Nuclear physics and astronomical observations of compact objects

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Abstract

We discuss our predictions of two astrophysics observations: neutrino emission and element abundances. We studied the emission and possible detection of neutrinos from past black hole accretion disks. We find neutrinos are copiously emitted from these sites and encourage the development of large facilities for detection. We also studied changes in the synthesis of neutron-rich elements due to the suppression of key nuclear processes. We find important changes in the element abundances due to the, previously overlooked, alpha decay.

Key words: *astronomy; astrophysics; neutrino detection; element abundance; black holes; accretion disks; neutron-rich isotopes; alpha decay.*

Física nuclear y observaciones astronómicas de objetos compactos

Resumen

Discutimos nuestras predicciones de dos observaciones astrofísicas: la emisión de neutrinos y las abundancias de elementos. Hemos estudiado la emisión y posible detección de neutrinos emitidos por discos de acreción alrededor de agujeros negros en el pasado. Encontramos que los neutrinos son emitidos en abundancia por discos de acreción y sugerimos el desarrollo de detectores de gran escala para mejorar su detección. También hemos estudiado los cambios en la síntesis de elementos ricos en neutrones, debido a la supresión de procesos nucleares claves. Encontramos que hay cambios importantes en la abundancia de elementos debido al decaimiento alfa.

Palabras clave: *astronomía; astrofísica; detección de neutrinos; abundancia de elementos; agujeros negros; discos de acreción; isótopos ricos en neutrones; desintegración alfa.*

Introduction

There is a strong connection between gravity, nuclear and neutrino physics, stellar explosions and the synthesis of heavy elements. A Supernova, has as an outcome a neutron star or a black hole with some matter accreting into it. It is also possible that two neutron stars or a neutron star and a black hole encounter each other and coalesce. In all these scenarios the vast majority of the energy is released as neutrinos. They can travel freely and interact with matter becoming part of a chain of nuclear reactions that produce new elements. On the other hand, there are also other reactions taking place in these sites, all of them occurring on hundreds of nuclei. The unstable nuclei can decay and produce electromagnetic signals. Furthermore, some of the initially emitted neutrinos travel cosmological distances to our planet. Therefore, the formation and coalescence of compact objects is an extraterrestrial laboratory, providing us with a broad range of multi-messenger signals, from gravitational, to electromagnetic, to neutrinos, as the recent detection of a double neutron-star merger has shown us [1]. In this work, we present results of two possible observations: neutrino emission from mergers and abundances of heavy elements.

In the last decades large efforts have been devoted to the simulation of the element abundances observed in the solar system (see for example [2,3]). However, there are disparities with observations, which come from diverse uncertainties, including those relating to the astrophysical conditions, and those from nuclear physics (e. g. decay rates, neutron capture rates, etc.). In this study, we present nucleosynthesis calculations for conditions relevant to supernovae and black-hole accretion disk outflows. We investigate the changes in the abundances due to the suppression of a set of reactions and decays. Unlike the very important contributions of sensitivity studies [4], where the impact of nuclear properties of individual nuclei on the final abundances is considered, our aim is to guide future nucleosynthesis studies to explore the effect of, perhaps overlooked, processes. Particularly, we find that alpha decay has a strong impact on the final abundances, and we will focus future work to study how this process can be influenced by thermodynamical conditions.

On the other hand, several works have made predictions of neutrino detection from supernovae occurring beyond the Milky Way [5,6]. More recent work has been presented on the detection of neutrinos from mergers in the Galaxy and the resulting accretion disks [7,8]. However, very few works, have studied the possible detection of neutrinos from accretion disks from the past, i. e. neutrinos that have been produced since the occurrence of the first mergers. These neutrinos form a uniform flux that comes to Earth from all directions of the Universe (analogous to the cosmic microwave background) and can, in principle, be detected at current facilities. In this paper, we present results of spectra and detection rates for this diffuse background at superkamiokande (SK) [9]. This opens the investigation at cosmological scales and potentially grants insights into star formation history, initial mass functions, and cosmic metallicities [10,11]. We find that the detection depends on astrophysical input such as the rate at which matter is accreted into the black hole, as well as on cosmological rate at which these events occurred in the past Universe. Further details can be found in reference [12].

In the next sections we discuss our methodology for both of these observations, offering extra background, and then with present our results and conclusions.

Materials and methods

Nucleosynthesis studies

The production of neutron-rich heavy elements takes place via the rapid neutron capture process (r-process), in which neutron captures occur at about the same rate as beta decays. To favor neutron captures the astrophysical environment should be explosive like the one found in the core-collapse supernovae and the outflowing matter in black-hole (BH) accretion disks (AD). We focus on the High Entropy Winds (HEW), which are one of the more promising sites for the r-process [13]. The HEW is produced by neutrinos leaving the stellar medium and interacting (via weak interactions) with outer layers of matter resulting in neutron-rich outflows.

In a HEW, the matter can be modeled as expanding adiabatically, inside a bubble, and the thermodynamical conditions of the medium change such that the temperature depends on the velocity of expansion and the initial ratio of the bubble, R_0, in the following way:

$$T(GK) = T_0(GK)\frac{R_0}{R_0+v_{exp}t},$$

where v_{exp} is the expansion velocity, t is the time, and T0(GK) and T(GK) are the initial and time-dependent temperatures, respectively, in Giga Kelvin. The density is given by

$$\rho_5 = 1.21\frac{T(GK)^3}{S}\left(1+\frac{7}{4}\frac{T(GK)^2}{T(GK)^2+5.3}\right),$$

with ρ_s in units of 10^5g /cm^3. In our study, we took T_0 = 3GK , R_0 = 390 km and v_{exp} = 7500 km/s. Also the entropy was taken to be S = 270 kg.

The synthesis of heavy elements in HEW starts with the recombination of free neutrons and protons into alpha particles, which react to determine other nuclides such ^{12}C and ^{9}Be [14], under the thermodynamical conditions described above. The triple alpha reaction that forms ^{12}C and the double alpha reaction with a neutron that forms ^{9}Be strongly depend on the matter density, reducing the rate of further reactions. When this happens, the alpha-rich-freeze out ends up with an important neutron to light nuclei (seeds) ratio; then the neutron capture (r-process) begins leading to highly concentrated neutron-rich nuclei.

After neutron captures decrease, due to drop in the neutron density, the remaining nuclides can be highly unstable. After considerable time, these nuclei will decay to stability. The final abundances of elements will depend, besides of neutron capture, on other processes such as beta decay, alpha decay, photo dissociation, alpha capture and beta-delayed neutron emission. We show the contribution that these processes have to the final abundances of certain nuclides and study the dependence of that contribution in the presence of each one of the other processes. When the neutrons are almost exhausted the path to equilibrium begins, mainly through alpha and beta decay. In this work, we used the thermodynamical conditions of the HEW described above. The initial abundances after alpha-rich freeze-out were taken from Farouqi et al. Those abundances were allowed to evolve in time with a nuclear reaction network, r-Java (a specialized software for r-process nucleosynthesis simulations) [15]. We manipulated the network to suppress some reactions and decay channels as will be presented in the Results section.

Neutrino emission from past and present black hole accretion disks

In the event of a compact object merger between a Neutron Star (NS) and either a Black Hole (BH) or a NS (hereafter, BH-NS and NS-NS), the likely result is an accretion disk around a BH [7,16]. As mentioned in the introduction, these events release gravitational energy via neutrinos, possibly detectable here on Earth. This goal is attainable through, e. g., the use of SK [9]. By extending the investigation into the past Universe, additional data points can be found. This work aims to study the contributions of thick BH accretion disks (AD) to this diffuse neutrino background. The first point of investigation for this work is the anticipated spectra from the AD. We based our study on a model of the hot matter that forms a torus around the BH [17]. The second point of investigation takes these spectra, and converts it into diffuse fluxes. To do this we used the cosmological merger rate calculations from Dominik, et. al. [18]. Finally we used the fluxes to calculate a detection rate for SK based on the cross section of the main weak process, i. e. the electron antineutrino absorption by protons. The above steps are explained in what follows.

To calculate the neutrino spectra we used a general relativistic disk model [17]. The disk is composed by a gas of nucleons, α-particles, and electrons in nuclear statistical equilibrium. This model will be referred to, in our results section, as “C0” and “Ca”, corresponding to BH spin of 0 and 0.95. The BH mass is set to $3M_o$ and α viscosity of 0.1. Further, the model assumes that the accretion rate M_O is constant. Within the ADs, produced neutrinos are trapped in highly dense matter. As a result, until they reach the surface of the neutrino sphere, they cannot escape. Since the neutrinos become free at this surface, their thermodynamical properties will be inherited from it, and the spectra can be found as a Fermi-Dirac distribution with temperature given by the neutrino surface temperature. Due to the abundance of neutron matter, the electron neutrino sphere is much larger than the corresponding electron antineutrino sphere [8]. As we are interested on the neutrino spectra as seen at distant points, the neutrino energy E must then be red shifted to account for the gravitational effects imposed by the BH via the Kerr metric as well as due to universal expansion.

To step from spectra to diffuse fluxes the Friedman equation is used to relate time and cosmological red shift [19], with the aforementioned merger rates [17], particularly the “high-end metallicity standard model” as a loose middle ground amongst their other models. Finally, an integral over cosmological red shift is done to generate the diffuse flux. Combining this result with the cross-section between protons and electron antineutrinos and factoring in the number of available protons in SK yields the expected detection rates (see for details [12]).

Results and discussions

Nucleosynthesis studies

We analyze the contribution of the main nuclear processes that intervene in the r-process and in the decay to stability. Figure 1 shows the final abundances of the simulated r-process and the subsequent equilibrium as well as the abundances without each one of the reactions. The thermodynamical conditions are described in the Methods section. Figure 2 zooms in the region where there are more differences with and without alpha decay process.

The green line of the figure 1 shows the abundances taking out beta delayed neutron emission. As shown, around A=80 the distribution is shifted to the right. The abundance of elements higher than A> 200 is slightly increased with the inclusion of beta delay neutron emission. The reason is that the emitted neutrons are available for later captures producing heavier neutron-rich nuclei. The red line of Figure 1 shows the abundances suppressing alpha captures. Bellow A=80 there is a no-

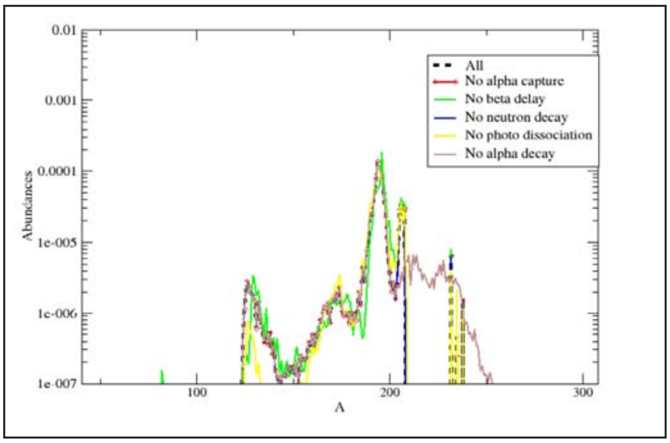

Figure 1. Abundances with and without nuclear processes.

table difference in abundances when switching on alpha capture (range not shown here). The presence of the process allows the synthesis of lighter elements and because the greater Coulomb barrier, alpha capture stops being important in the formation of heavy elements. Therefore, no significant differences are found a large mass numbers by suppressing or not alpha capture. The yellow line of Figure 1 depicts the abundance taking out photodissociation (PD). Nuclides with A<80 are more abundant switching off PD. The presence of PD allows higher amounts of neutrons that later on will be recaptured. That’s why nuclides when A>80 are more abundant with PD. The differences are less notorious for nuclides with more than 160 nucleons where elements are giving up neutrons easily.

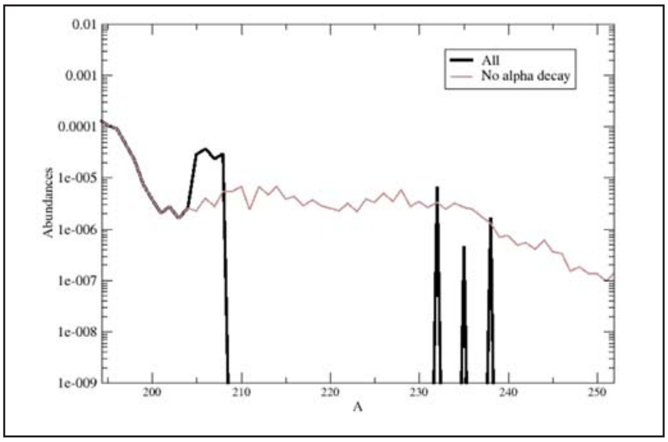

Figure 2. Abundance with and without alpha decay.

As shown in Figure 2, alpha decay, important after neutron captures ceased, has a mayor impact in nuclides with mass number between A=208 and A=232. The most stable nuclei at the 208 peak is ^{208}Pb, which means that the difference in the abundances shown in the graph come from radioactive elements such as ^{212}Po that at the same time is the product of the alpha decay of ^{216}Rn. Within the 208-isobar chain, some of the nuclei undergo electron capture and beta decay, leaving these nuclei with the same initial mass number. Large probabilities of alpha decay occur in proton-rich nuclei, above the ^{212}Po. A nuclear mass region that usually doesn’t make part of the r-process and hence the abundances of A=204 are similar with and without alpha decay. The difference around A=230 comes mainly for the alpha decay of this isobar chain, with ^{230}Th and ^{231}Pa the most stable elements, since in the neutron-rich region with A=234 and A=235, alpha decay rates are considerable small. The stability of these nuclei results in the peaks observed in the A=230 mass number when alpha decay is included. However, suppressing this decay implies all nuclei are equally alpha-decay stable and the abundances pattern in this mass region is more even.

Neutrino emission from past and present black hole accretion disks

While most signal detections will be through electron antineutrinos, a comparison will be made to electron neutrinos as shown in Figure 3. This figure shows several AD scenarios. For both the C0 and Ca models, M_o is set to 3 M_o/s. Several things can be inferred from Figure 3. Firstly, the effect of neutrino sphere sizes and temperatures results in the antineutrino spectra being significantly larger at high energies compared to the electron neutrino. This is beneficial for facilities such as SK, which utilizes Cherenkov light. Secondly, systems with a spinning black hole produce more neutrinos and antineutrinos. Importantly, this is biased toward higher energies as shown by comparing the Ca and C0 cases. Rates are presented in Figure 4, where BH-NS mergers are used and the accretion rate is varied in the Ca model. As can be seen, increases to the accretion rates leads directly to an increase in detection rate. The rates are quite small, but can be circumnavigated.

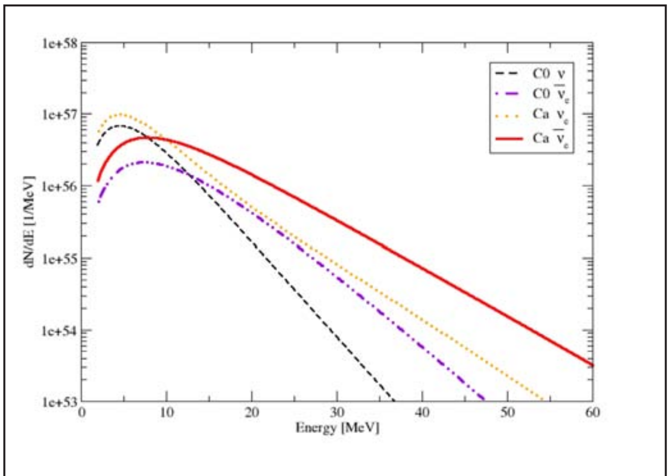

Figure 3. Electron (anti)neutrino spectra from Galactic accretion disks.

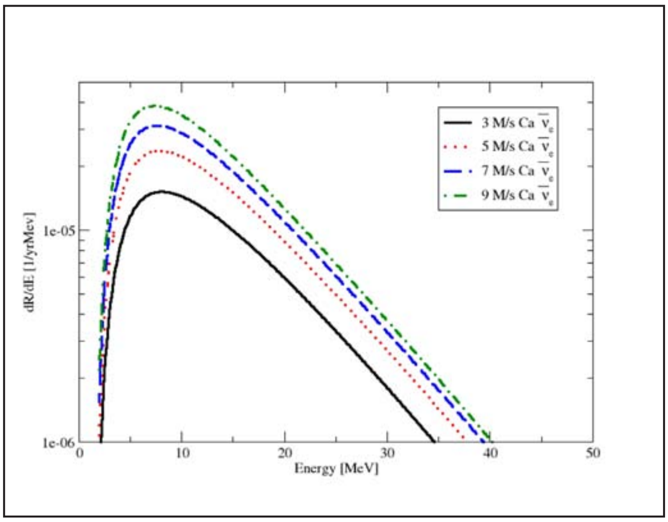

Figure 4. Electron antineutrino counts at SK per year per MeV.

In our nucleosynthesis studies we acknowledge that although nuclear processes are not totally independent one of each other, it is worthwhile to analyze them separately to know approximately the effect they have over the final abundance of heavy elements. We find that together with beta decay, alpha decay is one of the main process in which heavy nuclides reach the equilibrium. Alpha capture has some influence in light elements' abundances. Beta delayed neutron emission helps to smooth out the distribution and provides the system with more neutrons. Likewise, photodissociation (but in a higher amount) increase the pool of neutrons to be captured and helps with the formation of heavier elements. Since there is no experimental data about alpha and beta decay rates for every nuclei, is important to improve the theoretical estimations. In future work we will explore the way in which different models of alpha decay rates affect the final abundances.

In relation to the neutrino diffuse background, the primary conclusion to be drawn is the need for both more effective detection methods through improved cross-sections and larger or more numerous detection facilities. As was discussed, several facilities are luckily on their way already. With a refined understanding of the nature of the neutrino signal, namely the bands of energy that will evade detectors' background noise (roughly 40-60 MeV), a lot can be learned. Topics such as nucleosynthesis, cosmic metallicity, star formation history, and initial mass functions can all be probed with neutrino detections.

Conclusions

We have entered an unprecedented era of astronomical observations, that will unveil several nuclear physics mysteries. The multi-messenger signals from different observatories provide us with meaningful information that awaits to be interpreted. Models, simulations and predictions of these signals are first priority in our work. In this paper we presented two possible observations: nuclear element abundances and the neutrino counts from past accretion disks.

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