Nuclear $\gamma$-ray line emission induced by energetic ions in solar flares and by galactic cosmic rays

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Abstract. The $\gamma$-ray spectra of the strongest solar flares often show a broad and complex structure in the 0.1-10 MeV region sitting on a bremsstrahlung continuum. This structure is composed of several outstanding narrow lines and of thousands of unresolved narrow and broad lines forming a quasi-continuum. The major part of this emission is due to prompt deexcitation lines following nuclear interactions of accelerated light and heavy ions with the atomic nuclei composing the solar atmosphere. A similar emission is expected from interactions of galactic cosmic rays with the interstellar gas and dust. Experimental nuclear reaction studies coupled with extensive calculations have been done in the last one and a half decade at Orsay for the modelling of this $\gamma$-ray emission. After a description of the nuclear reaction studies the analysis of one solar flare spectrum and predictions for the emission from the inner Galaxy will be presented.

1. Introduction

Nuclear $\gamma$-ray line emission from astrophysical sources is a potentially very rich source of information about energetic particle populations and the interacting medium. The different line intensities depend of course on the abundances of the ambient nuclei, but also on the composition and spectra of the energetic particles. Furthermore, most lines from astrophysical sources are Doppler broadened because the ambient media like the solar atmosphere and the interstellar gas have very low densities such that the recoiling nuclei emit almost always in flight. The line shapes may then add another piece of information on the energetic particle properties.

It appears that only lines from interactions of protons and $\alpha$-particles with the major isotopes of 6 out of the 7 most abundant heavier elements $^{12}\text{C}, ^{16}\text{O}, ^{20}\text{Ne}, ^{24}\text{Mg}, ^{28}\text{Si}$ and $^{56}\text{Fe}$ and from $\alpha + ^4\text{He} (\alpha\alpha)$ interactions have been unambiguously identified up to now from strong solar $\gamma$-ray flares. A first comprehensive study including a compilation and evaluation of cross sections as well as line shape calculations for these reactions has been started in the pioneering work of Ramaty et al. [21]. This work has been continued including many new cross section data measured mainly at the tandem accelerator facilities of Washington [3, 4, 24] and Orsay.
We present an overview of experimental nuclear reaction studies coupled with extensive calculations which have been done in Orsay for the modelisation of \( \gamma \)-ray emission from astrophysical sources. A brief description of the solar flare interaction model and the analysis of one solar flare spectrum will be presented in the following. A similar emission is expected from interactions of low-energy cosmic rays with the interstellar gas and dust. We present estimates of the nuclear \( \gamma \)-ray line emission induced by these particles in the inner Galaxy and discuss its detectability with future space-borne \( \gamma \)-ray telescopes.

2. Nuclear reaction studies
The strongest nuclear deexcitation lines in solar flares are, with the exception of two lines from \( \alpha \alpha \) reactions, the lines resulting from the deexcitation of the first few excited states in the above cited nuclei. For the latter \( \gamma \)-ray production cross sections in proton and \( \alpha \)-particle induced reactions have been measured in three experimental campaigns at the tandem Van-de-Graaff accelerator of the IPN Orsay [18, 1, 2]. In a fourth experiment we studied \( ^3 \text{He} \)-induced reactions with \( ^{16} \text{O} \) and \( ^{24} \text{Mg} \) [5, 6]. Typically 4-5 large-volume Ge detectors with BGO shielding have been employed for the \( \gamma \)-ray detection covering a large angular range in order to accurately determine the \( \gamma \)-ray angular distributions.

Cross section excitation functions have been measured typically in the energy range 5-25 MeV for protons and 5-40 MeV for \( \alpha \)-particles. Small steps of \( \sim 0.2 \)-0.5 MeV were usually employed at projectile energies below \( \sim 15 \) MeV where often prominent compound-nucleus (CN) resonances show up in the cross sections. The most important reactions for these lines are inelastic scattering reactions, however, for certain lines fusion-evaporation and spallation reactions of a very abundant isotope may significantly contribute.

About 100 different cross section excitation functions have been measured at Orsay during these campaigns, providing an important experimental database for energetic-particle induced \( \gamma \)-ray emission. Many are included in the latest compilation containing 181 excitation functions for \( \gamma \)-ray line production in \( p, \alpha \) and \( ^3 \text{He} \)-induced reactions [19]. Extrapolations to higher energies and cross sections for other lines are mainly based on calculations with the nuclear reaction code TALYS [13], which generally shows good agreement with experimental \( \gamma \)-ray data.

The shapes of the narrow line components (from energetic light-particle induced reactions) are determined by the fast particle ratios (essentially the \( \alpha \)-to-proton ratio \( \alpha/p \)) and their energy
spectra, and the particle angular distributions, which may be far from isotropic in solar flares. Contrary to cross section data, very few line shape data were published before our work (see e.g. [21]). Therefore we insisted at Orsay on good statistics for the strongest lines and completed the measurements by precise determinations of the beam-induced $\gamma$-ray background. Based on these data, complete parameterizations for the calculations of the 4.438-MeV [10] and later the 6.129-MeV line shapes have been obtained [11].

Since then, a new method has been developed, relying on optical-model and resonance calculations specifically to improve the line-shape descriptions in the region dominated by CN resonances [12]. An example is shown in Fig. 1 for the 4.438-MeV line. There, the inelastic scattering is calculated in the coupled-channels (CC) approach. The closest CN state at $E_p = 6.5$ MeV is the 7.900 MeV, $3/2^+$ states of $^{13}$N. The best fit for the CN resonance was found for 60% $l=0$ and 40% $l=2$ proton emission to the 4.439-MeV $2^+$ state of $^{12}$C, representing 76% of the cross section. CN and direct components are added incoherently. Besides the choice of the optical potential for the CC calculation, the only free parameters are the direct-to-CN resonance and the decay angular momentum ratios. It will be applied to proton and $\alpha$-particle reactions producing the 4.438-MeV and 6.129-MeV lines for which we have extensive sets.

3. Solar flare $\gamma$-ray emission

Particle acceleration in impulsive-type solar flares is believed to occur mainly in the low-density solar corona. For the strongest flares, electrons are accelerated to energies exceeding 20 MeV and nuclei can be accelerated to energies above several GeV per nucleon [20]. Part of the energetic particles are injected into magnetic loops where they are trapped and eventually interact with the denser parts of the solar atmosphere, the chromosphere and photosphere. Electromagnetic radiation from the radio to the $\gamma$-ray band as well as secondary particle radiation is produced in these interactions. The $\gamma$-ray emission below several hundred keV is mostly due to electron bremsstrahlung where the differential photon flux usually follows a power law in energy. At higher photon energies one often observes an additional component superposed on the power-law continuum which is mainly from nuclear $\gamma$-ray line emission and sometimes becomes the dominant process in the several MeV range. Beneath the nuclear deexcitation lines, strong narrow lines at 511 keV and 2.223 MeV from positron annihilation and neutron capture on $^1$H, respectively, are often present. At still higher energies, $\pi^0$-decay emission is sometimes observed.

One of the strongest solar flares ever observed occurred on Oct. 28, 2003, shortly after 11:00. Its $\gamma$-ray emission, lasting about 15 min., has been detected by the Ge spectrometer SPI onboard the Integral spacecraft [7]. Relatively good statistics for the $\gamma$-ray spectrum in the 0.6-10 MeV range has been obtained despite a spacecraft orientation which required the radiation to penetrate the satellite bus and the 5cm-thick BGO shield before reaching the Ge detector stack. The observed spectrum (Fig. 2) is dominated by nuclear line emission in the range 1-8 MeV. It shows a very prominent 2.223-MeV line and clearly the 4.438-MeV and 6.129-MeV lines. Assuming power-law spectra in energy, the $2.223/(4.438+6.129)$ ratio allowed determination of the spectral index $s \sim -3.5$. The $\alpha/p$ ratio was determined by line-shape analysis (see [11]).

The best overall reproduction of the observed spectrum could be obtained with an accelerated heavy-ion content close to the average composition of impulsive-type flares measured in interplanetary space [22], i.e. strongly enhanced in heavier elements Mg-Ni. In this case, accelerated heavy ions are responsible for more than 80% of the emission, which, because of the large line broadening forms an important continuum in the observed energy range. Compositions with lower enhancements like e.g. the coronal composition are unable to reproduce simultaneously the narrow line and continuum intensities.

In the line shape analysis the 4.438-MeV and 6.129-MeV lines were simultaneously fitted by scanning the parameter space $\alpha/p$ ratio - particle angular distribution around the flare axis. The latter is supposed to be perpendicular to the solar surface at the flare location. The best
4. Cosmic-ray induced γ-ray emission

The cosmic-ray (CR) spectrum is relatively well established above 1 GeV and up to at least $10^{19}$ eV. Interstellar particles with energies below 1 GeV per nucleon, however, are strongly deflected by magnetic fields in the heliosphere such that practically nothing is known about them. There is only indirect evidence that our Galaxy contains an important component of low-energy cosmic rays (LECRs). The most compelling is probably the observation of the molecule $\text{H}_3^+$ in diffuse interstellar clouds which requires an $\text{H}_2^+$ ionization rate $\zeta_2 = 4 \times 10^{-16} \, \text{s}^{-1}$ [8]. This ionization must be due to CRs because UV photons cannot penetrate these clouds. Standard CRs produce an ionization rate which is ten times smaller than that.

Supposing that this ionization is due to nuclei, one can construct a CR spectrum that satisfies the observed $\zeta_2$ by adding a component below $E/A = 1$ GeV. Sources of these LECRs could be acceleration in weak shocks at astrospheres as proposed by [23]. We used their model for source spectra and composition and propagated the ions with a leaky-box model. The intensity was normalized to produce $\zeta_2 = 3.6 \times 10^{-16} \, \text{s}^{-1}$ and then added to the standard CRs. Fermi-LAT recently observed the diffuse γ-ray emission above 100 MeV from the inner Galaxy [25]. From their preliminary data they extracted the component due to $\pi^0$-decay. Calculating the total γ-ray emission from our CR spectra (using the model of [9] for the $\pi^0$-decay emission) and adjusting the flux above 100 MeV to the observation provides a robust normalization of the
nuclear \(\gamma\)-ray line emission. A \(\gamma\)-ray spectrum for LECRs accelerated at astrospheres with an exponential cutoff of 750 MeV [23] is shown in Fig. 3.

Integrated fluxes of the inner Galaxy for the 4.438-MeV and 6.129-MeV lines are within the reach of \(\gamma\)-ray satellites projects equipped with state-of-the-art detector systems currently used in nuclear and particle physics. Still more favorable is the large bump at \(E_{\gamma} \sim 3\text{-}10\) MeV with an integrated flux of the order of \(10^{-4} \text{cm}^{-2} \text{s}^{-1}\). This lies comfortably above the survey broadband 3-\(\sigma\) sensibility limits of the projects presented to the latest (2010) ESA Cosmic Vision call for a medium-size mission (e.g. \(\sim 10^{-5} \text{cm}^{-2} \text{s}^{-1}\) after 5 years for CAPSiTT).

5. Conclusions
We presented nuclear reaction studies done in the last 15 years contributing to the database for energetic-particle induced nuclear \(\gamma\)-ray line emission. Two examples for application of these data in astrophysical sites have been discussed. The analysis of the Oct. 28, 2003 solar flare illustrated the rich potential of nuclear \(\gamma\)-ray line emission reflecting the energetic particle properties. It has been shown that such an emission could eventually be observed in the near future from the inner Galaxy which would give important clues to low-energy cosmic rays.

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