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Propagation of cosmic rays: nuclear physics in cosmic-ray studies

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Abstract. The nuclei fraction in cosmic rays (CR) far exceeds the fraction of other CR species, such as antiprotons, electrons, and positrons. Thus the majority of information obtained from CR studies is based on interpretation of isotopic abundances using CR propagation models where the nuclear data and isotopic production cross sections in p- and α-induced reactions are the key elements. This paper presents an introduction to the astrophysics of CR and diffuse γ-rays and discusses some of the puzzles that have emerged recently due to more precise data and improved propagation models. Merging with cosmology and particle physics, astrophysics of CR has become a very dynamic field with a large potential of breakthrough and discoveries in the near future. Exploiting the data collected by the CR experiments to the fullest requires accurate nuclear cross sections.

INTRODUCTION

The origin of CR have been intriguing scientists since 1912 when V. Hess carried out his famous balloon flight to measure the ionization rate in the upper atmosphere. The energy density of relativistic particles (CR) is $\sim$1 eV cm^{-3} and is comparable to that of the interstellar radiation and magnetic fields, and turbulent motions of the interstellar gas. This makes CR one of the essential factors determining the dynamics and processes in the interstellar medium (ISM). The observations of the Small Magellanic Cloud [1] by the EGRET (Energetic Gamma Ray Experiment Telescope) on board of the Compton Gamma Ray Observatory (CGRO) have shown that the CR are a Galactic and *not* a “metagalactic” phenomenon. Observations of the Large Magellanic Cloud [2], in turn, have shown that γ-ray flux is consistent with CR having a density comparable to that in our Galaxy.

Major cosmic accelerators are supernova remnants (SNRs), with a fraction of CR coming from pulsars, compact objects in close binary systems, and stellar winds. Observations of X-ray and γ-ray emission from these objects reveal the presence of energetic electrons thus testifying to efficient acceleration [3]. The total power of Galactic CR sources needed to sustain the observed CR density is estimated at 5×10^{40} erg s^{-1} which implies the release of energy in the form of CR of $\sim 5\times10^{49}$ erg per supernova (SN) if the SN rate is $\sim$ 3 per century.

Propagation in the ISM changes the initial composition and spectra of CR species (Fig. 1). The destruction of primary nuclei via spallation gives rise to secondary nuclei and isotopes which are rare in nature, antiprotons, and pions ($\pi^{\pm}$, π^0) that decay producing secondary $e^{\pm}$'s and γ-rays. CR are “stored” in the Galaxy for tens of millions years before escaping into the intergalactic space.

Although much progress has been made since the direct measurements in space have become possible, the detailed information refers only to the environment near to the sun. The CR source composition and CR propagation history are imprinted in their isotopic abundances while diffuse γ-rays and synchrotron emission from different directions carry clues to the proton and electron spectra in distant locations. These are the only pieces of the universal puzzle that we have and exploiting them requires extensive modeling.

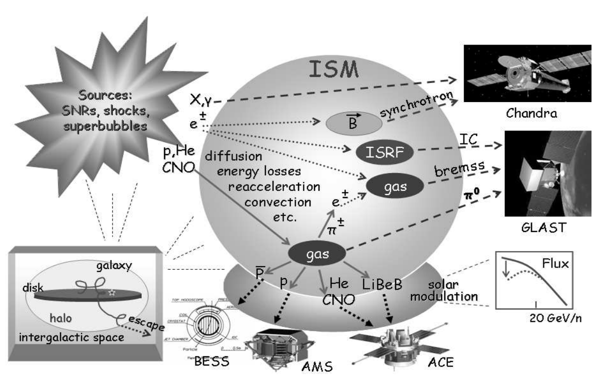

FIGURE 1. Basic processes in the ISM.

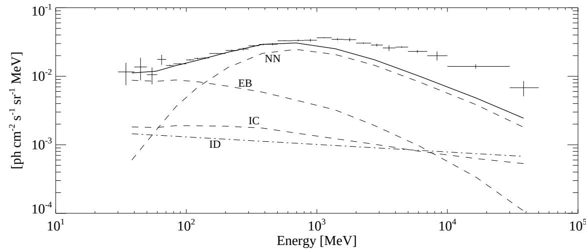

FIGURE 2. Spectrum ($E^2 \times Flux$) of diffuse γ-rays from the inner Galaxy as measured by the EGRET. Curves indicate individual components: π^0-decay (NN), electron bremsstrahlung (EB), inverse Compton (IC), and isotropic diffuse emission (ID). Adapted from [4].

INDICATIONS OF NEW PHENOMENA?

The puzzling excess in the EGRET data above 1 GeV (Fig. 2) relative to that expected [4, 5] has shown up in all models that are tuned to be consistent with local nucleon and electron spectra [6, 7]. The excess has shown up in all directions, not only in the Galactic plane. An apparent discrepancy between the radial gradient in the diffuse Galactic γ-ray emissivity and the distribution of CR sources (SNRs) has worsened the problem [6].

Positron fraction e^+/(all leptons) in CR as measured by HEAT [8] also exhibits an excess above $\sim$8 GeV (Fig. 3) compared to predictions of the diffusion model for secondary production [9].

Secondary antiprotons are produced in the same interactions of CR particles with interstellar gas as e^+'s and diffuse γ-rays. Recent $\bar{p}$ data with larger statistics [12] triggered a series of calculations of the secondary $\bar{p}$ flux in CR. The diffusive reacceleration models have certain advantages compared to other propagation models: they naturally reproduce secondary/primary nuclei ratios in CR, have only three free parameters, and agree better with K-capture parent/daughter nuclei ratio. The detailed analysis shows, however, that the reacceleration models underproduce $\bar{p}$'s by a factor of $\sim$2 at 2 GeV [13] (Fig. 4) because matching the B/C ratio at all energies requires

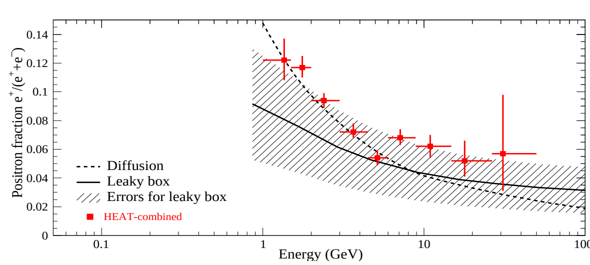

FIGURE 3. Positrons/(all leptons) ratio in CR compared to calculations in a leaky-box model [10] (solid) and GALPROP diffusion model [9] (dashes). Adapted from [11].

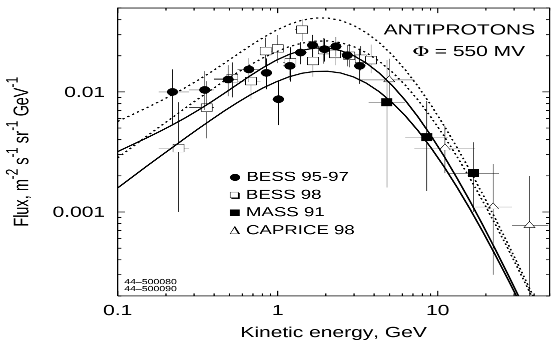

FIGURE 4. Spectrum of secondary antiprotons in CR as calculated in reacceleration (solid lines) and optimized (dots) models. The upper curves – interstellar, lower curves – modulated ($\Phi = 550$ MV) to compare with data. Adapted from [7].

the diffusion coefficient to be too large.

If these excesses are not a simple artefact, they may be telling us about processes in the ISM, in the Local Bubble, or signaling exotic physics (e.g., WIMP annihilation, primordial black hole evaporation), but also may indicate a flaw in the current models.

COSMIC RAYS AND DIFFUSE γ-RAYS

The modeling of CR diffusion in the Galaxy includes the solution of the transport equation with a given source distribution and boundary conditions (free escape into the intergalactic space) for all CR species. The transport equation describes diffusion and energy losses and may also include [14] the convection by a hypothetical Galactic wind, distributed acceleration in the ISM due to the Fermi second-order mechanism (reacceleration), and non-linear wave-particle interactions.

The study of transport of the CR nuclear component requires the consideration of nuclear spallation, radioactive decay, and ionization energy losses. Calculation of isotopic abundances involves hundreds of secondary nuclei produced in CR interactions with interstellar gas. A thorough data base of isotopic production and fragmentation cross sections is thus a critical element of propagation models that are constrained by the abundance measurements of isotopes, $\bar{p}$'s, and e^+'s in CR.

As solar activity changes with a period of 11 years so does the intensity of CR, but in opposite direction: with an inverse correlation. The "solar modulation" is a combination of effects of convection by the solar wind, diffusion, adiabatic cooling, drifts, diffusive acceleration and affects CR below 20 GeV/nucleon. The theory of solar modulation is far from being complete [15]. The Ulysses spacecraft first provided measurements of the solar wind and magnetic field outside the ecliptic helping us to un-

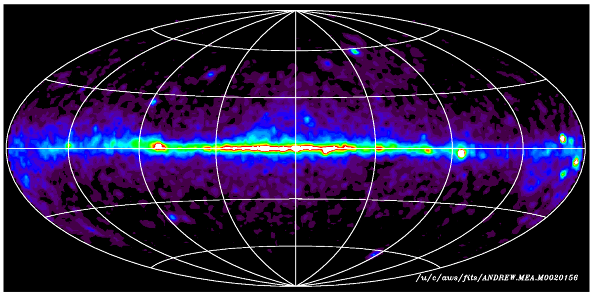

FIGURE 5. The EGRET sky: diffuse γ-ray emission [5].

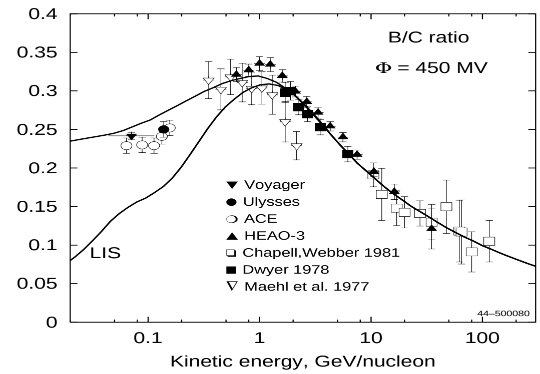

FIGURE 6. Boron/carbon ratio in CR as calculated in the reacceleration model. Lower curve – interstellar ratio, upper curve – modulated ($\Phi = 450$ MV) to compare with data. Adapted from [7].

derstanding the global aspects of modulation, while Pioneer and the two Voyagers have explored the outer solar system. Recently there appear some indications that Voyager 1, currently at 13.3×10^9 km (88 AU) from the sun, may be close to the termination shock, the heliospheric boundary. If true, in a few years it will become the first spacecraft ever to reach interstellar space.

The diffuse continuum emission is the dominant feature of the γ-ray sky (Fig. 5). It is evidence of CR proton and electron interactions with gas and the interstellar radiation field (ISRF), and is created via π^0-decay, inverse Compton, and bremsstrahlung. This emission in the range 50 keV – 50 GeV has been systematically studied in by OSSE (Oriented Scintillation Spectrometer Experiment), COMPTEL (Imaging Compton Telescope), and EGRET on the CGRO and in earlier experiments [4, 5]. The GLAST (Gamma-ray Large Area Space Telescope) will improve the sensitivity for the diffuse emission by a factor of 30.

Increasingly accurate balloon-borne and spacecraft experiments are demanding propagation models with improved predictive capability. Incorporation of the realistic astrophysical input increases the chances of the model to approach reality and dictates that such a model should be numerical. Besides the nuclear data, such a model has to include the detailed 3-dimensional maps of the Galactic gas derived from radio and IR surveys, the Local Bubble and local SNRs, the spectrum of the ISRF, magnetic fields, details of composition of interstellar dust, grains, as well as theoretical works on CR acceleration and transport in Galactic environments. The most advanced model to date, GALPROP, is a three dimensional model [6, 13, 16]. It is widely used as a basis for many studies, such as search for dark matter signatures, origin and evolution of elements, the spectrum and origin of Galactic and extragalactic diffuse γ-ray emission, heliospheric modulation. The model calculates CR propagation for nuclei ($^1_1$H to $^{64}_{28}$Ni), $\bar{p}$'s, $e^{\pm}$'s, and computes γ-rays and synchrotron emission in the same framework; it includes all relevant processes and reactions. It is an excellent tool to cross-test various hypotheses [7, 17].

NUCLEAR PHYSICS IN CR STUDIES

The abundances of stable ($_3$Li, $_4$Be, $_5$B, $_{21}$Sc, $_{22}$Ti, $_{23}$V) and radioactive secondaries ($^{10}_4$Be, $^{26}_{13}$Al, $^{36}_{17}$Cl, $^{54}_{25}$Mn) in CR are used to derive the diffusion coefficient and the halo size [16, 18]. The derived source abundances of CR may provide some clues to mechanisms and sites of CR acceleration. However, the interpretation of CR data, e.g., the sharp peak in the secondary/primary nuclei ratio (Fig. 6), is model dependent. The leaky-box model fits the secondary/primary ratio by allowing the path-length distribution vs. rigidity to vary. The diffusion models are more physical and explain the shape of the secondary/primary ratio in terms of diffusive reacceleration (distributed energy gain) in the ISM, convection by the Galactic wind, or by the damping of the interstellar turbulence by CR on a small scale.

The secondary/primary nuclei ratio is sensitive to the value of the diffusion coefficient and its energy dependence. A larger diffusion coefficient leads to a lower ratio since the primary nuclei escape faster from the Galaxy producing less secondaries and vice versa. The abundance of radioactive secondaries (e.g., ^{10}Be/^{9}Be) is sensitive to the Galactic halo size, the Galactic volume filled with CR. The larger the halo the longer it takes for radioactives to reach us thus decreasing the ratio ^{10}Be/^{9}Be.

Current CR experiments, such as Advanced Composition Explorer (ACE), Ulysses, and Voyager, deliver excellent quality spectral and isotopic data. Meanwhile, isotopic production cross sections have for a long time been the Achilles' heel of CR propagation models, and now become a factor restricting further progress. Interpretation of CR data requires massive calculations of isotopic production involving p's and α's, however, the widely used semi-empirical systematics are frequently wrong by a significant factor [22, 23]; this is reflected in

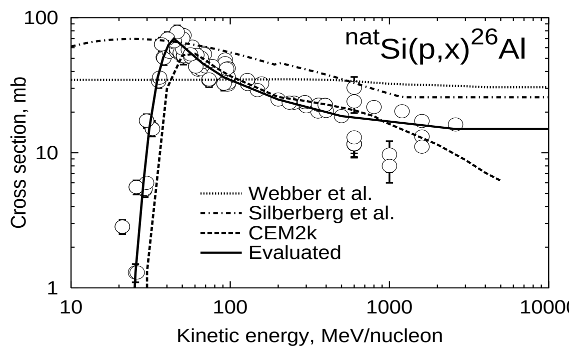

FIGURE 7. Cross section for the reaction ${}^{nat}\mathrm{Si}(p,x)^{26}\mathrm{Al}$. Calculations: semi-empirical systematics [19, 20], CEM2K [21], evaluated [22]. Adapted from [21].

the value of propagation parameters. Figs. 7 and 8 illustrate the effect of isotopic cross sections on the derivation of the halo size from radioactive secondaries. Using the semi-empirical systematics leads to the huge error bars where the upper limits are consistent with infinite halo size [24]. Using the evaluated cross sections dramatically reduces the error bars and gives a consistent value: 4–6 kpc [22]. Unfortunately, the evaluated cross sections in the required energy range are mostly unavailable.

K-capture isotopes in CR (e.g., ${}^{49}_{23}\mathrm{V}$, ${}^{51}_{24}\mathrm{Cr}$) can serve as important energy markers and can be used to study the energy-dependent effects such as diffusive reacceleration in the ISM and heliospheric modulation [25, 26, 27]. Such nuclei usually decay via electron-capture and have a short lifetime in the medium. In CR they are stable or live longer as they are created bare by fragmentation of heavier nuclei while their β^+-decay mode is suppressed. At low energies, their lifetime depends on the balance between the processes of the electron attachment from the ISM and stripping. The probability of attachment is strongly energy-dependent, increasing toward low energies, while the probability of stripping is flat. This makes the abundances of K-capture isotopes in CR energy-dependent (Fig. 9). Without K-capture, the ratio ${}^{51}\mathrm{V}/{}^{51}\mathrm{Cr}$ in CR would be flat because both nuclei are secondary. The electron K-capture ${}^{51}\mathrm{Cr(EC)}{}^{51}\mathrm{V}$ increases the ratio at low energies. Reacceleration (energy gain) increases it even further. On the contrary, solar modulation flattens the ratio (Fig. 10), which is very steep in the ISM.

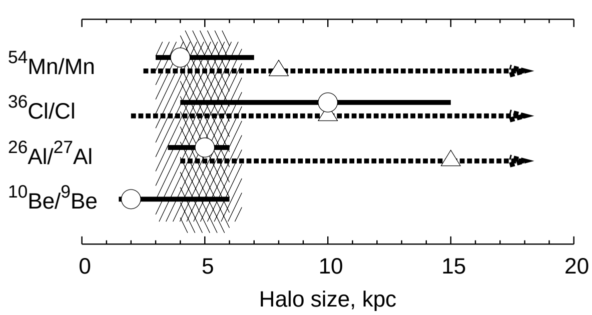

FIGURE 8. Determination of the Galactic halo size based on radioactive secondaries: using semi-empirical systematics [24] – dashes, light shaded area shows the range consistent with all ratios; using evaluated cross sections – solid, heavy shaded area shows the range consistent with all ratios. Adapted from [22].

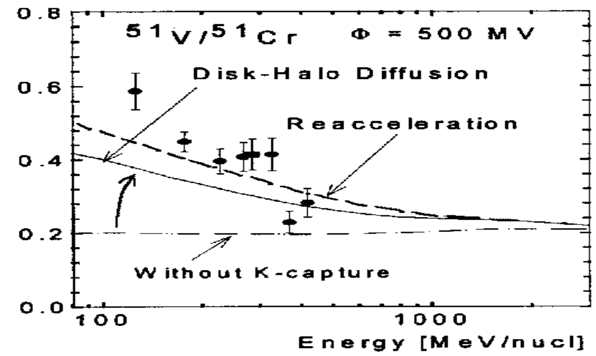

FIGURE 9. ${}^{51}\mathrm{V}/{}^{51}\mathrm{Cr}$ ratio in CR as calculated with/without K-capture. Adapted from [26].

Study of the light nuclei in CR (Li–O) allows us to determine propagation parameters averaged over a larger Galactic region, but the local ISM is *not* necessarily the same and the *local* propagation parameters may significantly differ. The best way to study the local ISM is to look at isotopes with shorter lifetimes (e.g., ${}^{14}\mathrm{C}$) and heavy nuclei since large fragmentation cross sections lead to a small "collection area."

The CR source composition is derived from direct CR data by correcting for the effects of propagation, spallation, and solar modulation. The elements with low first-ionization potential (FIP) appear to be more abundant in CR sources relative to the high-FIP elements, when compared with the solar system material (Fig. 11). This might

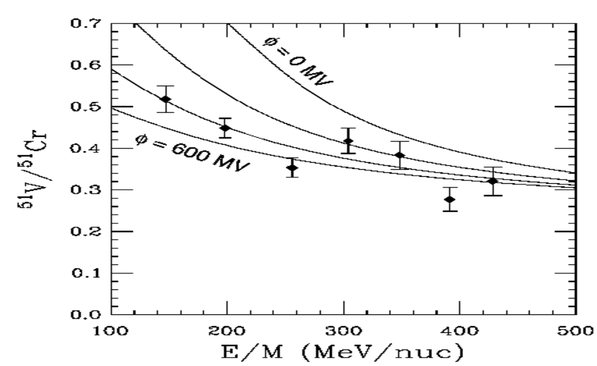

FIGURE 10. ${}^{51}\mathrm{V}/{}^{51}\mathrm{Cr}$ ratio in CR as calculated for different levels of solar modulation. Interstellar ratio corresponds to $\Phi = 0$ MV. Adapted from [27].

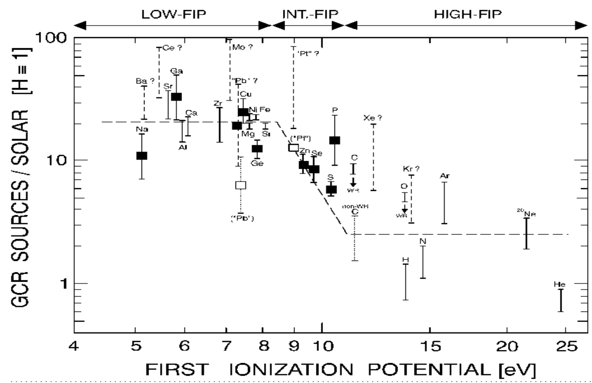

FIGURE 11. (Galactic CR sources)/(solar system) abundances of different elements vs. FIP. Adapted from [28].

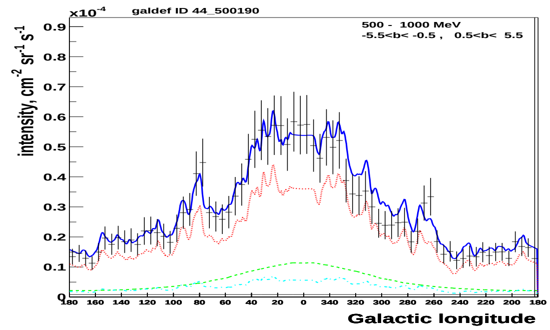

FIGURE 12. Longitude profile of diffuse γ-ray emission [7]. Lines (top to bottom): total, π^0-decay, inverse Compton, bremsstrahlung, extragalactic background.

imply that the source material for CR includes the atmospheres of stars with temperatures $\sim 10^4$ K [29]. A strong correlation between FIP and "volatility" (most of low-FIP elements are refractory while high-FIP elements are volatile) suggests that CR may also originate in the interstellar dust, pre-accelerated by shock waves [28, 30]. $_{11}$Na, $_{31}$Ga, $_{37}$Rb and some other elements $Z > 28$ break this correlation. CR data tend to prefer volatility over FIP, but uncertainties in the derived source abundances (cross sections!) prevent an unambiguous solution.

Isotopic peculiarities of CR composition are also important. For example, the $^{22}_{11}$Ne/$^{20}_{11}$Ne enrichment might tell us that CR are produced in cores of superbubbles [31] created by multiple correlated SNe.

SCENT OF NEW PHYSICS

Galactic and extragalactic space presents a test range where nature runs its numerous experiments continuously for billions of years. This is an arena where all fundamental forces perform in an exotic show involving yet-to-be-discovered particles, new elements, giant nuclei bound by gravitation – neutron stars, and singularities – black holes, and engineering the largest-scale grid of structures in the universe. CR and diffuse γ-rays, therefore, could contain signatures of exotic physics, however, conventional CR present an enormous background for tiny exotic signals.

The growing number of experiments forces us to the conclusion that the universe is dominated by the dark matter (DM) and dark energy. A preferred candidate for non-baryonic DM is a weakly interacting massive particle (WIMP). The WIMP is the lightest neutralino χ^0 [32], which arises in supersymmetric models of particle physics, or a Kaluza-Klein hypercharge B^1 gauge boson [33]. Annihilation of neutralinos creates a soup of particles, which eventually decay to ordinary baryons and leptons. The DM particles in the halo or at the Galactic center [34] may thus be detectable via their annihilation products (e^+, $\bar{p}$, $\bar{d}$, γ-rays) in CR [35]. The approach is to scan the SUSY parameter space to find a candidate able to fill the excesses in diffuse γ-rays, $\bar{p}$'s, and e^+'s over the predictions of a conventional model (as discussed above). Preliminary results of the "global fit" to the e^+'s, $\bar{p}$'s, and diffuse γ-ray data simultaneously look promising [36]. In particular, the DM distribution with two-ring structure allows the EGRET γ-ray data and the rotation curve of the Milky Way to be fitted, while the ring radii, 5 and 14 kpc, surprisingly well coincide with the observed rings of cold H_2 gas and stars, respectively.

In terms of conventional physics, the spatial fluctuation of CR intensity may also provide a feasible explanation. The CR $\bar{p}$ data can be used to derive the Galactic average proton spectrum (Fig. 4, optimized model), while the electron spectrum is adjusted using the diffuse γ-rays [7]. The model shows a good agreement with EGRET spectra of diffuse γ-ray emission ($<$100 GeV) from different sky regions (Fig. 12). The increased Galactic contribution to the diffuse emission reduces the estimate of the extragalactic γ-ray background [7, 37]. The new extragalactic background [37] shows a positive curvature (Fig. 13), which is expected if the sources are unresolved blazars or annihilations of the neutralino DM [38, 39]. The discrepancy between the radial gradient in the diffuse Galactic γ-ray emissivity and the distribution of SNRs can be solved [40] if the ratio H_2/CO in the ISM increases from the inner to the outer Galaxy. The latter is expected from the Galactic metallicity gradient.

The difficulty associated with $\bar{p}$ may also indicate new effects. The propagation of low-energy particles may be aligned to the magnetic field lines instead of isotropic diffusion [13]. Our local environment (the Local Bubble) may produce a fresh "unprocessed" nuclei component in CR at low energy [41]; the evidence for SN activity in the solar vicinity in the last few Myr supports this idea.

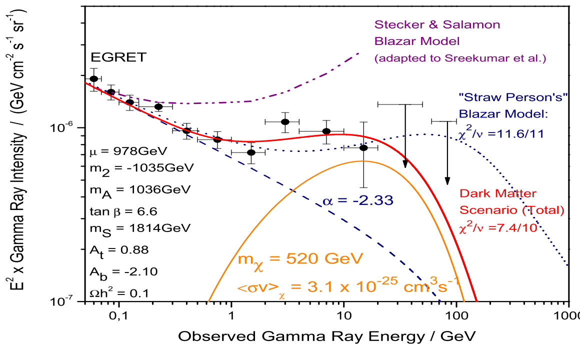

FIGURE 13. Spectrum of extragalactic diffuse γ-ray emission [37]. Adopted from [39].

CONCLUSION

Several topics are expected to become the subject of intensive studies in the coming years. PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) is designed to measure $\bar{p}$'s, $e^{\pm}$'s, and isotopes H–C over 0.1–300 GeV. Future Antarctic flights of a new BESS-Polar instrument (Balloon-borne Experiment with a Superconducting Spectrometer) will considerably increase the accuracy of data on $\bar{p}$'s and light elements. The AMS (Alpha Magnetic Spectrometer) onboard the International Space Station will measure CR particles and nuclei $Z \lesssim 26$ from GeV to TeV energies. This is complemented by measurements of heavier nuclei $Z > 29$ by (Super-)TIGER (Trans-Iron Galactic Element Recorder). The future GLAST mission will be capable of measuring γ-rays in the range 20 MeV – 300 GeV; besides other goals, it should deliver a final proof of proton acceleration in SNRs – long awaited by the CR community. A breakthrough on SUSY and high-energy interactions should come with operation of the new CERN large hadronic collider, LHC. Not surprisingly, the success of the state-of-the-art CR experiments depends heavily on the quality of nuclear data and especially p- and α-induced reactions at intermediate energies from tens of MeV – few GeV. Challenging these new frontiers is thus impossible without involvement of the nuclear physics community.

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