

## CREATION AND TRANSMUTATIONS OF ULTRAMAGNETIZED ATOMIC NUCLEI

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Nucleosynthesis in ultramagnetized stellar media at nuclear statistical equilibrium is investigated while accounting for magnetic effects in nuclear structure. The ‘iron peak’ in the mass distribution of nuclides is found to be strongly modified due to magnetic shift of magic nuclei. Such a shift originates from a replacement of nucleon levels caused by an interaction of magnetic moments with a field. Nuclear transmutation in astrophysical plasma under an intense neutron flux is considered while accounting for radiative n-capture on ultramagnetized atomic nuclei. Implications for r-process are discussed.

### 1. Introduction

The supernovae (SNe) for a long time have been considered as promising astrophysical site candidates for synthesis of iron group and heavier chemical elements, e.g., e-, s-, p-, r-process nuclides, cf. [1]. Enormous amplification of stellar magnetization represents plausibly an inherent feature [2] of such spectacular astronomical phenomenon. Such a *magnetar* concept (see, e.g., [2, 3] and refs. therein) is strongly corroborated by numerous observations of soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs). Magnetic fields of strengths ranging up to hundred of *tera-tesla* might be developed due to the violent convection bringing magneto-rotational instabilities and/or dynamo-action. These fields can, in fact, modify the structure of atomic nuclei (see [4] and refs. therein) and give urgency to analyze possible magnetic effects in nuclide transformations [5 - 8]. Incorporating such field effects in an analysis of nuclear reaction network may provide more insights on neutron stars and supernovae, e.g., magnetodynamics at neutron star crusts formation.

In recent paper [7] the nucleosynthesis has been analyzed by employing a simplified model of ultramagnetized stellar media with completely polarized spin components of nuclear species. The statistics of spin distribution in nuclide formation at conditions of nuclear statistical equilibrium (NSE) is accounted for in ref. [8]. As is demonstrated the magnetic effects in the properties of atomic nuclei can, in fact, lead to significant change of nuclear composition of ultramagnetized astrophysical plasma when a maximum in the mass distribution of nuclides is replaced from the iron peak to the region of light nuclei approaching titanium. This is the result of magnetic modifications in nuclear shell structure shifting a bottom of fusion-fission valleys on the nuclear binding energy chart with the most tightly bound atomic nuclei from transition metals of iron series towards nuclides of smaller masses.

In this contribution we perform comparative analysis of nuclide creation in ultramagnetized astrophysical plasma, examine magnetic effects in nuclear reactions (on an example of n-capture process) and discuss some of consequences important for nuclear transmutations.

### 2. Nuclear composition of ultramagnetized stellar media

The NSE approximation in the theory of synthesis of chemical elements is used very successfully for the description of abundance of atomic nuclei with the greatest binding energy (i.e. transition metals of iron group and nearby nuclides) for over half a century. The magnetic field leads to an increase of nuclear reaction (transformation) rates [6] and, accordingly, to an acceleration of an establishment of statistical equilibrium. Therefore, as an initial step we suggested [7] to use such an approach to consider an influence of magnetic fields on nuclide formation processes in stars. The detailed description of NSE model is widely presented in the literature (see, e.g., [1], and [9] for comprehensive discussion of statistical models). Therefore, we stress here up just basic steps, amendments, modifications and additions to NSE due to presence of a magnetic field.

Statistical equilibrium represents a condition of entropy  $S$  extreme (i.e. zero change)

$$TdS = \sum_i \lambda_i dY_i = 0, \quad (1)$$

indicating, thereby, that an abundance of the  $i$  th nuclear particle  $Y_i$  at a temperature  $T$  is determined by the respective nucleon chemical potential  $\lambda_i$ .

The thermodynamic formalism based on implications of self-consistent mean field approach for an analysis of barion magnetism has been already described in [4, 5]. We just remind that at magnetic field strengths ( $H \leq 10^{14}$  T) considered here realistic description of a finite size nucleon aggregates can be achieved within the framework of a non-relativistic treatment. At temperatures ( $T \sim 10^{9.5}$  K) and field strengths less than ( $H \leq 10^{14}$  T) the effects associated with quantization of spatial motion for charged nucleons (i.e. the Landau levels) are washed out because of thermal fluctuations. Thus barion kinetic energy distribution can be assumed to correspond to an ideal gas. Moreover, the magnetic fields considered leave unchanged the conditions of  $\beta$ -equilibrium (i.e. charge composition) of astrophysical plasma (see [5] and refs. therein). Then the portion of chemical elements  $Y$  is mainly determined by binding energy  $B$  of corresponding atomic nuclei through the Saha equation (see [1])  $Y \propto \exp\{-B/T\}$ .

The magnetization of stellar media brings a sensitivity of nuclide creation processes to a projection of respective magnetic moment on the field direction. As is shown in ref. [7] for a case of complete spin polarization the interaction of the magnetic moments with a field results in some reduction of production volume for heavier elements in the region of average mass nuclei. Since the total commutative moment of the free nucleons making the nucleus exceeds the moment of this nucleus the interaction with a field effectively reduces the binding energy in greater degree for more massive nuclides. When accounting for thermal fluctuations of the spin projection on the field vector the dependence of relative output for nucleosynthesis products ( $y = Y(H)/Y(0)$ ) on magnetic field strength  $H$  is defined by a change of binding energy  $\Delta B = B(H) - B(0)$  in the field and magnetic components in the partition function  $G$ . With exponential accuracy this ratio can be written as

$$y \approx G_n^{-N} G_p^{-Z} G_i \exp\{\Delta B/kT\}. \quad (2)$$

Here the spin-magnetic part in the partition function is represented by  $G_i = \sum_M \exp\{g_i M \omega_L / kT\} / (2I_i + 1)$  and, respectively, is determined by an energy for an interaction of magnetic field with the magnetic moments of atomic nuclei  $i = {}^A_Z$  with spin  $I_i$ , free  $N$  neutrons and  $Z$  protons,  $g_{n(p,i)}$  gives  $g$ -factor of a neutron (proton, atomic nucleus), and  $\omega_L = \mu_N H$  with a nucleon magneton  $\mu_N$ . Two possible spin projections on a quantization axis for nucleons lead to relatively simple form  $G_N = \cosh[g_N \omega_L / 2kT]$ , while nucleon aggregates require explicit calculations.

### 2.1. Structure of magnetized nuclei

As is shown in refs. [4, 5] shell effects dominate for atomic nuclei at considered magnetic field strengths. We recall here, that within the Hartree self-consistent mean field approach the single-particle energy levels determine the shell corrections. Applications of the Nilsson model (see, e.g., [7]) is very successful in understanding of many properties of stable nuclei in the region of average mass numbers  $A \sim 10 - 100$ . Employing such a model one incorporates the harmonic oscillator (HO) spectrum of a frequency  $\omega_0 \approx 41/A^{1/3}$  MeV and accounts for the spin-orbit splitting of energy levels with a gap  $\eta_{so} \approx 0.12$  (in units  $\omega_0$ ).

Spin magnetization of Pauli type dominates for the neutron magnetic reactivity. Interaction of a field and the spin-magnetic moment corresponding to a spin projection  $m_n$  on a field vector gives rise to linear shift of energy levels  $\Delta = m_n g_n \omega_L$ . It results in a phase shift for a dependence of shell energy on neutron number [4, 5].

Magnetic response of protons is represented by a superposition of field interaction with spin and orbital magnetic moments [4, 5]. The presence of spin-orbit interaction results in abnormal dependence of proton shell correction energy on field strength. For instance, when the value of parameter  $h = \omega_L / \omega_0$  approaches the strength of spin-orbit interaction  $\eta_{so}$  the shell oscillation amplitude can increase up to a factor 5. Apparently, as seen in Fig. 1 total shell effect due to neutron and proton contributions at field strength  $h = 0.07$  results in the most bound nucleus of  ${}^{44}\text{Ti}$  as compared to other symmetric nuclei.

### 2.2. Synthesis of ultra magnetized atomic nuclei

As discussed above an influence of a magnetic field is determined by shell structure of nuclei. Thus, identifying magnetic field dependence of binding energy  $\Delta B(H)$  with a change of shell correction energy  $C$

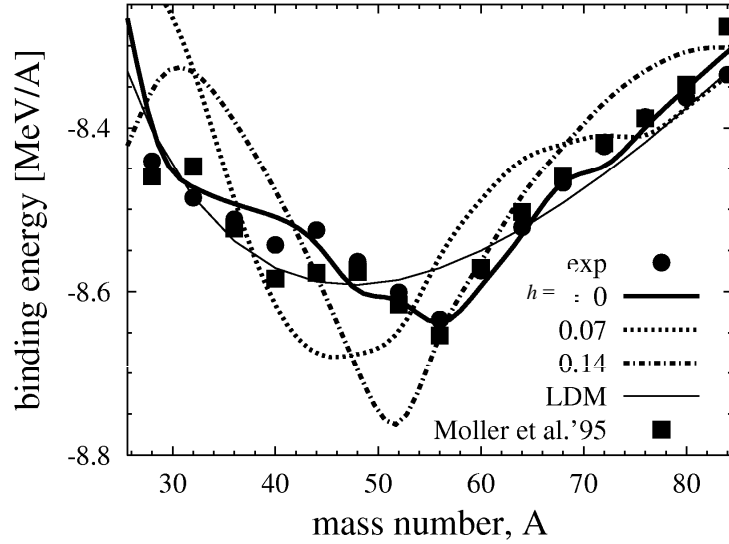


Fig. 1. Binding energy of even-even symmetric ( $N = Z = A/2$ ) nuclei in the iron region. Thin and thick solid lines represent results of liquid drop model (LDM) [10] without and with accounting for shell corrections. Circles and squares illustrate experimental data [10] and calculations by P. Moller et al. [11]. Dotted and dashed-dotted lines show the results when taking into account modification of shell corrections because of magnetic fields  $h = 0.07$  and  $0.14$ , accordingly.

(i.e.  $\Delta B \approx C(H) - C(0)$ ) and using Eq. (2) we examine some features of nuclide composition in ultra-magnetized astrophysical plasmas. The observations (see, e.g., [1] and refs. therein) suggest that NSE meet conditions of  $\beta$ -equilibrium with an equal amount of protons and neutrons (i.e.  $Y_e = 0.5$ ). Consequently, production of symmetric ( $N = Z$ ) nuclei prevails. Therefore we consider relative outputs of nucleosynthesis products on an example of  $^{56}\text{Ni}$  and  $^{44}\text{Ti}$ . It is worthy to notice here that relative abundance for this pair of nuclides, double magic and anti-magic in the Earth based laboratory, i.e. at a zero field, is often used for testing the supernova models. Apart from practical importance such a choice of symmetric atomic nuclei gives a transparent picture for an influence of magnetism on processes of formation of chemical elements with fundamental consequences on the nature of transmutation and synthesis of nuclides in superstrong magnetic fields.

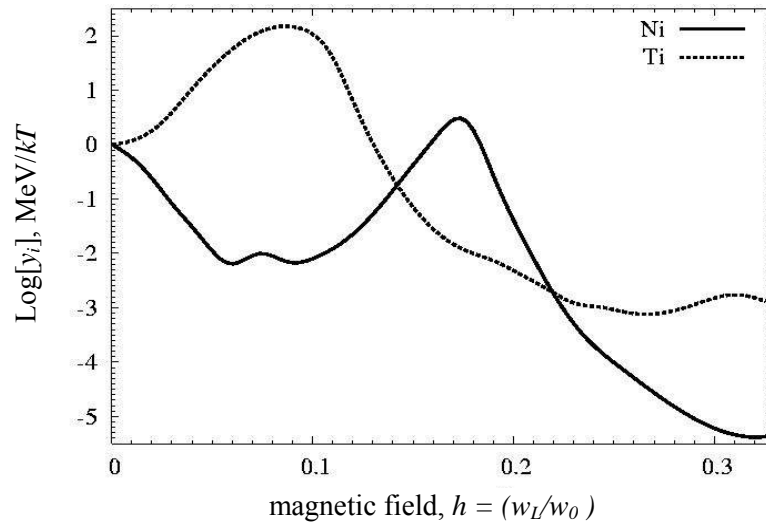


Fig. 2. Dependence on a magnetic field of relative yield  $y_i = (Y_i(H)/Y_i)$  for  $^{56}\text{Ni}$  (solid line) and  $^{44}\text{Ti}$  (dashed line) nucleosynthesis at NSE conditions.

As is evident from Fig. 2 oscillations of nuclide yields as a function of field strength represent perhaps the most interesting magnetic phenomenon. Change in the nuclear level structure caused by magnetic field results in rather different field dependence of relative abundance for  $^{56}\text{Ni}$  and  $^{44}\text{Ti}$ . Considering an increasing

strength  $H$  in the range of relatively “weak” fields the production of  $^{56}\text{Ni}$  is significantly suppressed, while the total volume of  $^{44}\text{Ti}$  grows. Such a behavior is connected with magic- anti-magic switching in nuclear shell structure in a variable magnetic field. For example, the slightly anti-magic in laboratory nucleus of  $^{44}\text{Ti}$  corresponds to growing binding energy at increasing field strength and becomes a magic nucleus at  $h = 0.07$ . At the same time for nucleus of  $^{56}\text{Ni}$ , double magic at the Earth conditions, the contribution of shell energy at such "weak" fields decreases. As a result an output of  $^{44}\text{Ti}$  considerably exceeds the yield of  $^{56}\text{Ni}$ .

### 3. Transmutations of ultramagnetized atomic nuclei under intensive neutron flux

The key quantity for an understanding of transmutations of atomic nuclei is represented by the rate of nuclear reaction  $X(x,o)O$

$$r = \int \sigma v dD_x dD_x. \quad (3)$$

Here the reaction cross section  $\sigma$  for nuclear particles  $x$  and  $X$  at relative velocity  $v$  is averaged over the density distribution  $dD_x$  (see above). In the vicinity of a neutron star (where ultrastrong magnetization can be met) the intense neutron flux gives rise to an importance of radiative  $n$ -capture process. For high enough density of neutrons ( $D_n/D_A \geq 10 - 20$ ) corresponding to the canonical  $r$ -process (see [1] and refs. Therein) the plasma reaches conditions of nuclear  $(\gamma, n) \rightleftharpoons (n, \gamma)$  equilibrium and the relation

$$r_A Y_A \approx \lambda_{A+1} Y_{A+1} \quad (4)$$

is met for all the nuclei  $^A Z$  in an isotopic chain with atomic number  $Z$ . Furthermore, the photo-disintegration rate  $\lambda$  is related to the reaction rate  $r$  by the detailed balance  $\lambda_{A+1}/r_A \sim \exp\{-(Q_{A,n} + E_M)/kT\}$  which in addition to the reaction  $Q$ -value (associated with the neutron separation energy) includes the magnetic energy  $E_M \sim -MH$  (see above). The relationship between these quantities defines, therefore, the  $r$ -process path of nuclear transmutations under intensive neutron flux in an ultramagnetized media. The nuclear magnetization suggests then an increasing portion of high spin states nuclei at an  $r$ -process.

The reaction rates Eq. (3) determine the speed for the creation of  $r$ -process nuclides. As discussed in ref. [6] the respective cross section can be well described within the Hauser-Feshbach statistical approach. While the neutron channel dominates the cross section can be expressed as  $\sigma \sim \Gamma/\kappa^2$ , through the neutron wave number  $\kappa$  and total width  $\Gamma$  for the  $\gamma$ -emission of compound nucleus. Consequently,  $\sigma \sim 1/v$  at the energies of astrophysical importance and the relative rate at a field  $H$  is given by respective ratio of the cross sections  $r(H)/r(0) = \sigma(H)/\sigma(0)$ . Accounting for predominant contribution of giant dipole resonance to the total  $\gamma$ -transition width (see, e.g., [6, 12]) we calculate the neutron radiative capture rate shown in Fig. 3.

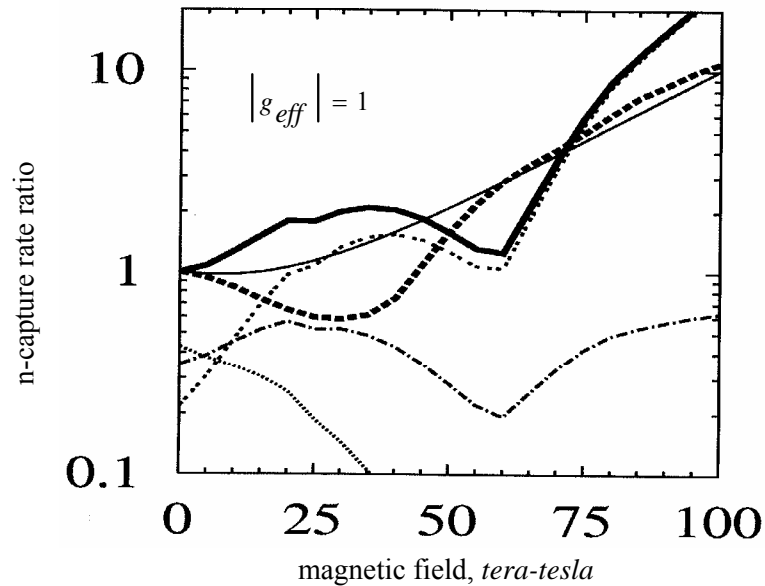


Fig. 3. The rate of radiative neutron capture versus magnetic field. Plotted are the normalized at zero-field total rate for  $^{56}\text{Ni}$  and  $^{44}\text{Ti}$  indicated by thick solid and thick dashed lines, while thin dotted, dashed-dotted and double-dotted lines represent the partial contributions of  $^{56}\text{Ni}$  states with spins 0, 1, and 2, respectively. The thin solid line show an effect of magnetic energy (see text).

We find considerable enhancement of n-capture process due to the magnetic contribution to Q-reaction value (cf., [6, 8], Eq. (4) and discussion therein). The shell effect introduces, however, oscillations on such an overall increase. This is due to the magnetic change in level spacing, which gives rise to considerably different rate ratios for  $^{56}\text{Ni}$  and  $^{44}\text{Ti}$  nuclei. For the case of product-nucleus  $^{56}\text{Ni}$ , with closed shell at vanishing field, n-capture process displays an extra enhancement, while for  $^{44}\text{Ti}$  the reaction can be suppressed at weak fields.

The magnetization redistributes also the spin-states in an out-channel. The largest contribution of zero-spin states at zero field sharply vanishes with increasing field strength, while the population of the highest allowed spin-states grows. In magnetic fields of large strengths such highest spin-states of final nuclei give predominant contribution to the total production rate because of large magnetic extra-energy in  $\gamma$ -channel.

#### 4. Conclusions

We have considered nuclear composition of stellar media at the superstrong magnetic fields predicted for supernovae and neutron stars. Magnetic replacement of magic numbers is found to represent perhaps the most interesting phenomena at NSE conditions. Such a replacement originates from a shift of single-particle levels due to magnetic field and essential influence on nuclear shell energy. As a result, magnetic shift of the most tightly bound atomic nuclei from transition metals of iron group towards the titanium results in exponential growth of  $^{44}\text{Ti}$  portion and, accordingly, excess of these products of nucleosynthesis over a yield of the  $^{56}\text{Ni}$  and, consequently, an output of  $^{56}\text{Fe}$ . We remind in these regards that the puzzling large abundance ratio ( $^{44}\text{Ti}/^{56}\text{Fe}$ ) is observed for a supernova remnant in the nebula Cassiopeia A [13, 14]. Several observational data [15] point to a magnetar scenario for an evolution of this object. Respectively, certain part of matter might be plausibly formed at the presence of ultra-strong magnetic fields. As seen above it leads to an overabundance of  $^{44}\text{Ti}$  as compared to a scenario with moderate magnetization, in the conjunction with observations.

We analyzed magnetic effects in neutron radiative capture representing a key nuclear reaction for transmutations of chemical elements exposed under an intensive neutron flux. Making use of arguments of the Hauser-Feshbach statistical model it is found for ultra-magnetized atomic nuclei that the plasma magnetization speeds the nuclear reactions up and leads to oscillations of n-capture rates around an overall acceleration. Such properties can give rise to magnetic shift of r-process path with increasing portion of heavy nuclides and high spin states. It is worthy to notice, finally, that nuclear reaction rates can be affected by some processes in ultra-magnetized stellar media, e.g., accompanying electronic excitations, cf. [16, 17].

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### **ОБРАЗОВАНИЕ И ТРАНСМУТАЦИЯ УЛЬТРАНАМАГНИЧЕННЫХ АТОМНЫХ ЯДЕР**

**В. Н. Кондратьев, И. Н. Каденко**

Нуклеосинтез в условиях ультра намагниченного вещества звезд исследован в предположении ядерного статистического равновесия и с учётом магнитных эффектов в структуре ядер. Установлено, что «пик железа» в распределении нуклидов по массе сильно изменяется из-за магнитного сдвига магических ядер. Такой сдвиг возникает из-за перераспределения уровней энергии нуклонов, что вызвано взаимодействием магнитных моментов с полем. Трансмутация атомных ядер в астрофизической плазме при интенсивном потоке нейтронов рассмотрена, учитывая радиационный захват нейтронов ультра намагниченными атомными ядрами. Обсуждены приложения магнитных эффектов к г-процессам.

### **УТВОРЕННЯ ТА ТРАНСМУТАЦІЯ УЛЬТРАНАМАГНІЧЕНИХ АТОМНИХ ЯДЕР**

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Нуклеосинтез в умовах ультра намагніченої речовини зірок досліджено в припущенні ядерної статистичної рівноваги й з огляду на магнітні ефекти в структурі ядер. Установлено, що «пік заліза» в розподілі нуклідів по масі сильно змінюється через магнітний зсув магічних ядер. Такий зсув виникає через перерозподіл рівнів енергії нуклонів, що викликано взаємодією магнітних моментів з полем. Трансмутацію атомних ядер в астрофізичній плазмі при інтенсивному потоці нейтронів розглянуто, з огляду на радіаційний захват нейтронів ультра намагніченими атомними ядрами. Обговорюються додатки магнітних ефектів до г-процесів.