Nuclear Resonances:
The quest for large column densities and a new tool

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coordinated by J. Greiner
Max-Planck-Institut für extraterrestrische Physik, Garching

with contributions from:

S.E. Boggs – SSL Berkeley (USA)
G. DiCocco – IASF Bologna (Italy)
K.T. Freese – University of Michigan (USA)
N. Gehrels – Goddard Space Flight Center (USA)
D.H. Hartmann – Clemson University (USA)
A. Iyudin – Moscow State University (Russia)
G. Kanbach – MPE Garching (Germany)
A.A. Zdziarski – Copernicus Center Warszawa (Poland)

Abstract:

Nuclear physics offers us a powerful tool: using nuclear resonance absorption lines to infer the physical conditions in astrophysical settings which are otherwise difficult to deduce. Present-day technology provides an increase in sensitivity over previous gamma-ray missions large enough to utilize this tool for the first time. The most exciting promise is to measure gamma-ray bursts from the first star(s) at redshifts 20–60, but also active galactic nuclei are promising targets.

Nucleonic Absorption-Line Spectroscopy

We propose to add the utilization of gamma-ray absorption line spectroscopy to the astronomical toolbox. Nuclear level transitions carry their own specific information, which can complement studies in particular of violent and embedded objects such as GRBs and nuclei of active galaxies.

I. The physical effect

I.1 Nucleonic cross sections

The detection of (resonant) absorption lines is the most frequently used tool for studying matter towards an astrophysical source at low and high redshifts as illuminated by distant background sources such as quasars. The depth and shape of these absorption lines tell us about the physical conditions of gas located between the source and the observer. These are used to derive densities, velocities and metallicities, in order to constrain and unravel cosmological structure and evolution.

Similar to X-ray and optical absorption lines which are due to transitions between electronic levels, resonant absorption processes in atomic nuclei exist which leave characteristic absorption lines in the γ-ray range. The most prominent and astrophysically relevant are the nuclear excitation and Pygmy resonances (element-specific narrow lines between 5–9 MeV), the Giant Dipole resonance (GDR; proton versus neutron fluid oscillations; $\sim$ 25 MeV; two nucleons and more) and the Delta-resonance (individual-nucleon excitations, 325 MeV; all nucleons, including H!). The following is a short description of each of these astrophysically relevant resonances - a more detailed description can be found in Iyudin et al. (2005, A&A 436, 763).

Delta Resonance: At photon energies exceeding the threshold for pion production, the total absorption cross section of a photon interacting with an individual nucleon or with a nucleus shows a remarkably universal feature, a resonance that corresponds to the isovector magnetic dipole transition that connects the nucleon and the $\Delta(1232)$ isobar. The position of the Δ-resonance in the photon absorption cross section is $\approx$305 MeV for protons and 327$\pm$5 MeV for nuclei from helium up to uranium; the width is somewhat larger for nuclei as compared to that of protons.

Giant Dipole Resonance: First observed in 1947 in photonuclear reactions, the GDR is a collective oscillation of all protons against all neutrons in a nucleus, and as such does not occur for hydrogen. All other elements contribute, and for A>4 the maximum of the cross section is in the 20-30 MeV range. For a solar abundance medium, Helium provides the largest contribution.

Pygmy Resonances: Resonance-like absorption below the photoproduction threshold can be produced either via photon absorption to the excitation level of the nuclei or via the photon capture into the so-called "Pygmy" dipole resonance. The majority of the abundant isotopes in the interstellar matter have the ground state with a zero spin value and a positive parity; e.g., ^{4}He, ^{12}C, ^{16}O, ^{24}Mg, ^{28}Si, and ^{56}Fe, producing a cross-section maximum around 7 MeV. Single resonances are narrow, but in any realistic observing condition many elements with cross-section maxima at slightly different energies overlap - so this is the most challenging resonance for observational astronomy.

Nuclear Level Transitions: These are the more conventional analogue to atomic line transitions, if the nuclear shell model is adopted. They cover the energy range between about 0.5 and 8 MeV, one prominent example being the 4.430 MeV line of ^{12}C excitation.

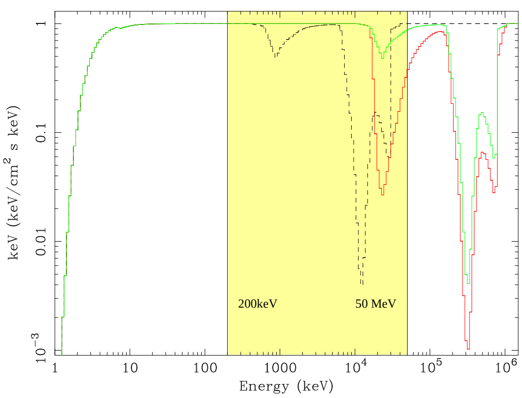

Figure 1: A flat νF_ν spectrum with $N_H = 10^{28}$ cm^{-2} resonance absorption lines for two different redshifts (black: z=25; color: z=0) and different metallicities: Z=0.1 (green) and Z=1 (red) solar metallicity. Note the obvious difference in the relative strengths of the absorptions. The solid vertical lines bracket the energy band from 200 keV to 50 MeV which would be ideal to measure resonances in the high-redshift Universe. Some galactic foreground absorption has been been included (curvature of the green line at the very left).

One extremely important property is that all the above resonant absorptions only depend on the presence of the nucleonic species, and not on ionization state nor temperature. This is different to electronic transitions in atomic shells. A draw-back, at least in the past, is that large column densities are required to detect these absorption features, due to relatively-low overall cross sections combined with rather poor instrumental opportunities: past detector technology would have required of order 10^{28} cm^{-2}, while present-day technology (when flown in 5–10 years) is able to detect column densities of 10^{25} cm^{-2}. Since in general the continuum spectra of γ-ray sources such as GRBs or blazars are otherwise featureless, these resonances imprint well-defined spectral features which provide information which is unaccessible otherwise.

I.2 Cosmic column densities and scattering: What is the limit?

When studying absorption in a given source with either UV or X-ray observations, one finds that the optical depth derived from the UV line is always $\sim$50 times smaller than the X-ray derived depth (e.g. Arav et al. 2002, 2003 in application to quasars). This is a consequence of the wavelength difference between absorption lines in UV and X-rays for the same ion, which means that X-rays are sensitive to a much higher column density than the UV, and can be used to provide a saturation test for the UV absorptions. Observations at soft X-rays in the early 90ies have expanded the maximum known source-intrinsic absorption values from 10^{19} cm^{-2} to 10^{22} cm^{-2}[1]. Similarly, the advent of sensitive observations at harder X-rays (first up to 10 keV, later at 20–40 keV) have shifted the maximum known absorption to 5–10$\times10^{24}$ cm^{-2}, first for NGC 1068 (e.g. Matt et al. 1997, A&A, 325, L13), recently for many sources as seen with Swift/BAT. Along the same line of arguments, γ-ray absorption will probe even higher column densities, which thus can be used to critically review saturation in X-ray absorption lines.

This is completely new territory, but with the great promise to 1) probe even higher column densities than possible in the past, thus leading to a better understanding of source geometries and conditions in various source classes, especially the ones emitting high-energy radiation and being deeply embedded, which are probably of prominent cosmological relevance; 2) measure redshifts directly from the gamma-ray spectrum, i.e. without the need for optical/NIR follow-up work for their identification! The most promising sources to observe this effect are, fortunately, the brightest known γ-ray sources: active galactic nuclei (AGN) in outburst (particularly blazars), and gamma-ray bursts (GRBs).

Is the resulting absorption detectable? This question has three aspects: (1) What are required instrumental sensitivity and source statistics? (2) What are the constraints from candidate sources we know? (see separate Sections below), and (3) Could different physical effects destroy the obvious absorption-line features? We address the latter now. If the density is too high, multiple-scattering of higher energy photons could partly fill the energy window of a resonance, thus smearing the absorption trough. This may happen via Compton scattering or the cascading of high-energy photons. While the total pair production or Compton scattering cross sections are about a factor of 30-40 larger than the peak cross section of the Giant Dipole or Delta Resonance, the jet geometry in both, GRBs as well as blazars, over-compensates for this statistical measure: it is the differential cross section which matters. At the Dipole Resonance energy, the Compton-scattered photon beam has a full-width-half-maximum of 16°, or 0.5 sr. For a 1° opening angle of the jet, the resulting GDR absorption is a factor $\sim$12 more efficient than the Compton re-scattering of higher energy continuum photons into the beam. In addition, Compton scattering changes the energy of the scattered photon by arbitrary large values, much greater than the width of the nuclear resonance - this adds another factor of E/ΔE ($\gtrsim$3 for the GDR) in favor of the nuclear resonance absorption. For pair production, only the latter effect comes into play. Thus, as the bottom line, all environments with a density smaller than about 10^5 cm^{-3} will not self-destroy the nuclear absorption feature by refilling of the lines due to scattering. Even in situations with still higher density environments, there are two possibilities which further alleviate the problem of re-filling: (i) the transverse dimension of the absorber is less than $\sim$1.5 attenuation lengths at the energy of the highest attenuation value (Varier et al. 1986) or (ii) the absorber consists of many clumps (clouds) of matter.

[1]Hydrogen absorption N_H in units of 10^{21} cm^{-2} scales roughly with extinction A_V; the local ISM density times the distance to the Galactic Center corresponds to $A_V \approx 25$ mag, or 10^6 in flux reduction.

II. Gamma-Ray Bursts

GRB afterglows are bright enough to serve as pathfinders to the very early universe. Since long-duration GRBs are related to the death of massive stars, it is likely that high-z GRBs exist. Theoretical predictions range between few up to 50% of all GRBs being at $z > 5$ (Lamb & Reichart 2001, Bromm & Loeb 2002), and stellar evolution models suggest that 50% of all GRBs occur at $z > 4$ (Yoon et al. 2006). The polarisation data of the Wilkinson Microwave Anisotropy Probe (WMAP) indicate a high electron scattering optical depth, hinting that the first stars formed in the range $20 \lesssim z \lesssim 60$ (Kogut et al. 2003, Bromm & Loeb 2006, Naoz & Bromberg 2007). Measuring GRB spectra with sufficient sensitivity in the γ-ray range, the detection of resonance absorption by matter near the GRB will allow us to determine redshifts up to 100, and thus measure the death of these first stars.

Is there enough matter along the sight lines to GRBs? Apart from galactic foreground extinction, relatively little intrinsic extinction has been found in the afterglow spectral energy distributions of GRBs, both at X-rays and at optical/NIR wavelengths. A recent combined analysis of Swift XRT and UVOT data shows that the absorbers associated with the GRB host galaxy have column densities (assuming solar abundances) ranging from (1-8)$\times 10^{21}$ cm^{-2} (Schady et al. 2007). There is evidence, both theoretical as well as observational, that there is a substantial amount of matter along the line of sights to GRBs. This applies to the local GRB surroundings as well as to the larger environment of the host galaxy in which the GRB explodes. Temporally variable optical absorptions lines of fine-structure transitions indicate that (i) all material at distances within a few kpc is ionized, most likely by the strong UV photon flux accompanied with the emission front of the GRB, and (ii) beyond this ionized region the absorbing column is still at a level of 10^{21} cm^{-2} (Vreeswijk et al. 2007, A&A 468, 83). The present-day measurement capabilities in the optical/NIR as well as X-rays are not adequate to determine the density of local matter around GRBs. However, at γ-rays this matter will be measurable through nuclear resonance absorption even though this matter is simultaneously being ionized: the GRB gamma-ray radiation has to pass through it - and it will suffer resonance absorption independent on whether this material is ionized or not.

A variety of theoretical simulations of GRB progenitors have been made (e.g. Bate & Bonnell 2003, Yoshida et al. 2006, ApJ 652, 6; Abel et al. 2007, ApJ 659, L87; Gao et al. 2007, MN 378, 449), pertaining to the formation of the first stars, the fragmentation rate, and density structure around the first stars. The first stars are thought to form inside halos of mass $10^5 ... 10^6 M_\odot$ at redshifts 10-60. It is generally accepted that most of the $10^5 ... 10^6 M_\odot$ halo mass remains in the surroundings of the forming proto-star, with about the original dimensions of the proto-cloud. The resulting mass of the star as well as the density structure are difficult to predict because they depend on the collapse conditions (merger or not, strength of winds, etc). However, it is important to realize that some simulations in fact predict column densities of up to 10^{29} cm^{-2} around the first stars (Yoshida et al. 2006, Spolyar et al. 2008; see also Fig. 2). These simulations have been done irrespective of nuclear resonance absorption. It remains to be demonstrated (preferentially through observations) whether the conditions in these simulations are realized. Yet, the existence of what one “normally” would refer to as “unbelievably high” column densities is plausible – note that even pristine and fully-ionized hydrogen imprints resonant absorption! GRBs are the best (and possibly only) tool to measure such conditions.

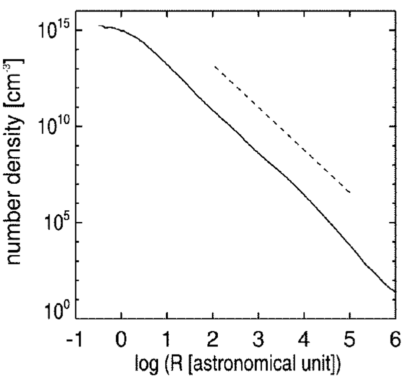

Figure 2: Radial density around a GRB progenitor at a redshift z=19. The density profile is close to a power law $\propto R^{-2.2}$ (dashed line). It contains about 10^{28} cm^{-2} column density within the inner 1-2 AU, and further 10^{28} cm^{-2} in each shell from 2-10, 10-100, 100-1000 AU! (From Yoshida et al. 2006, ApJ 652, 6)

But even for low-redshift GRBs, high column densities are not really excluded. In the standard picture, GRBs form in star-forming regions. Furthermore, the distribution of GRB positions relative to the centers of their host galaxies does not show large offsets. Thus, GRB occur in or near the densest gas/dust regions in their hosts. From our own Galaxy we know that the clouds near the Galactic Center are different from those in the Galactic disk: the incidence of dense clouds is higher, with densities over 10^4 cm^{-3} (Tsuboi et al. 1999, ApJS 120, 1). In particular, the Midcourse Space Experiment (MSX) has revealed the presence of compact clouds seen in absorption against bright mid-infrared emission from the Galactic plane (Egan et al. 1998, ApJ 494, L199). Typical column densities of these dark clouds are estimated to be $N(H_2) = 10^{23-25}$ cm^{-2}. About 2000 such clouds were found in a $1^o \times 180^o$ scan along the Galactic equator. There is no reason to believe that such clouds would not exist in other galaxies, even at high redshift. Any medium to bright GRB happening behind one such cloud, seen from redshift 1–3, would be an easy target to detect nuclear resonance absorption, and allow to study the surroundings of GRBs and the metallicity of those clouds at large redshifts.

III. Active Galactic Nuclei

The class of active galactic nuclei (AGN) includes those high-energy sources for which the largest column densities have been found so far by maesurements at hard X-rays or infrared wavelengths. Thus, it is not surprising that these were also the first class of objects for which signatures of nuclear resonance absorption has been searched for. Indeed, the combined spectra of COMPTEL and EGRET, both onboard the former Compton Gamma-Ray Observatory, have revealed features in the brightest sources that are at the correct energies. Despite individual features being at the 1–2σ level, since these features are seen in different sources located at different redshifts, and the absorption troughs are seen consistently at the rest-frame energies of the Delta resonance, the combined evidence for the reality of these resonance absorptions is remarkable (Iyudin et al. 2005, A&A 436, 763). Fig. 3 shows one example for 3C 279 as measured during the 1996 flare: when fitting a Gaussian to the absorption trough, the derived redshift is 0.57, compared to the optically known redshift of 0.54!

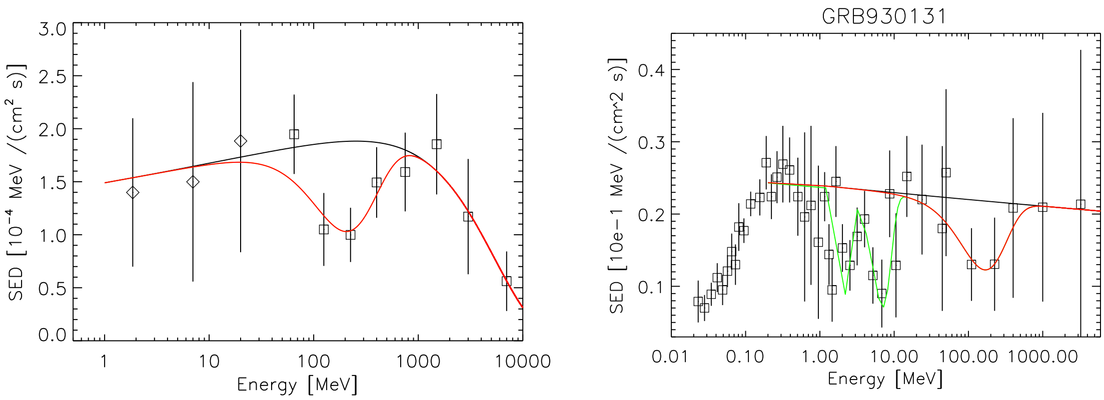

Figure 3: **Left:** 3C 279 spectrum during the January 1996 flare as measured by COMPTEL (diamonds) and EGRET (squares), which includes the Δ resonance absorption in the circumnuclear environment (red line) in addition to a cut-off power law (black line). The best-fit energy for the Δ resonance is 208±25 MeV, implying a redshift 0.57 ± 0.12, close to the optically determined z=0.536. **Right:** Fit to the combined COMPTEL/EGRET spectrum of GRB 930131. The throughs at 5–8 MeV and 100–200 MeV are compatible with the Giant Dipole and Delta resonance, respectively, at z$\sim$1 (Iyudin et al. 2007, in "Gamma-Ray Bursts: Prospects for GLAST", AIP Conf. 906, p. 89). The inferred column densities in both cases are $\approx 2\times10^{26}$ cm^{-2}.

In fact, the potential of measuring redshifts once absorption troughs are established and are seen in more than a few sources will provide a new, powerful tool in the identification of new γ-ray sources (Iyudin et al. 2007, A&A 468, 919). EGRET alone left us with about 150 unidentified sources – Fermi/LAT is expected to provide many more new sources. Measuring the redshifts of these bright (for LAT standards) EGRET sources would help dramatically in establishing counterparts at other wavelengths, which has been a daunting task over the last decade.

Another aspect involves Compton-thick sources. The shape of the spectrum of the cosmic X-ray background (Ajello et al. 2008, ApJ 689, 666) cannot constrain the number of objects with a column density of $>10^{25}$ cm^{-2}, the so-called extra-thick AGN. However, column densities of $>10^{25}$ cm^{-2} have been inferred from the spectra of several reflection-dominated AGN. Only a method able to measure such column densities in a direct way will be able to move us beyond the present state of hypotheses.

Unfortunately, the number of objects having spectral energy distributions with indications of absorption features remains small due to the low sensitivity of the previous gamma-ray telescopes in this energy range. Fermi/LAT is expected to provide new impetus in this direction, though the Delta resonance is close to the lower energy boundary of LAT, and the low-energy upturn of the continuum spectrum may be difficult to establish.

Looking ahead on a time scale of 10 years, nucleonic absorption line spectroscopy can be expected to be a growth industry. A mere factor 5 more in instrumental sensitivity over that of presently proposed instruments will bring column densities of 1×10^{24} cm-2 in their sensitivity range. These column densities have been seen already in hard X-ray spectra with Swift/BAT and INTEGRAL/IBIS in AGN. But many more object classes are then expected to be in reach for nucleonic absorption line spectroscopy, such as inner accretion disks in black hole systems, sources buried in dense molecular clouds, or population III stars if they are powered by dark matter heating rather than by fusion (e.g. Freese et al. 2008, 8th UCLA Symp: Sources and Detection of Dark Matter and Dark Energy in the Universe, arXiv:0812.4844).

IV. Fermi/LAT prospects and requirements for a new mission

Fermi/LAT, in operation since June 2008 and just in the course of performing a sensitive all-sky survey, is expected to provide the first proof of existence of nuclear absorption lines in astrophysical sources, and in turn the existence of source environments with column densities larger than presently known from INTEGRAL and Swift/BAT 20–50 keV spectra. In particular, it is the Delta resonance line at 327 MeV which is in the LAT energy range. Thus, bright low-redshift sources will imprint a clear signal in the LAT spectra, and consequently low-redshift AGN like 3C 279 are the most promising sources to discover nuclear absorption lines. With its all-sky survey, LAT will probe the low-redshift (z<1) Universe for large column densities. In contrast, for GRBs with typical redshifts beyond 1, and fluxes above 100 MeV not very high in general (GRB 080916C was the only exception so far), the prospects provided by LAT are somewhat worse. Thus, GRBs would benefit from measurements in the lower MeV range.

For a future mission, this new strategy of using nuclear resonance absorption requires sensitive spectroscopy in the 0.5–100 MeV band. The detection of GRBs or AGN flares, both highly variable objects, requires a large field of view. Therefore, the logical detection principle is the combination of Compton interaction and pair creation. Several detailed mission proposals have been developed over the last years around the world (one example, which explicitely has included the quest for nuclear resonance absorption, is described at http://www.springerlink.com/content/a7148g437188rl44/).