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^{60}Fe and Massive Stars

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Abstract. Gamma-ray line emission from radioactive decay of ^{60}Fe provides constraints on nucleosynthesis in massive stars and supernovae. We detect the γ-ray lines from ^{60}Fe decay at 1173 and 1333 keV using three years of data from the spectrometer SPI on board *INTEGRAL*. The average flux per line is $(4.4 \pm 0.9) \times 10^{-5}$ ph cm^{-2}s^{-1} rad^{-1} for the inner Galaxy region. Deriving the Galactic ^{26}Al gamma-ray line flux with using the same set of observations and analysis method, we determine the flux ratio of ^{60}Fe/^{26}Al gamma-rays as 0.15 ± 0.05. We discuss the implications of these results for the widely-held hypothesis that ^{60}Fe is synthesized in core-collapse supernovae, and also for the closely-related question of the precise origin of ^{26}Al in massive stars.

Keywords. ISM: abundances, nucleosynthesis

1. Introduction

The radioactive isotope ^{60}Fe is believed to be synthesized through successive neutron captures on Fe isotopes (e.g., ^{56}Fe) in a neutron-rich environment inside He burning shells in AGB stars (^{60}Fe is stored in white dwarfs and cannot be ejected) and massive stars, before or during their final evolution to core collapse supernovae (CCSN). ^{60}Fe can be also synthesized in Type Ia SNe (Woosley 1997). It is also destroyed by the ^{60}Fe (n, γ) process. Since its closest parent, ^{59}Fe is unstable, the ^{59}Fe(n, γ) process must compete with the ^{59}Fe(γ^{-}) decay to produce an appreciate amount of ^{60}Fe .

The decay chains of ^{60}Fe are shown in Figure 1. ^{60}Fe firstly decays to ^{60}Co, with emitting γ-ray photons at 59 keV, and then decays to ^{60}Ni, with emitting γ-ray photons at 1173 and 1333 keV. The gamma-ray efficiency of the 59 keV transition is only $\sim 2\%$ of those at 1173 and 1333 keV, so the gamma-ray flux at 59 keV is much lower than the fluxes of the high energy lines. The 59 keV gamma-ray line is very difficult to be detected with present missions. Measurements of the two high energy lines have been the main scientific target to study the radioactive ^{60}Fe isotope in the Galaxy.

^{60}Fe has been found to be part of meteorites formed in the early solar system (Shukolyukov *et al.* 1993). The inferred ^{60}Fe /^{56}Fe ratio for these meteorites exceeded the interstellar-medium estimates from nucleosynthesis models, which led to suggestion that the late supernova ejection of ^{60}Fe occurred before formation of the solar system (Tachibana *et al.* 2006). Yet, this is a proof for cosmic ^{60}Fe production, accelerator-mass spectroscopy of seafloor crust material from the southern Pacific ocean has revealed an ^{60}Fe excess in a crust depth corresponding to an age of 2.8 Myr (Knie *et al.* 2004). From this interesting measurement, it is concluded that a supernova explosion event near the solar system occurred about 3 Myr ago, depositing some of its debris directly in the earth's atmosphere. All these measurements based on material samples demonstrate that ^{60}Fe necleosynthesis does occur in nature. It is now interesting to search for current ^{60}Fe production in the Galaxy through detecting radioactive-decay γ-ray lines.

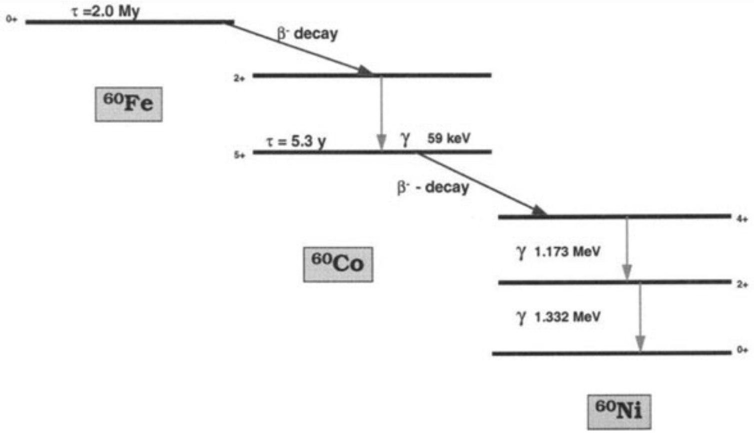

Figure 1. The decay scheme of ^{60}Fe . The mean lifetime is 2×10^6 years. The gamma-ray flux at 59 kev line is $\sim 2\%$ of those at 1173 and 1333 keV.

2. ^{60}Fe emission in the Galaxy

Due to its long decay time ($\tau \simeq$2.2 My), ^{60}Fe survives to be detected after the supernova ejected it into the interstellar medium, by β-decay via ^{60}Co and γ emission at 1173 keV and 1333 keV – like other radioactive isotopes: ^{44}Ti, ^{56,57}Co, and ^{26}Al. These isotopes provide evidence that nucleosynthesis is ongoing in the Galaxy (The *et al.* 2006; Diehl *et al.* 2006). Specially, measurements of ^{60}Fe promise to provide new information about the massive star nucleosynthesis in the late pre-supernova stages.

Gamma-ray signal of ^{60}Fe from the sky is very weak, so there are no confident detections of ^{60}Fe in the Galaxy reported in the previous measurements. Recently, RHESSI reported observations of the gamma-ray lines from ^{60}Fe with an average flux of $(6.3 \pm 5.0) \times 10^{-5}$ph cm^{-2} s^{-1} (Smith 2004).

Now, the spectrometer aboard INTEGRAL (SPI) operates on space. The *INTE*rnational *G*amma-*R*ay *A*strophysics *L*aboratory (INTEGRAL) is an European (ESA) Gamma-Ray Observatory Satellite Mission for the study of cosmic gamma-ray sources in the keV to MeV energy range (Winkler *et al.* 2003). INTEGRAL was successfully launched from Baikonur Cosmodrome (Kazakhstan) on October 17, 2002. The INTEGRAL orbit is eccentric, with an apogee of 153 000 km, a perigee of 9000 km, and a 3 day period. INTEGRAL will continue to work until 2012 approved by ESA. SPI/INTEGRAL consists of 19 high purity germanium detectors which allow for high spectral resolution of $\sim$ 2.5 keV at 1 MeV, suitable for astrophysical studies of individual gamma-ray lines and their shapes, e.g. the 511 keV line, γ-ray lines from radioactivities of ^{44}Ti, ^{26}Al and ^{60}Fe . The basic measurement of SPI consists of event messages per photon triggering the Ge detector camera. We distinguish events which trigger a single Ge detector element only (*single event*, SE), and events which trigger more than two Ge detector elements nearly simultaneously (*multiple event*, ME).

We analyzed the first year of INTEGRAL data to detect the γ-ray lines from ^{60}Fe with an average line flux of $(3.7 \pm 1.1) \times 10^{-5}$ph cm^{-2} s^{-1} (Harris *et al.* 2005). But the strong background lines near ^{60}Fe lines still contaminate the spectra, which makes this preliminary results questionable. At present, we use three years of INTEGRAL data (from 2003.3 – 2006.3), aiming at a consolidation of the INTEGRAL/SPI measurement of ^{60}Fe gamma-rays.

The newest results on ^{60}Fe gamma-ray lines by INTEGRAL/SPI are presented in Figure 2. All the fluxes given by different databases are consistent with each other. The

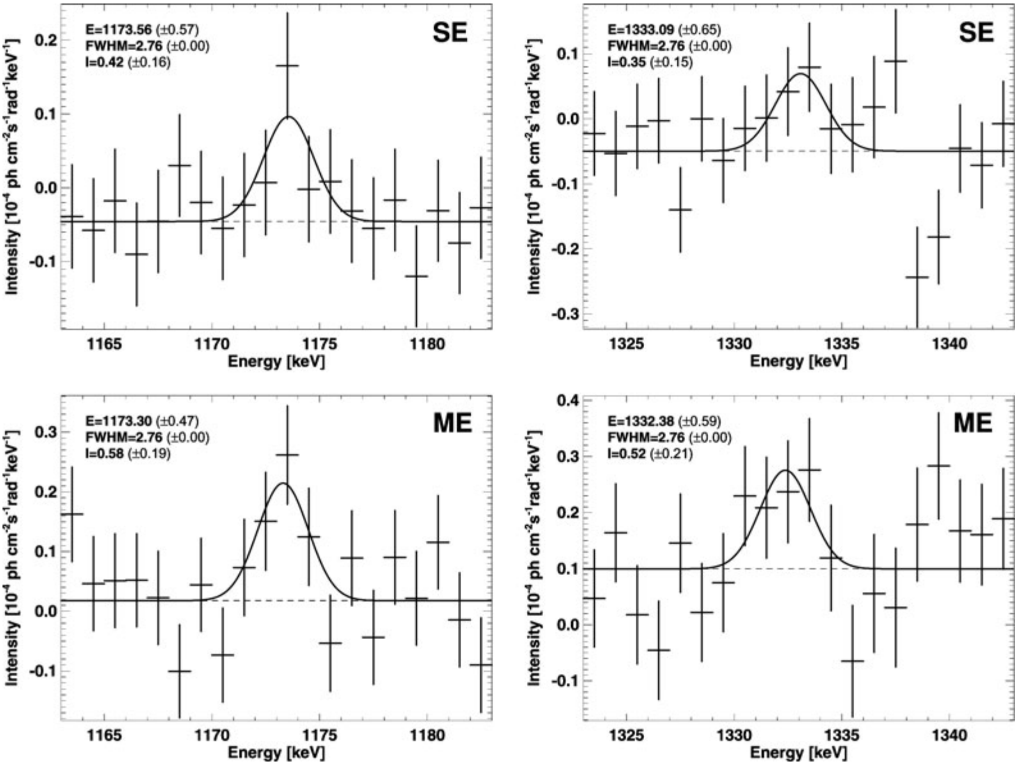

Figure 2. The spectra of two gamma-ray lines of ^{60}Fe from the inner Galaxy: 1173 keV and 1333 keV. We have shown the results both from SE and ME databases. For the SE database, we find a line flux of $(4.2 \pm 1.6) \times 10^{-5}$ph cm^{-2} s^{-1} rad^{-1} for the 1173 keV line and $(3.5 \pm 1.5) \times 10^{-5}$ph cm^{-2} s^{-1} rad^{-1} for the 1333 keV line. For the ME database, the line flux is $(5.8 \pm 1.9) \times 10^{-5}$ph cm^{-2} s^{-1} rad^{-1} for the 1173 keV line and $(5.2 \pm 2.1) \times 10^{-5}$ph cm^{-2} s^{-1} rad^{-1} for the 1333 keV line.

strong background line at 1337 keV has also been eliminated rather well. Furthermore, a superposition of the four spectra of Figure 2 is shown in Figure 3. The line flux estimated from the combined spectrum is $(4.4 \pm 0.9) \times 10^{-5}$ph cm^{-2} s^{-1} rad^{-1}. Our significance estimate for the combined spectrum is $\sim 5\sigma$ (Wang *et al.* 2007).

3. The ratio of ^{60}Fe /^{26}Al

^{26}Al is an unstable isotope with a mean lifetime of 1.04 Myr. ^{26}Al can first decay into an excited state of ^{26}Mg, which de-excites into the Mg ground state by emitting gamma-ray photons with the characteristic energy of 1809 keV . ^{26}Al is produced almost exclusively by proton capture on ^{25}Mg in a sufficiently hot environment. ^{26}Al origin is dominated by massive star and core-collapse supernovae, and small part of ^{26}Al is attributed to AGB stars and novae.

Therefore, ^{26}Al and ^{60}Fe would share at least some of the same production sites, i.e. massive stars and supernovae. In addition both are long-lived radioactive isotopes, so we believe their gamma-ray distributions are similar as well. We derive the ratio of ^{60}Fe /^{26}Al , which can be directly compared with theoretical predictions.

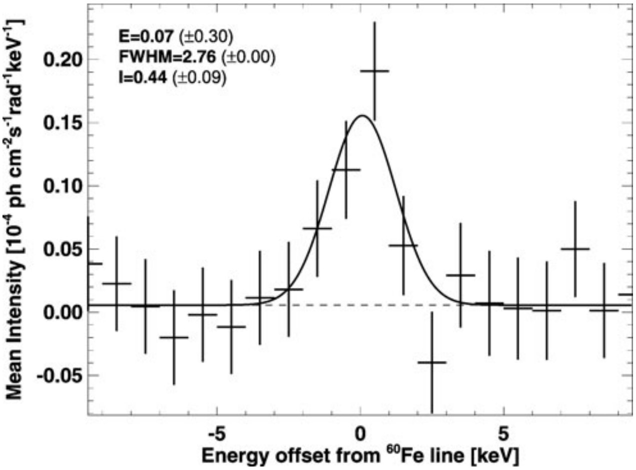

Figure 3. The combined spectrum of the ^{60}Fe signal in the inner Galaxy, superimposing the four spectra of Figure 2. In the laboratory, the line energies are 1173.23 and 1332.49 keV; here superimposed bins are zero at 1173 and 1333 keV. We find a detection significance of 5σ. The average line flux is estimated as $(4.4 \pm 0.9) \times 10^{-5}$ph cm^{-2} s^{-1} rad^{-1}.

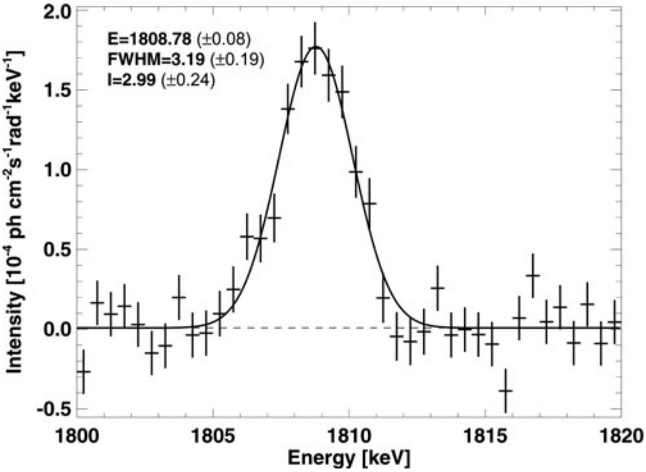

Figure 4. ^{26}Al spectrum derived by INTEGRAL/SPI with 3 years of data. ^{26}Al flux in the Galaxy is $(2.99 \pm 0.24) \times 10^{-4}$ph cm^{-2} s^{-1} rad^{-1}.

We also obtain the ^{26}Al spectrum in the Galaxy using three years of INTEGRAL data which is shown in Figure 4. ^{26}Al flux is $(2.99{\pm}0.24){\times}10^{-4}$ph cm^{-2} s^{-1} rad^{-1}. Combining the ^{60}Fe result in Figure 3, we find a flux ratio of ^{60}Fe /^{26}Al of $15 \pm 5)$%.

Many experiments and efforts were made to measure the ^{60}Fe/^{26}Al flux ratio, and we now provide the most significant detection to date (see Table1 and Figure 5). In the same time, different theoretical models have predicted the ratio of ^{60}Fe/^{26}Al. Timmes *et al.* (1995) published the first detailed theoretical prediction. In their paper, they combined a model for ^{26}Al and ^{60}Fe nucleosynthesis in supernova explosions with a model of chemical evolution, giving a gamma-ray flux ratio $F(^{60}\mathrm{Fe})/F(^{26}\mathrm{Al}) = 0.16 \pm 0.12$. Since 2002, theoreticians have improved various aspects of the stellar-evolution models, including improved stellar wind models and the corresponding mass loss effects on stellar structure and evolution, of mixing effects from rotation, and also updated nuclear cross sections

Table 1. Different measurements of ^{60}Fe/^{26}Al flux ratio

Experiments	$F(^{60}\mathrm{Fe})/F(^{26}\mathrm{Al})$	references
HEAO-3	0.09 ± 0.08	Mahoney *et al.* 1982
SMM	0.1 ± 0.08	Leising & Share 1994
OSSE	0.21 ± 0.15	Harris *et al.* 1997
COMPTEL	0.17 ± 0.135	Diehl *et al.* 1997
GRIS	$< 0.14(2\sigma)$	Naya *et al.* 1998
RHESSI	0.16 ± 0.13	Smith 2004
SPI	0.15 ± 0.5	this work

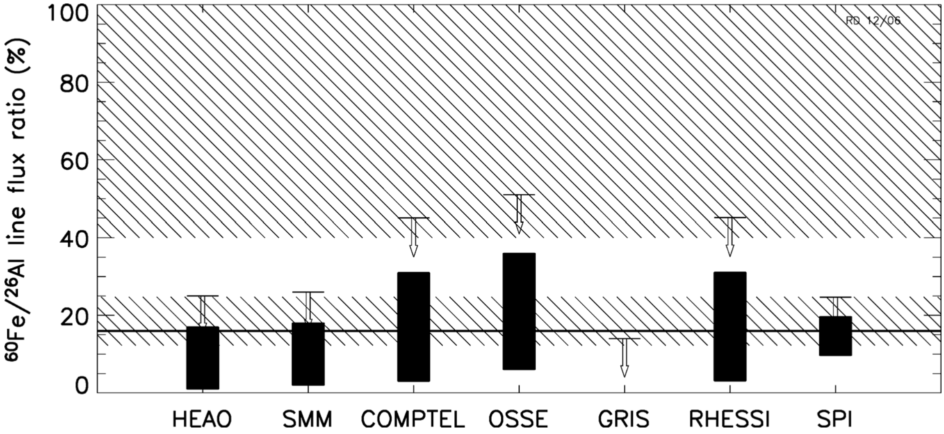

Figure 5. Flux ratio of the gamma-ray lines from the two long-lived radioactive isotopes ^{60}Fe/^{26}Al from several observations, including our SPI result (also see Table 1, from Wang *et al.* 2007), with upper limits shown at 2σ for all reported values, and comparison with the recent theoretical estimates (the upper hatched region from Prantzos 2004; the straight line taken from Timmes *et al.* 1995; the lower hatched region, see Limongi & Chieffi 2006). Our present work finds the line flux ratio to be $(15 \pm 5)\%$. See more details in the text.

in the nucleosynthesis parts of the models. As a result, predicted flux ratios ^{60}Fe/ ^{26}Al rather fell into the range 0.8 ± 0.4 (Prantzos 2004, based on, e.g. Rauscher *et al.* 2002, Limongi & Chieffi 2003) – such high values would be inconsistent with several observational limits and our SPI result. Limongi & Chieffi (2006) combined their individual yields, using a standard stellar-mass distribution function, to produce an estimate of the ^{60}Fe/ ^{26}Al gamma-ray flux ratio expected from massive stars. Their calculations yield a lower prediction for the ^{60}Fe/ ^{26}Al flux ratio of 0.185 ± 0.0625, which is again consistent with the observational constraints.

4. Summary and discussion

Now, we have detected both 1173 keV and 1332 keV lines of ^{60}Fe in the Galaxy (near 5 σ significance) with the 3 years of SPI/INTEGRAL data, which is the best results on detections of ^{60}Fe in the Galaxy, and confirms its existence. The average ^{60}Fe line flux from the inner Galaxy region is $(4.4 \pm 0.9) \times 10^{-5}$ph cm^{-2} s^{-1} rad^{-1}. From the same observations and analysis procedure applied to ^{26}Al, we find a flux ratio of ^{60}Fe/ ^{26}Al of $(15 \pm 5.0)\%$.

Though large error bars and uncertainties exist, the original and the latest theoretical prediction of the flux ratio of ^{60}Fe/ ^{26}Al are consistent with our SPI result. But improvements are needed both in observations and theories. For gamma-ray astronomy, more precise measurements of gamma-ray lines in the Galaxy are required, especially for the ^{60}Fe signals, which may require the more SPI data and the development of next-generation gamma-ray spectrometers/telescopes. Stellar evolution models have potential for improvements in processes related to the production of ^{60}Fe and ^{26}Al, e.g. convective layers in the inner stars, wind models for WR and O stars and the possible effects of stellar rotation (Hirschi *et al.* 2004). The nuclear physics still has serious uncertainties for the productions of ^{26}Al and ^{60}Fe. For example, the cross section of $^{12}\mathrm{C}(\alpha,\gamma)^{16}\mathrm{O}$ is uncertain, which affects the prediction of both ^{26}Al and ^{60}Fe; the situation of ^{60}Fe is strongly influenced by the cross sections of neutron capture and β-decay which are purely theoretical: no experimental data exist for the $^{59}\mathrm{Fe}(n,\gamma)$ and $^{60}\mathrm{Fe}(n,\gamma)$ rates. Therefore, a concerted effort among stellar models, nucleosynthesis theory, and gamma-ray observations is required for a more satisfactory assessment of ^{60}Fe synthesis in the Galaxy.

Acknowledgements

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