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Nuclear magics at explosive magnetization

V. N. Kondratyev

Physics Department, Taras Shevchenko National University of Kiev, 03022-UA Kiev, Ukraine
Bogolubov LTP, JINR, 141980, Dubna, Russia

Abstract

Effects of ultra-strong magnetization in creation of iron group nuclides are considered by employing arguments of nuclear statistical equilibrium. Nuclear magnetic reactivity is demonstrated to enhance the portion of titanium product due to magnetic modification of nuclear structure. The results are corroborated with an excess of ^{44}Ti revealed from the Integral mission data.

1 Introduction

Ultrastrong magnetic fields exceeding *teratesla* (TT) arise at core-collapse supernovae (SNe) [1, 2] and in heavy ion collisions [3]. Nuclides produced in such processes contain an information on matter structure and explosion mechanisms. In this contribution we analyze possibilities for using radionuclides to probe internal regions of respective sites. Magnetization of hot dense matter makes plausible explosion mechanism and can leave its trace at nucleosynthesis [1, 2]. Such fields (i.e., larger than 0.1 TT) can modify the structure and properties of atomic nuclei (see. [1, 2, 4–6] and refs. therein), that requires to consider a possible influence of magnetism on structure, transformation and transmutation of radionuclides. Employing relevant data in analyses of nucleosynthesis and nuclear reaction chains may provide more detailed information as on dynamics and mechanism of supernova (SN) explosions as on heavy ion collisions.

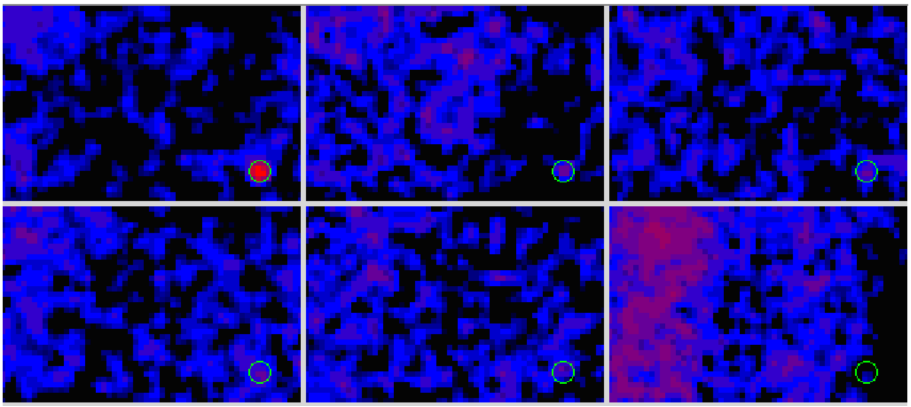

Figure 1: Direction (pixel number) dependence of the registered gamma-ray flux at different energy ranges; top: left - 20 − 50 keV, middle - 50 − 67 keV, right - 67 − 70 keV, bottom: left - 70 − 77 keV; middle −77 − 82 keV, right - 82 −− 100 keV; for the Cassiopeia region. SNR CAS A, (J2000) R.A. 350.86^o, decl. 58.81^o, indicated by circle.

In present study we demonstrate that the magnetic effects in the nuclear binding energy lead to an increase of the titanium portion in a synthesis of nuclides of mass numbers close to the iron "peak". Consequently, the characteristic lines of respective nuclei in spectra of astrophysical objects are considerably strengthened and become noticeable allowing for an analysis of synthesized elements. The radioactive decay chain ^{44}Ti→ ^{44}Sc→ ^{44}Ca gives rise to an emission of lines with energies of 67.9 keV and 78.4 keV (from ^{44}Sc*) and 1157 keV (from ^{44}Ca*) of approximately equal intensity. The respective image-mosaics from Integral data (e.g., [1, 2]) for the Cassiopeia region in various energy ranges of registered photons are presented in Fig. 1. The color (brightness) is proportional to the gamma-quanta flux: as larger the flux as lighter (brighter) the color of a pixel. As is seen the SNR CAS A gives the brightest spot for energies matching ^{44}Sc lines,

Then ^{44}Ti half-life, about 60 years, allows to determine this isotope initial mass in SN remnants. Table. 1 shows the observational results for the total mass of ^{44}Ti nuclide synthesized in SN explosions [6]. These values are significantly larger as compared to model predictions, see. [7], giving the mass of initially synthesized ^{44}Ti, $M_{\rm Ti} \sim 10^{-5} M_{\rm Sun}$ (in solar masses $M_{\rm Sun}$) in an absence of magnetic effects.

Table 1: Volume $M_{\rm Ti}$ of nuclides ^{44}Ti (in solar masses $M_{\rm Sun}$) initially synthesized in young SNe, CAS A and SN1987A, see [6] and refs. therein.

SN	$M_{\rm Ti}/10^{-5}M_{\rm Sun}$
CAS A	$3.3^{+0.9}_{-0.7}$
SN1987A	3.1 ± 0.8

2 Nucleosynthesis in strong magnetic field

The nuclear statistical equilibrium (NSE) approach is used very successfully for a description of abundances of iron group and nearby nuclides for over half a century, cf. [1, 2, 6, 7]. We briefly recall that at NSE conditions abundance of i-th nuclear particle Y_i (e.g., nucleons, nuclei, electrons) at a temperature T is determined by the respective chemical potential from the condition of entropy S extremum. At considered parameters of magnetized matter, i.e. magnetic field strengths H <100 TT, the yield Y_i of atomic nucleus i is mainly determined by corresponding binding energy B_i as: $Y_i \approx \exp\{-B_i/kT\}$, [6, 7], for more extended discussion of statistical models see [8]. The magnetization brings, however, a sensitivity of nuclide creation processes to a projection of respective magnetic moments on the field direction. When accounting for thermal fluctuations of the spin projection on the field vector in corresponding magnetic components of the partition function G, the dependence of the relative output for nucleosynthesis products ($y = Y(H)/Y(0)$) on the magnetic field strength H with statistical accuracy can be written as

$$y \simeq G_{\rm n}^{-N} G_{\rm p}^{-Z} G_i \exp\{\Delta B/kT\}. \qquad (1)$$

Here the spin-magnetic part in the partition function is represented by $G_i = \sum_M \exp\{g_i M \omega_{\rm L}/kT\}/(2I_i + 1)$ and is determined by the energy for an interaction of the magnetic field with magnetic moments of atomic nuclei $i =^A_N Z$ with spin I_i, free N neutrons and Z protons, $g_{n(p,i)}$ gives the g-factor of a neutron (proton, atomic nucleus), and $\omega_{\rm L} = \mu_{\rm N} H$ with nucleon magneton $\mu_{\rm N}$. At conditions $\omega_{\rm L} \gg kT$ Eq. (1) is reduced to simplified exponential limit [1, 2].

Since magnetic effects are determined by nuclear shell structure [1,2,4–6] we identify magnetic field dependence of binding energy $B(H)$ with a change of shell correction energy C (i.e. $\Delta B(H) = C(H) - C(0)$). Employing the Nilsson model with harmonic oscillator (HO) spectrum of a frequency $\omega_0 = 41/A^{1/3}$ MeV and using Eq. (1) we examine features of nuclide composition in ultra-magnetized matter. As is seen in Fig. 2 the nuclide relative

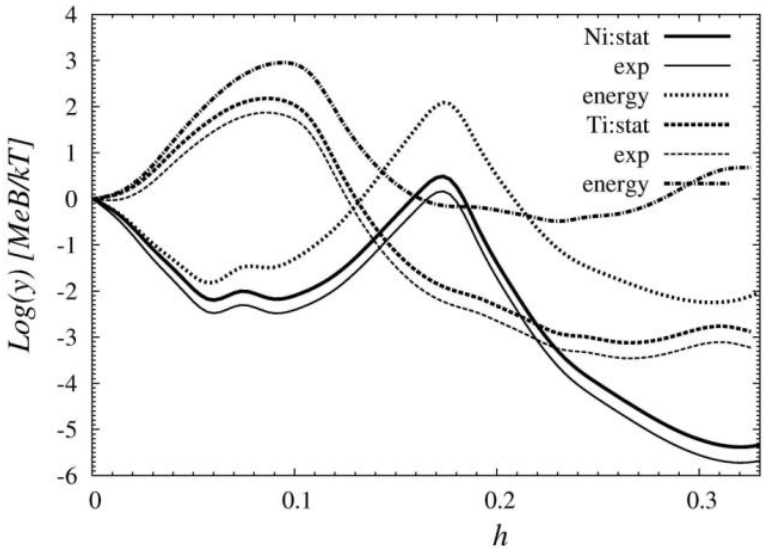

Figure 2: Magnetic field dependence ($h = \omega_L/\omega_0$) of relative yield for ^{56}Ni and ^{44}Ti. Statistical accuracy given by Eq. (1) is indicated by notation *stat*, *exp* denotes exponential limit, and *energy* corresponds to an effect of binding energy.

yields display oscillations as a function of field strength. The production of Ti grows and Ni is reduced with increasing magnetization at small field strengths where various approximations give very similar results.

3 Conclusion

Creation of atomic nuclei at conditions of nuclear statistical equilibrium is investigated for the ultra-magnetized matter. For iron group nuclides the magnetic modification of nuclear structure shifts a maximum of nucleosynthesis products towards smaller mass numbers approaching titanium. Magnetic effects in nucleosynthesis are favorably compared to observational Integral data. However, detail comparison requires accounting for realistic field geometry [6]. Thermal effects can also affect structural and collective properties of atomic nuclei at high temperatures, see [9]. Finally, we notice that similar magnetic effects in atomic clusters [10] will also lead to a shift of electronic magic numbers and change the mass distribution.

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