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Estimation of the Abundances of Heavy Elements Isotopes in Neutron Stars

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Abstract

The cataclysmic merger of two rotating neutron stars in an explosive event is called a Kilonova. Such an event (17 August 2017) leads to the production of more than an Earth's mass of precious metals like gold, platinum, uranium, and many of the rare elements. The merger led to the emission of gravitational waves that travel with the speed of light. When two stars collide, gravitational waves arrive on the earth earlier, and there is a delayed emission of γ-rays. In fact, light arrives 1.7 seconds after the gravitational waves. The merger of stars leads to the creation of isotopes of these heavy elements. A criteria is proposed as to which isotopes of these elements may be in abundance. Since the merger of dense solar bodies leads to the creation of neutron stars, it is proposed that the magnitude of the neutron pairing energy (p_N) should be the criteria to determine their abundance. Six elements (Fe, Ag, Au, Pt, Th, U) have been chosen to ascertain the validity of the criteria; and the criteria is that the most abundant isotope should have least positive value of P_N. The criteria is slightly violated in the case of Pt since it has three isotopes that are almost equally abundant.

Keywords: Kilonova; Gravitational Waves; Pairing Energy of Neutrons

Introduction

Neutron Star

The collapsed core of a large (10-29 solar masses) is known as the neutron star. Neutron stars are the smallest and densest stars known to exist in the Universe [1]. The radius of the neutron stars is generally of the order of 10km, but their masses are about twice the mass of the sun $(M = 2M_{\oplus})$, where M=mass of the star, and $M_{\oplus}$ is the mass of the sun. The neutron stars result from the super-nova explosion of a massive star, combined with gravitational collapse, that compresses the core past the white dwarf star of that of atomic nuclei ρ_s or even more than ρ_s . In all the proposed models of such objects, neutron stars are assumed to be composed almost entirely of neutrons. Neutron degeneracy pressure, a phenomena described by the Pauli exclusion principle, does not allow further collapse. If the remnant has too great a density, something that happens, when the upper limit of the size of neutron stars exceeds 2-3 solar masses, it will continue collapsing to form a black hole [2]. Neutron stars that can be observed are very hot and generally have a surface temperature of the order of 6 X 10^5K [3]. They are so dense that a normal-sized match box containing neutron-star material would have mass of the order of 3 million tons, or a 0.5 cubic mile chunk of the Earth (or a cube with edges of about 800 metres). Their magnetic fields are between 10^8 and 10^{15} time as strong as that of the Earth. The gravitational field at the neutron star surface is of the order of 2 X 10^{11} times that on the Earth's surface [4]. In contrast to the isolated star, a neutron star (NS) is a binary system with a convetional star that can accrete matter from its companion, replacing the crust with a complex mixture. The hydrogen rich material falling on the NS often undergoes explosive nuclear burning when the protons are rapidly captured by seed nuclei (this process is called rp-process nucleosynthesis) to build up heavier nuclei and isotopes with mass numbers A upto A □ 107 [5,6]. This upper limit is due to a closed cycle burning known as the SnSbTe cycle, which limits rp-process nucleosynthesis to $Z \leq 52$ [5]. Due to further accretion, the rp-process material is buried, and the results in rising electron Fermi (surface) energy that induces electron capture to produce a range of neutron rich isotopes (nuclei) from O (oxygen) to roughly Selenium (Z=34) [7]. This material freezes when the density exceeds about 10^{10}g/cm^3, and the Coulomb parameter

$\tau = \frac{Coulomb\ Energy}{Thermal\ Energy} = \frac{Z^2e^2}{akT}$, where $a = \left(\frac{3}{4\pi n}\right)^{1/3}$, $n = ion\ density, Z$ is the charge of the ion, T=Temperature and k is the Boltzmann constant, is such that τ □ $175.$ It is found that the complex rp-process ash freeze and the chemical separation takes place so that liquid phase is greatly enriched in low atomic number (Z) elements, and the newly formed solid crust is enriched in high atomic number (Z) elements [8]. This chemical separation has been studied for a variety of compositions [9-11]. Current models suggest that matter at the surface of the neutron star is composed of ordinary atomic nuclei crushed into solid lattice with a sea of electons flowing through the gaps between them. The thickness of the atmosphere of neutron star is assumed to be at the best some micrometers. It is also surmised that its dynamics is completely controlled by the magnetic field of the neutron star. Below the atmosphere, there will be solid crust. This crust is extremely hard and very smooth, with maximum surface irregularities of □ 5mm, and this is due to the extremely large gravitational field [12]. The crust could be composed of very heavy elements, like, platinum, gold, uranium etc. There could exist a hierarchy of phases of nuclear matter in their inner crust. Proceeding inwards, there could be nuclei with ever-increasing number of neutrons, and ultimately the whole system may be composed of neutrons only and hence the name neutron star. When a star collapses such that protons and electrons combine to form neutrons; hence the name neutron star (NS). Recently it was observed that gravitational waves emitted by two merging black holes (16 October 2017) travel with the speed of light. Both light and gravitational waves travel with the speed of light. When two stars collide, gravitational waves arrive earlier, and there is a delayed emission of γ-rays; infact, light arrives 1.7 seconds after gravitational waves. when two stars spiraled together, they emitted gravitational waves that were detectable for about 100 seconds, and ultimately when they collided, they emitted a burst of γ-rays in the form of light that was detected on the Earth. Albert Einstein, a century ago, had predicted that accelerating masses will produce oscillations of space-time known as gravitational waves (GWs) [14]. After about a century of work, GWs were ultimately observed by the Laser Interferometer Gravitational-Wave Observatory (LIGO) [13]. Having briefly described the structure of neutron star and the event named GW 170817, we now discuss the exact meaning of writing this manuscript. Inside the neutron star, heavy elements like gold, platinum, uranium and other rare elements could be in the form of isotopes of these elements. It will be interesting to understand which isotopes will be in abundance, and what may be the criteria to decide as to which isotopes may be in abundance. The criteria will depend on the neutron-neutron interaction and the density of the neutron star. For low-density neutron matter, the neutron pair will be in the spin-singlet (${}^1S_0$) state. In the low-density S-wave scattering the phase shift is positive and hence the neutron-neutron interaction is attractive. In the high-density neutron-neutron scattering, the dominant pairing is ${}^3P_2$ which means triplet pairing. The spins of the neutron pair will be aligned in the same direction and this will lead to repulsive interaction between the two neutrons constituting the neutron pairs [15-17]. Thus the pairing energy of a neutron-pair will be positive in a high density neutron star. Now since the elements are produced due to the smash-ups of the neutron stars, resulting in the creation of a high density neutron star, the pairing energy of the neutron pair (P_N) should determine the abundance of the isotopes. It is surmised that the isotope for which (P_N) is minimum positive for a given element should be in abundance. The variation in the value of (P_N) can determine the relative abundance of each isotope.

Theory

The pairing gap is fundamental for the cooling of neutron stars. Neutron star crust is made of nuclei arranged on a lattice surrounded by a gas of neutrons. Cooling of neutron star is dependent on the pairing gap which is related to the pairing energy of the neutron pair. Dense neutron matter density is, $\rho \square (0.5 - fewtimes)\rho_o$ where ρ_o = saturation density of nuclei.

Keeping this in mind it is proposed that the pairing energy P_N of the neutron pair in a neutron star of high density, and its relative magnitude, will determine the isotope abundance of an element. The neutron pairing energy is defined as, in terms of the biding energies of the nuclei;

$$P_N(A,Z) = \frac{1}{4}(-1)^{A-Z+1}\left[-B(A+1,Z) + 3B(A,Z) - 3B(A-1,Z) + B(A-2,Z)\right] \tag{1}$$

where A is the mass number of the nuclei, Z is the proton number and N is the neutron number such that A=N+Z, and B stands for the binding energy of the nucleus [18,19].

The elements selected for this study is; Iron (Fe), Silver (Ag), Gold (Au), Thorium (Th), Uranium (U) and Platinum (Pt). On the experimental basis, the wavelength of the light (colour of the light) received from a merger can give an idea of the nature of elements, and the relative intensity of the light radiation can give an idea of its abundance. Las Campanas Observatory in Chile observed the light source generated by a neutron-star merger on 28th April 2017. A light in the form of bright blue source of light was observed, and NASA spotted a burst of gamma-rays-the highest energy form of light.

Results and Discussion

Table 1 shows binding energy per nucleon $(\frac{B}{A})$, neutron pairing energy and percentage abundance of the nuclei chosen. Binding energy per nucleous is obtained from reference 18 for the chosen elements. Neutron pairing energy is calculated from equation (1) using the values of the biding energy for the elements in reference 18. The percentage abundance of the elements is obtained from the tables in reference [19]. Our calculations show that in most cases, the maximum percentage abundance corresponds to minimum positive pairing energy of neutrons. The exception being ${}^{232}_{90}Th$ and ${}^{195}_{78}Pt.$ The element gold, ${}^{197}_{79}Au,$ is a unique example with hundred percent abundance. No other isotope of gold exists. The element platinum (Pt) has many isotopes with varying percentage abundance. Three isotopes have more or less equal abundance, and hence our criteria may not be exactly applicable. Still the criteria fits for ${}^{195}_{78}Pt.$ isotope that has the largest abundance between the three or two isotopes ${}^{196}_{78}Pt\ and\ {}^{195}_{78}Pt$.

Name of Element	Isotopes	Binding Energy (B/A) (Mev)	Neutron Pairing Energy P_N (Mev)	% abundance	Most abundant Isotope
Iron (Fe)	$^{54}_{26}Fe$	8.736	6.773	5.845	$^{56}_{26}Fe$
	$^{56}_{26}Fe$	8.790	5.450	91.754	
Silver (Ag)	$^{107}_{47}Ag$	8.554	3.857	51.839	$^{107}_{47}Ag$
	$^{108}_{47}Ag$	8.542	-4.177	0.000	
	$^{109}_{47}Ag$	8.547	4.288	48.161	
Gold (Au)	$^{185}_{79}Au$	7.909	3.122	0.000	$^{197}_{79}Au$
	$^{193}_{79}Au$	7.924	3.489	0.000	
	$^{195}_{79}Au$	7.921	3.334	0.000	
	$^{197}_{79}Au$	7.916	2.990	100	
Thorium (Th)	$^{230}_{90}Th$	7.631	3.212	0.000	$^{232}_{90}Th$
	$^{232}_{90}Th$	7.615	2.975	100	
	$^{234}_{90}Th$	7.597	2.926	0.000	
Uranium (U)	$^{234}_{92}U$	7.600	2.630	0.0055	$^{238}_{92}U$
	$^{235}_{92}U$	7.590	2.795	0.7200	
	$^{238}_{92}U$	7.570	2.473	99.2745	
Platinum (Pt)	$^{190}_{78}Pt$	7.947	4.644	0.014	$^{195}_{78}Pt$
	$^{192}_{78}Pt$	7.942	4.616	0.782	
	$^{194}_{78}Pt$	7.934	4.339	32.967	
	$^{195}_{78}Pt$	7.927	4.064	33.832	
	$^{196}_{78}Pt$	7.927	3.892	25.242	
	$^{198}_{78}Pt$	7.914	3.708	7.163	

Table 1: Binding energy per nucleon ($\frac{B}{A}$), neutron pairing energy and percentage abundance of the nuclei chosen

Conclusion

Thus, the calculations, to a greater extent have established that the neutron pairing energy (P_N) should be the criteria to determine the abundance of isotopes of a given heavy element in neutron stars, and that the value of P_N should be minimum positive when compared with the values of P_N for the various isotopes of the element under study. These costly precious metals which face extinction from the surface of the Earth happen to be much needed on the Earth for economic, energy and environmental sustainability; uranium is needed for nuclear power generation as an alternative to fossil fuel, while the other elements like gold, silver, platinum etc. are used in industry. The inexhaustible source of all these elements is apparently the neutron stars.

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