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Letters to the Editor

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Abstract. Neutron stars (pulsars) are here proposed as the sources of superheavy (SH) nuclei $Z \geqslant 110$ in primary cosmic rays. Taking into account the 1969 result of Berlovich and Novikov that these SH nuclei can be formed by the r process when the temperature is greater than $1{\cdot}8 \times 10^9$ K and at sufficiently high neutron number density, it is here pointed out that this temperature condition can prevail in a neutron star for approximately 10^3 years when the cooling behaviour is governed by the synchrotron radiation of neutrinos according to the photon–neutrino weak coupling theory. On the basis of this result, it is argued that the formation of SH nuclei in our galaxy can be considered as a continuous event. Finally, some remarks are made about the expected flux of these SH nuclei.

Recently, Fowler (1969—unpublished) has reported the detection of superheavy (SH) nuclei having $Z \geqslant 110$ in the primary cosmic radiation. Silvestro (1969) has suggested that pulsars may be the likely source of these SH nuclei, though the problem of formation of these SH nuclei was not discussed in detail. In this letter we discuss the possibility of formation of these SH nuclei and shall show that pulsars (neutron stars) can indeed be taken to be the source of such nuclei.

Silvestro (1969) has pointed out that extreme conditions such as high density of neutrons in a neutron star can favour the formation of these SH nuclei. However, according to the prevailing notions, such heavy elements cannot result from the r process (Burbidge *et al.* 1957, Seeger *et al.* 1965). The reason is that the r process is terminated as a result of the neutron-induced nuclear fission which occurs at mass numbers $A \simeq 270$ to 275 ($Z = 93$) (Hoyle and Fowler 1960). However, when the number of neutrons is close to the magic $N = 184$, shell corrections are essential in the calculation. Pointing this out, and taking into account that $Z = 114$ is magic, Berlovich and Novikov (1969) have considered the possibility of the formation of SH nuclei $Z \geqslant 110$ and have concluded that, for neutron binding energies $B_n \leqslant 2{\cdot}7$ MeV, the r process can indeed reach the magic number $N = 184$ and develops at $N > 184$. However, for this the limiting values of neutron number density n_n and temperature T are found to be $n_n \geqslant 10^{27}\,\mathrm{cm}^{-3}$ and $T_9 \geqslant 1{\cdot}8$ ($T_9 = T/10^9$). From this we see that, for a pulsar to act as the source of such SH nuclei, it must have an internal core temperature above 10^9 K for a considerable period of time.

Pulsars are generally taken to be neutron stars which are formed as remnants of supernova outbursts. In a neutron star, high density can develop and the neutron number density can be as large as $n_n \simeq 10^{38}$ to 10^{39} cm^{-3} and the Fermi energy may be of the order of 100 MeV. However, neutron star models as developed by Tsuruta and Cameron (1966), taking into account the cooling effect caused by the process

$$\mathrm{n}+\mathrm{n} \rightarrow \mathrm{n}+\mathrm{p}+\mathrm{e}^{-}+\bar{\nu} \qquad (1)$$

do not permit a temperature of the order of 10^9 K for a considerable period of time. In such a model a neutron star with $T_c \simeq 10^9$ K will cool too fast (in 1 day to 10 years for models of different mass) and so the r process cannot generate these SH nuclei for an appreciable period of time. So, if the cooling behaviour of neutron stars is supposed to be due to the modified urca process (1), SH nuclei can be formed mainly at the time of the supernova outburst, when the core temperature can be as high as 10^{12} K. In that case, the formation of SH nuclei in our galaxy can not be considered to be a continuous phenomenon.

Here it may be noted that it is not beyond doubt whether the cooling behaviour of neutron stars is governed by the modified urca process (1). For, in this process, neutrons are considered as individual particles. However, it seems that at very large densities the concept of individual particles is not appropriate. Moreover, the thermodynamics of hadrons leads to a mass spectrum which is entirely different from its free-particle analogue. Thus it is unlikely that the modified urca process plays a significant role. The other neutrino emission processes which are important in neutron stars are the plasma process

$$\Gamma \rightarrow \nu+\bar{\nu}$$

and the synchrotron radiation of neutrinos. If the plasma process, when calculated according to the current–current coupling theory, is taken into account, the cooling behaviour becomes more complicated. Indeed, the possible age of a detectable neutron star can be anywhere from about 1 day to about 10^6 years (Tsuruta 1964). Again, Landstreet (1965) has calculated the synchrotron radiation of neutrinos according to the current–current coupling theory and has observed that it has a negligible effect in cooling the neutron stars.

In a recent paper, Ray Chaudhuri (1970) has calculated the synchrotron radiation of neutrinos on the basis of the photon–neutrino weak coupling theory proposed by Bandyopadhyay (1968) and has shown that it has a significant effect in cooling the neutron stars, though the plasma process when calculated according to this theory has no appreciable effect in such stars. The neutrino luminosity for the synchrotron radiation process

$$\mathrm{e}^{-} \xrightarrow[\text{field}]{\text{Magnetic}} \mathrm{e}^{-}+\nu+\bar{\nu}$$

when calculated according to the photon–neutrino coupling theory is found to be

$$L_\nu \simeq 3\times10^{-7} H_8^{2/3} T_7^{7/3} n_e^{4/9} \qquad \mathrm{erg\ cm^{-3}\ s^{-1}}.$$

Here $H_8 = H/10^8$, where H is the magnetic field strength, $T_7 = T/10^7$ and n_e is the number density of electrons. The neutrino luminosity (NSR) according to the photon–neutrino coupling theory together with photon luminosity and the total energy content of a neutron star are tabulated in table 1 (as calculated by Tsuruta and

Table 1. The characteristics of the hot neutron star model of Tsuruta and Cameron (1966) (V_β, $M = 0{\cdot}6\ M_0$) with Fe atmosphere

T_e (K)	lg L_{ph} (erg s^{-1})	lg L_ν (erg s^{-1})	lg T_c (K)	lg U_T (erg)	lg τ (τ in years)
10^9	44·56	42·21	11·40	52·24	0·18
5×10^8	43·36	41·30	11·10	51·64	0·77
2×10^8	41·77	40·58	10·70	50·84	1·54
10^8	40·56	39·88	10·40	50·24	2·10
5×10^7	39·36	39·30	10·08	49·60	2·54
2×10^7	37·77	38·20	9·68	48·74	2·90
10^7	36·56	37·23	9·26	47·88	3·07
5×10^6	35·36	36·37	8·90	47·17	3·26
2×10^6	33·77	35·42	8·47	46·30	3·37
10^6	32·56	34·42	8·04	45·51	3·58

T_e and T_c are the surface and core temperatures, L_{ph} is the photon luminosity, L_ν is the neutrino luminosity (NSR) according to the photon–neutrino coupling theory, U_T is the internal energy, and τ is the cooling time.

Cameron 1966 for an Fe atmosphere) for the model V_β of neutron star having $M = 0{\cdot}6\ M_0$. The magnetic field strength is taken to be 10^{14} gauss. These are the conditions which are believed to be prevailing in the neutron star in the Crab nebula, the remnant of a supernova outburst which occurred in A.D. 1054.

From table 1 we see that the neutron star in the Crab with $T_e \geqslant 10^7$ K will cool slowly and the star will be 10^3 years old when $T_e \simeq 10^7$ K ($T_c \simeq 2 \times 10^9$ K) and it will take approximately 4×10^3 years before it cools down to $T_e \simeq 10^6$ K ($T_c \simeq 10^8$ K). Thus the neutron star in the Crab, which is supposed to be the root cause of the Crab pulsation, can have $T_c \simeq 2 \times 10^9$ K for approximately 10^3 years, and as such can support the r process leading to the formation of SH nuclei having $Z \geqslant 110$ and $N \geqslant 184$. As Silvestro (1969) has shown, in a neutron star nuclei can exist in an outer layer within 1 to 2 km from the surface, and synthesis of SH elements may occur in the transition region to the almost pure neutron interior. Then a fraction of this can be carried to the surface by some mechanism operating in the star. It may be pointed out here that, as the galactic supernova occurs at the rate of 10^{-2} per year, the calculated cooling time suggests that the formation of SH nuclei in our galaxy can be considered as a continuous event.

From an estimate of the increase in period of the Crab pulsar, it is found that it should liberate energy at the rate of 10^{38} erg s^{-1}. From table 1 we see that the neutrino luminosity of the Crab pulsar at present is 10^{38} erg s^{-1} and hence is of the right order of magnitude to explain the dissipation mechanism. In view of this, Bandyopadhyay and Ray Chaudhuri (1970) have suggested that pulsars may be treated as radially pulsating neutron stars. As the energy loss rate is 10^{38} erg s^{-1}, and the internal thermal energy according to the present model is sufficient to maintain this, we can expect that high-energy particles can be generated from such pulsating stars. Though the acceleration mechanism is not well known at present, it is expected that the shock waves (hydromagnetic waves) generated by the pulsation of the star, which travel along magnetic field lines, will be capable of accelerating charged particles to high energies (Cameron 1965). However, it is to be noted that, as the mechanism of mass ejection is expected ultimately to depend on the release of stored up energy of the interior, the rate of mass ejection will also decrease in time.

The preliminary results of Fowler (1969—unpublished) give an abundance by number of SH nuclei in the primary cosmic rays of the order of 10^{-7} times that of the Fe group. This is estimated to be a fraction approximately 5×10^{-4} of the total cosmic ray abundance and thus the concentration n_{SH} of SH nuclei is found to be of the order of $5 \times 10^{-21}\ \mathrm{cm}^{-3}$.

Silvestro (1969) has pointed out that the mean life $T_{\mathrm{n,SH}}$ for nuclear interaction is of the order of $8{\cdot}5 \times 10^5$ years and is short compared with the estimated mean life for decay or fission and almost equal to the time of escape from spiral arms. SH nuclei generated in the disk are then nearly confined within the disk itself.

Taking into account that a neutron star can have a core temperature of approximately 2×10^9 K for 10^3 years and galactic supernova outburst occurs at the rate of 10^{-2} per year, we see that in our galaxy at least 10 neutron stars will be active enough at one time to allow the r process to generate the SH nuclei. Calling φ_{SH} the mean flux of SH nuclei from neutron stars per unit time, a rough estimate of this can be obtained from the relation

$$\varphi_{\mathrm{SH}} \simeq n_{\mathrm{SH}} \frac{V_{\mathrm{disk}}}{N_{\mathrm{p}} T_{\mathrm{n,SH}}}$$

where N_{p} is the number of neutron stars active in generating SH nuclei. Taking $N_{\mathrm{p}} \simeq 10$, we have

$$\varphi_{\mathrm{SH}} \simeq 5 \times 10^{32} \qquad \text{SH nuclei per second per neutron star.}$$

This gives a rough estimate of the luminosity corresponding to SH nuclei: $W_{\mathrm{SH}} \simeq 6 \times 10^{31}\ \mathrm{erg\,s^{-1}}$. A neutron star having $T_{\mathrm{c}} \simeq 2 \times 10^9$ K liberates energy at the rate of $10^{38}\ \mathrm{erg\ s^{-1}}$, and we can assume that a relevant part of this energy is emitted as energetic particles. This gives a fraction as low as 6×10^{-7} of SH nuclei in the matter ejected from neutron stars.

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