EXPLOSIVE NUCLEOSYNTHESIS AT STRONG STELLAR MAGNETIZATION

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ABSTRACT. Synthesis of iron group nuclides is considered for the ultra-magnetized astrophysical plasma in supernovae. Magnetic modification of nuclear structure is shown to shift maximum of nucleosynthesis products towards smaller mass numbers enhancing titanium yield. The results are corroborated with an excess of ^{44}Ti revealed from the INTEGRAL mission data for yang supernova remnants at a field strength ranging up to 10 teratesla.

Keywords: Stars: supernovae, magnetic field. – Nucleosynthesis: abundances.

1. Introduction

Supernovae (SN) represent promising candidates for synthesis of heavy atomic nuclei and renewing other nuclear components. 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 plasma makes plausible explosion mechanism and can leave its trace at nucleosynthesis (cf., e.g., (Kondratyev, 2012; 2014) and refs.therein). We reveal radiatioactivity and volume of ^{44}Ti in SN remnant (SNR) Cassiopeia A (CAS A) and SN1987A from the INTEGRAL data. The observational data are compared to theoretical predictions while accounting for an influence of astrophysical environment on creation and decay of ^{44}Ti in SNR.

2. Radionuclides probing the explosion active region

Radioactive nuclides synthesized at SN events provide an opportunity to probe the interior active nuclear reaction regions. Created at the SN explosions radioisotopes can be observed by registration of characteristic gamma-lines, accompanying their radioactive transitions. The decay chain $^{44}\mathrm{Ti} \rightarrow {}^{44}\mathrm{Sc} \rightarrow {}^{44}\mathrm{Ca}$ gives rise to the emission of lines with energies 67.9 keV and 78.4 keV (from ^{44}Sc*) and 1157 keV (from ^{44}Ca*) of approximately the same intensity. The ^{44}Ti half-life period of about 60 years allows to evaluate the mass of this isotope in SNR.

We analyze the data obtained by the INTEGRAL IBIS/ISGRI and SPI detector systems. As is described, e.g., by Kondratyev (2012) we analyze the Sciences Windows (scw) of type pointing from catalog VIRGO (http://virgo.bitp.kiev.ua). Here we discuss further results from processing of extended data sets accumulated during a period from 2002 to 2012. The total effective exposure time is about 1.5 Ms. The respective image-mosaics for vicinity of SNR CAS A 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 brighter (lighter) the color of a pixel. For the first range the confidence level (i.e., ratio signal/noise) reaches the level of 40, for other energy intervals it exceeds 5 indicating reliable registration. As discussed, see (Kondratyev, 2004a; 2012; 2014) and refs therein, respective energy spectra display peaks at energies 67.9 and 78.4 keV, i.e. characteristic lines of ^{44}Sc, with total flux 10^{-4} photons/cm^2/s.

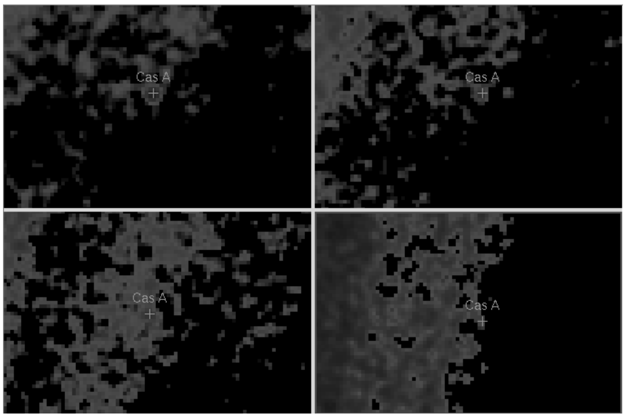

Figure 1: Direction (pixel number) dependence of the registered gamma-ray flux at different energy ranges. top: left – 20–62 keV, right – 62–72 keV, bottom: left – 72–82 keV; right – 82-100 keV; for vicinity of SNR CAS A, (J2000) R.A. 350.86°, decl. 58.81°, indicated by cross.

The corresponding flux of ^{44}Ca characteristic line revealed from INTEGRAL SPI detector system data is 0.5×10^{-4} photons/cm^2/s (Kondratyev, 2012a) displaying, thereby, very good agreement with ^{44}Sc results.

Table 1. ^{44}Ti initial mass M_{Ti}, in Solar masses M_{Sun}, for young Type II SNe.

SNR	$M_{\mathrm{Ti}}[10^{-4}\,M_{\mathrm{Sun}}]$
CAS A	$(3.3^{+0.9}_{-0.7})$
SN1987A	3.1 ± 0.8

Accounting for a distance to SN CAS A, half-life time of isotope and an averaged over lines isotropic emission of gamma-radiation we get a mass of initially synthesized ^{44}Ti at SN explosion. Table 1 compares the results with the one obtained by Grebenev et al. (2012) for SN1987A. The values show good agreement and exceed considerably predictions of SN models without magnetic effects. It is worthy to notice here that such a trend is met for other objects (cf., (Magkotsios et al., 2010) and refs. therein), as well.

3. Explosive synthesis of magnetized nuclei

The nuclear statistical equilibrium (NSE) approach is used very successfully for a description of abundance of iron group and nearby nuclides for over half a century, cf. (Kondratyev, 2004, 2012, 2014). 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 SN plasma, i.e. magnetic field strengths $H < 100$ teratesla, the yield Y_i of atomic nucleus i is mainly determined by corresponding binding energy B_i as: $Y_i \sim \exp\{-B_i/kT\}$. Respectively, 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 $\Delta B(H)$ in a field.. The normalized yield ratio $[i/j] = y_i/y_j$ with exponential accuracy can be written as

$$[i/j]\,(H) \sim \exp\{(\Delta B_j - \Delta B_i)/kT\}. \qquad (1)$$

Since magnetic effects are determined by nuclear shell structure (Kondratyev, 2002; 2004; 2012; 2014) we identify magnetic field dependence of binding energy $\Delta B(H)$ with a change of shell correction energy C (i.e. $\Delta B(H) = C(H) - C(0)$) and use Eq. (1) to examine features of nuclide composition in ultra-magnetized astrophysical plasmas. As is shown in Fig. 2 the often considered yield ratio [Ti/Ni] displays oscillations as a function of field strength due to magic-antimagic switching in nuclear structure. At weak fields the portion of Ti grows in conjuction with observations.

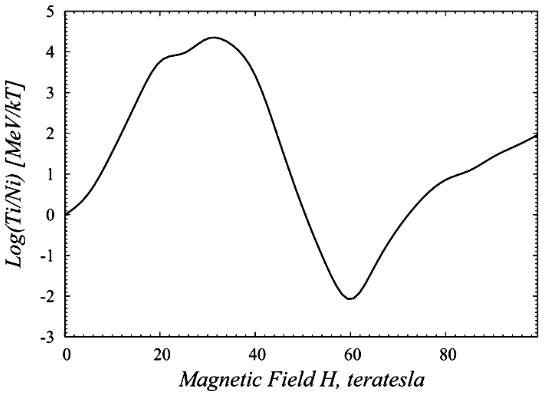

Figure 2: Magnetic field dependence of yield ratio ^{56}Ni and ^{44}Ti.

As can be seen in Fig. 2, at a typical freezing temperature of 0.1 MeV, for a formation of atomic nuclei at an expansion of nuclear matter in a jet at large entropy, magnetic effects can enhance up to an order of magnitude the yield of an isotope ^{44}Ti at a field strength from 1 to 10 teratesla. We remark that such a field ensures (Kondratyev, 2014) noticeable contribution of magnetic energy within shock wave front to total energy associated with blowing up the star material. Furthermore, magnetic pressure radial gradient is comparable with gravitational force, i.e., $dH_n^2/dR \sim 8\pi\, GM\, n(R)/R^2$, where M denotes the mass within neutrino sphere of radius R, with respective stellar matter density $n(R)$, and gravitational constant G.

4. Conclusion

We investigated an effect of the ultra-magnetized astrophysical plasma in supernovae on synthesis of chemical elements at conditions of nuclear statistical equilibrium. For iron group nuclides the magnetic modification of nuclear structure shifts a maximum of nucleosynthesis products towards smaller mass numbers approaching titanium. Direct signals of ^{44}Ti radioactive decay in the gamma-spectra and volume of the isotope in supernova remnants Cassiopeia A and SN1987A revealed from the INTEGRAL IBIS/ISGRI and SPI observational data are analyzed. Magnetic effects in nucleosynthesis are favorably compared to observational results at a field strength achieving 10 teratesla.

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