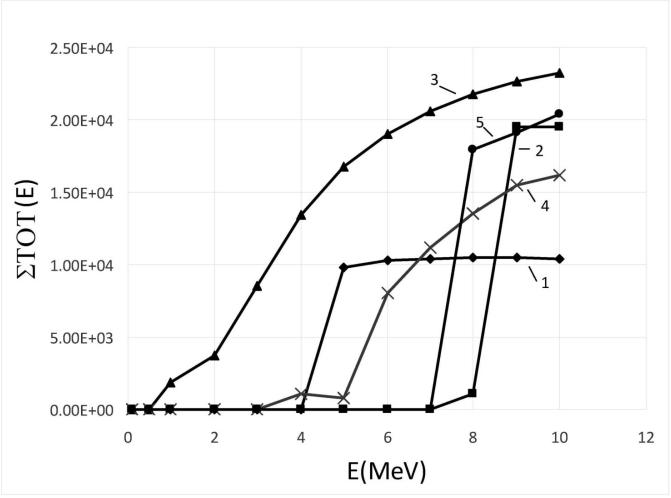


Figure 3 The total cross section ΣTOT(E) of γ-emission in mbn (10^{-27} cm^2) from energies E (MeV): 1, $\alpha + {}^{14}_{2}\,He \rightarrow \gamma + ...$; 2, $\alpha + {}^{12}_{6}\,C \rightarrow \gamma + ...$; 3, $\alpha + {}^{13}_{6}\,C \rightarrow \gamma + ...$; 4, $p + {}^{14}_{7}\,N \rightarrow \gamma + ...$; 5, $p + {}^{16}_{8}\,O \rightarrow \gamma + ...$.

of masses and dimensions of WD may be additional cause for distinguishing high energies of the accretion streams.

4.2 Neutron evaporation

One of the channels of nuclear transformation is neutron emitting after the proton-nuclear collision. The main consequence of this process is the formation of proton-excess nuclear with small half-time decays. The small cross sections of the processes are compensated by the density of the medium at the point where the matter falls

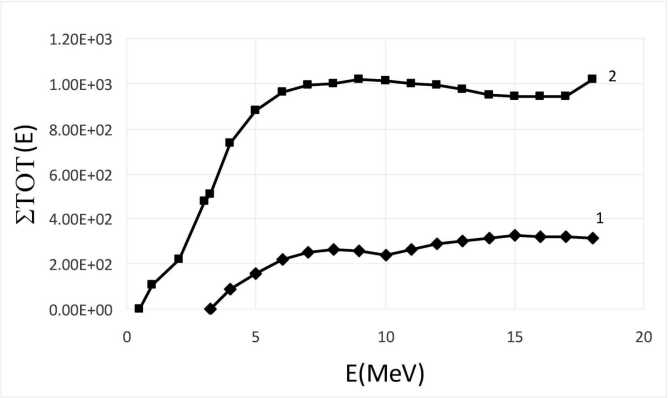


Figure 4 The total cross section ΣTOT(E) of γ-emission in mbn (10^{-27} cm^2) from energies E (MeV): 1 – $p + {}^{13}_{6}C \rightarrow n + ...$, E_b =3.235 MEV;
2 – $\alpha + {}^{13}_{6}C \rightarrow n + ...$, $E_b \approx 0.500$ MeV.

and at the point where it interacts with the matter of the WD is significant. From this, generation conditions are created that are characteristic of positron decays of γ-quanta into proton-rich nuclei. The characteristic chemical composition of single white dwarfs suggests the presence of He and C-N-O, more rarely, Ne elements. The masses and magnetic fields of WDs impose restrictions on the energy of collisions of accreting matter with the surface of a WD. As was shown in the previous Section, the processes of the combined action of intense gravitational and magnetic fields allow the atmospheric plasma of a WD to reach significant thermal energies to trigger the processes considered in Figs 4–5.

The dependencies shown in the graphs of Figs 4–5 allow the selection of the most probable channels of nuclear transformations leading to the formation of positrons. If such a scenario is realized in the spectra of WD, we expect the constant presence of γ-lines after electron–positron annihilation to describe such spectra and the method of positron spectroscopy described earlier by us in the study of peripheral regional active galactic nuclei is suitable. The main limitation for the formation of the proton-excess nucleus is the reaction threshold energy. Therefore, in the range of characteristic energies, nuclei with threshold energy not exceeding 10 MeV should be excluded.

The small collection of total cross sections for neutron evaporation of the C–N–O elements in the WD surface confirms the fact that the reaction threshold energy for this element often relates to larger values (up to 10 MeV). Thus, on the surface of WDs, the formation of positrons and the annihilation caused by them with thermal electrons during periods of relative calm is unlikely. The list of objects that systematically form proton-rich nuclei on their surface includes close binary systems with the participation of pulsars. In this case, the increase in the mean summary kinetic and magnetic energy is an increase of twenty five to thirty times. The average cross sections for neutron evaporation reactions increase to 10^4 mbn (Doikov, 2021). In other words, in addition to the thermonuclear combustion of hydrogen and helium, proton-excess nuclei are formed due to the competitive process of collision of protons and α-particles with C–N–O-elements in the pulsar's surface at its magnetic poles.

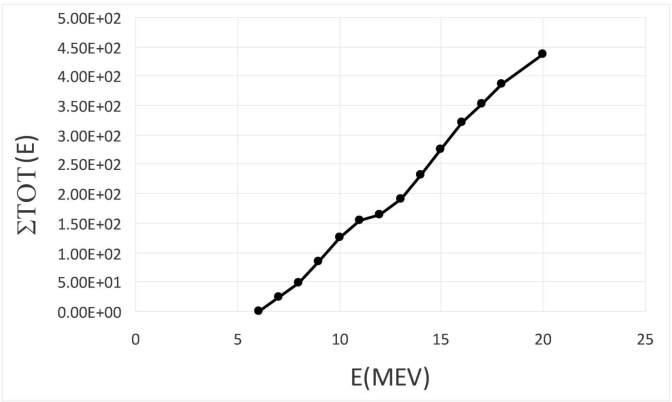


Figure 5 Dependence of total cross section in mbn (10^{-27} cm^2) on proton energies E (MeV) with the reaction channel $+^{14}_{7}N \rightarrow n + ...$ The point of intersection of the E axis with the graph is the reaction threshold energy $E_b \approx 6.088$ MeV.

Positron formation statistics have been considered in star flares (Bisnovatyi-Kogan, Pozanenko, 2017). This is the reaction set:

$$^{11}_{6}C \rightarrow ^{11}_{5}B + e^+ + ...; \;\; ^{13}_{7}N \rightarrow ^{13}_{6}C + e^+ + ...; \;\; ^{15}_{8}O \rightarrow ^{15}_{6}N + e^+ + ... \; . \qquad (3)$$

Discussion. The presented results show that between explosions in the WD surface in CVs we can expect a systematic, continuous component of the soft γ-spectrum that appears on the WD surface. From Figs 1–3, we conclude that the main contribution in soft γ-continuum is produced by the elements $^{4}_{2}$He, $^{12}_{6}$C, $^{13}_{6}$C, $^{14}_{7}$N, $^{16}_{8}$O. The luminosity in soft γ-ray spectra from these CVs consists mainly of the contribution from collisions between $^{4}_{2}$He, $^{13}_{6}$C and $^{14}_{7}$N nuclear and proton. Additionally, we have contributions from $^{13}_{6}$C and $^{14}_{7}$N nuclear and α-particle. The selection of contributors consists only of the threshold border of the emission cross section in the range from 0.1 MeV to 7 MeV.

Detection. The semiconductors made from heavy elements CsPbBr3 have been developed in the last 8 years. The mean atomic mass of CsPbBr3 is 57.35 a.u. In (Doikov, 2022; Fangze et al., 2022) considered that the size parameter of these semiconductors depends on γ-quants energies. On the other hand, the monochromatic mean linear absorption coefficient has nonlinear dependencies from energies (wavelength) of the projective γ-quanta. In the present time, the mean which is often found is $3 \times 3 \times 0.9$ mm, and the centred energy for this crystal is 5.5 keV. In the field of our interests, the detector must be 10–40 cm, which is unreal for this preparation. The mean energy point is 1 cm for 0.511 MeV and 10 cm for 1 MeV. The declared spectral is 1–2% for these energies or 1–2 keV. In these detectors for calibration electrons K-shell energies may be used (Fangze et al., 2022, Fig. 2 Picture C).

Conclusion

In the present work, we finished the preparation for the construction of the rapid γ-ray spectrograph on the base of the CsPbBr3-semiconductor. The regimes of exploitation

of longterm monitoring of the short rapid γ-ray events is used in various astrophysical systems, including CVs. The signal relaxation times and the signal-to-noise ratio make it possible to discretize and process γ-quanta incidents on the detector in the longterm monitoring mode.

Firstly, we use a model of the calibrating emission spectra the same as presented in Figs 1–3. For calculating the full number of the electron-dots pair in the CsPbBr3-semiconductor we put empirically measured creating energy $E_cr = 5.3$ eV. In the energy interval presented in Figs 1–3 current pulls from every penetrating γ-quanta after incidents with the surface of the detector are varied from 50 to 10 μA. At the same time, the dark current pulse is, on average, four times smaller than the amplitude of the useful signal.

Secondly, to exclude the loss of registration of fast, for example, explosive processes, it is necessary to provide a processing rate of useful signals that is suitable in time.

Thirdly, the background γ-spectrum of each object is calculated separately, taking into account the data obtained using other instruments.

Acknowledgements We acknowledge with thanks the use of the resource of the nuclear reaction data in [Tanaka et al., 1994]. We also thank Prof Chechetkin and Prof Bisnovaty-Kogan for productive discussion during the memorial Gamow conferences.

Authors' contributions Joint formulation of the problem and its solving, Introduction, Discussion, and Conclusion. DDN: Sections 2, 4. DMD: Sections 1, 3, Detection, References.

References

Bisnovatyi-Kogan G.S., Pozanenko A.S. (2017) Astrophysics 60 No. 2, 223
Doikov M. (2022) Odessa Astronomical Publications 35, 24
Doikov D.N., Yushchenko A.V. (2021) Odessa Astronomical Publications 34, 40
Fangze L., Rong W., Jing Wei, et al. (2022), ACS Energy Letters 7 (3), 1066
Tanaka S., Yamano N., Hata K., et al. (1994), Am. Nucl. Soc. Inc., *in* Proc. 8th Int. Conference on Radiation Shielding. Arlington, April 24–28, 2, 965; (2014). https://wwwndc.jaea.go.jp/ftpnd/sae/acl.html