Results from high energy direct measurements and future prospects

Oscar Adriani\textsuperscript{1,2,*} and Lorenzo Pacini\textsuperscript{2,**}

\textsuperscript{1}Department of Physics and Astronomy, University of Florence, I-50019 Sesto Fiorentino, Florence, Italy
\textsuperscript{2}INFN Sezione di Firenze, I-50019 Sesto Fiorentino, Florence, Italy

\textbf{Abstract.} In this contribution a review of the recent results from high energy cosmic ray measurements, in the ‘above TeV’ energy regions, will be presented. The future experiments that will be realised to significantly improve the current measurements, aiming to explore the PeV region with direct measurements, will also be described.

\section{1 Introduction}

Thanks to the experimental results obtained before and during the nineties, a ‘standard’ picture of cosmic ray (CR) physics has been at that time established. According to this picture, the all-particle spectrum was well approximated with a single power law from few GeV (above the solar modulation effect dominated region) to the PeV region, where a first spectral break (knee) is present: this could be connected to the effect of lack of magnetic containment of the CR in our Galaxy and/or to the limit of the galactic accelerator mechanism \cite{1}. The value of the spectral index (about \textasciitilde2.7) is explained by well known theoretical models related to the acceleration of particle inside CR sources \cite{2}, e.g. SuperNova Remnants (SNRs) and diffusive process \cite{3} inside the Galactic magnetic field. To better understand the CR physics, it is useful to separate different species in two categories: primaries, i.e. CRs originated and accelerated by astrophysical sources and secondaries, i.e. particles produced by the interaction of other particles (mostly primaries) with the InterStellar Matter. Several acceleration-diffusion models predict that all the primary CR fluxes have universal (species independent) spectral indices, while the spectral index of secondaries is expected to be different with respect to the one of primaries. Furthermore, another well accepted hypothesis was that the anti-matter components of CR are purely of secondary origin (i.e. no sources of CR anti-matter is present). Unfortunately, no accurate direct measurements of individual spectra were available during the nineties to confirm this hypothesis. Thanks to the recent astonishing and huge progresses of balloon and space detectors, very detailed measurements of many CR species (both primaries and secondaries) have been carried out in the last decades. These results, presented in this paper, created serious challenges to the ‘conventional scenario’ of CR.

A brief description of the main running CR space experiments is presented in Section 2, while several relevant results concerning CR direct measurements, by exploiting different and complementary probes, will be discussed in Sections 3, 4, 5, 6 and 7. Finally, a brief discussion on future CR space experiments is also presented in Section 8.

\section{2 Space experiments devoted to CR measurements}

In the late 1990s - early 2000s, new complex and refined balloon experiments (e.g. CREAM \cite{4}) have opened a new era of accurate measurements of the individual CR spectra. Then, the high precision and complete space experiments PAMELA \cite{5} and AMS-02 \cite{6} started a decade of important measurements with magnetic spectrometer, followed by space calorimeters (CALET \cite{7} and DAMPE \cite{8}) launched in orbit around 2015. Generally speaking, the spectrometer-based experiments are able to separate matter and anti-matter particles, thanks to the high magnetic field and accurate tracking capabilities. Silicon strip detectors are used to identify the sign of the particle charge by precisely reconstructing the track curvature, which also allow the reconstruction of the particle rigidity (i.e. the momentum divided by the charge). Additional sub-detectors are needed to provide complementary and redundant information, e.g. a calorimeter allows to to properly separate electromagnetic and hadronic showers. As an example, the scheme of the AMS-02 instrument is shown in Figure 1. Due to the weight, volume and power consumption constraints of space instruments, the main limitations of current on-orbit spectrometers are the acceptance and maximum detectable rigidity (MDR); as a result of these limitations, these detectors can not measure particle above few TeV.

The calorimetric-based experiments are not able to separate anti-matter from matter, but with a weight similar to the one of a typical spectrometer, these instruments feature significantly larger acceptances. Moreover, the
calorimeter energy resolution does not strongly decrease with the particle energy; space calorimeters are hence able to measure particles up to hundreds of TeV. Ancillary sub-detectors are anyway necessary to measure the particle direction and charge, in order to well reconstruct individual species. The schemes of the two space calorimeters, CALET [9] and DAMPE [8], are shown in Figure 2.

Beside the spectrometric and the calorimetric techniques here briefly described, several additional different detection techniques can be used to achieve specific goals in the field of CR observation. A brief reference of few peculiar detection methods which will be employed for future detectors is presented in Section 8.

3 First unexpected results: the hardening and softening of proton and helium.

The first unexpected feature discovered during this new era of CR detectors is the proton and Helium (He) spectral hardening, i.e. the increase of the spectral index at a total energy around 200 GeV. This hypothesis has been firstly suggested by CREAM [4], and later accurately measured by PAMELA [10], as shown in Figure 3. Afterwards, the hardening has been confirmed by several different experiments, even if the value of the difference in the spectral index and the turning energy (or rigidity) are not completely consistent among different results: for instance, the value of the difference in the spectral index increase ($\Delta\gamma$) measured by AMS-02 is $\sim 0.22$ [6] while the one measured by CALET is $\sim 0.28$ [11]. Furthermore, the He spectrum hardening is slightly smaller than the one of protons, with $\Delta\gamma \sim 0.12$ according to AMS-02 observation [12]. The hardening can be related either to new physics in the CR sources or to propagation phenomena. Several theoretical model predict that the hardening could be related to a change of the diffusive regime, e.g. [13].

Beside the hardening, DAMPE recently observed also a softening of the proton [14] and He [15] spectra above 10 TeV per nucleon: the proton softening has also been confirmed by CALET [11]. The spectra of proton and He measured up to tens TeV per nucleon are shown in fig. 4. At the time of the publication of this article, there are not well accepted models predicting the observed softening.

Another important observation is related to the proton/He ratio. Being these particle primaries, according to the assumptions explained in Section 1, the spectral indexes of both species should be the same. On the contrary, experimental results show that even if proton and He spectral features (hardening and softening) are similar, the overall spectral index is different. As a result, the proton/He ratio is not flat, as shown in Figure 5. This is another challenge for the CR models, and currently there is not a well accepted theory which is able to properly predict the proton/He ratio.
4 Primary heavier nuclei spectra: a clear confirmation of the hardening.

Measurements of spectra of nuclei heavier than He are necessary to understand if the same hardening is present in every primary spectrum. The first measurements showing an hardening consistent with the one observed for He are the Carbon (C) and Oxygen (O) fluxes, measured by the AMS-02 [16] and CALET [17] collaborations. As an example, the $\Delta\gamma$ measured by CALET for C and O is $\sim 0.15$. C and O spectra are shown in Figure 6. The figure also shows that the spectral shape of C and O measured by AMS-02 and CALET are similar, but the absolute normalizations are significantly different; the flux measured by AMS-02 is systematically larger than the one measured by CALET and previous experiments (e.g., PAMELA). Understanding the reasons of this discrepancy is an important challenge for the CR experimental community.

The measured spectra of Neon, Magnesium and Silicon are compatible with the hardening at a rigidity of about 200 $GV$. Even if the hardening is present, AMS-02 data [6] shows that the rigidity dependence of these three nuclei is different with respect to C, O and He, as shown in Figure 7. Even if Neon, Magnesium and Silicon are mainly primaries, there are models that could explain these different spectral shape with respect to lighter nuclei, by taking into account parameters like the different spallation rate and the non-homogeneous diffusion of heavier CR, e.g. [18].

Regarding even heavier nuclei, the Iron spectrum has been recently measured by CALET [19] and AMS-02 [20] (see...
Figure 7. Neon, Magnesium and Silicon spectra compared with Carbon, Oxygen and Helium spectra measured by AMS-02 [6].

Figure 8. Iron spectrum measured by several experiments [19].

Figure 9. Nickel spectrum measured by CALET [21].

Particularly, secondary/primary ratio rigidity dependence does not strongly depend on CR source physics, while it is strongly affected by CR propagation and mean path length inside the galactic magnetic field. Furthermore, secondary spectra could provide additional information about the physics of the hardening. A simplified speculation regarding this issue could be formulated as follow:

- if the hardening of secondaries and primaries is similar, this feature should be related to CR acceleration, i.e. to the physics of the sources;
- if the secondaries harden more than primaries, with $\Delta \gamma$ which is about twice the one of primaries, this feature should be related to propagation effects.

Few experiments have measured several secondary spectra and secondary/primary ratios. AMS-02 [6] data shows that Li, Be and B spectral shape are very similar each other: the hardening of these spectra is more evident with respect to He, C and O. This result supports the hypothesis which links the hardening to propagation effects. Recently, the CALET [22] collaboration published the observation of B spectrum and B/C ratio, while the DAMPE [23] collaboration published the B/C and B/O ratios. These results are compatible with AMS-02 ones and they support the presence of the hardening in secondary/primary ratio. Several measurements of B/C and B/O ratios are shown in Figure 10.

Other confirmations of the relation between the hardening and CR propagation is provided by the measurement of heavier nuclei spectra, made by AMS-02 [24]. A summary of the nuclei measurements by AMS-02 is shown in Figure 11. These results are consistent with the scenario already discussed in this section. Being Sodium, Aluminum, and Nitrogen a mixture of primaries and secondaries, the value of the spectral index of these particles is smaller than the one of He, C and O and larger than the one of B, Li and Be. Finally, Fluorine is a heavy secondary and it features slightly harder spectra with respect to light secondaries: currently it is not clear if this result is consistent with the CR standard scenario.
6 Investigating nearby CR sources with the electrons plus positron spectrum.

Differently form protons and nuclei, electrons (and positrons) lose a sizeable amount of their energy during the diffusion inside the Galaxy, due to synchrotron radiation and inverse Compton scattering. Thus, electrons with energies larger than few $TeV$ could be observed at Earth only if they are originated, roughly speaking, in sources within $\sim 1 \ kpc$ distance from the Solar System. Therefore, the high energy electron flux is strongly affected by nearby CR sources and provide complementary information with respect to heavier high energy particles, which are accelerated by sources distributed inside the entire Galaxy. Several measurement of the electron+positron spectrum are shown in Figure 12. The DAMPE experiment (blue points in figure) reported the presence of a cut-off of the spectrum at around 1 $TeV$ [26], which is consistent with the absence of CR nearby sources which significantly contribute to the TeV energy region. The data of CALET [25] (red points in the figure) are consistent with the ones of DAMPE above 1 $TeV$. During the ICRC2021 conference [27] the CALET collaboration have confirmed the presence of the electron cut-off observed by DAMPE, thanks to the improved statistics with respect to the already published data. Regarding the lower energies, around hundreds GeV, two group of experiments are clearly presents in the data reported in Figure 12; DAMPE and Fermi-LAT measured fluxes that are significantly higher with respect to the other experiments, in particular CALET and AMS-02. Understanding this difference is an important challenge for the experimental communities, since it could be related to unknown systematic errors; for instance, the work in [28] investigated the impact of scintillator non-linearity on the absolute energy scale of space calorimeters.

7 The puzzle of positron and anti-proton high energy spectra.

As described in Section 1, the standard scenario foresee that the anti-matter particles in CR are only secondaries. This hypothesis has been first questioned by the
Positron/electron ratio published by PAMELA [10], that observed a clear positron excess above tens GeV, which is not consistent with the theoretical models about secondary production of anti-matter. Later, AMS-02 [6] confirmed this result and extended the positron spectrum up to 1 TeV: the measured flux features a peak around 300 GeV, as shown in Figure 13. The positron excess could be related either to nearby CR standard sources, like pulsars, not properly modelling the production and acceleration of anti-matter component, either to dark matter (DM) annihilation in our Galaxy [6]. An accurate understanding of positron excess also require accurate measurement of electron+positron spectrum above the TeV region, as discussed in previous section.

Another unexpected feature is present in the anti-proton/proton ratio, shown in Figure 14. Typical models of purely secondary production predict a decrease of this ratio above tens GeV, while PAMELA [10] and AMS-02 [6] experiments observed an almost flat ratio at high energies. Unfortunately, the theoretical models predicting anti-proton secondary production are strongly affected by large errors due to the uncertainties in the knowledge of relevant cross sections. Thus, to accurately evaluate the difference between the measured spectrum and the model predictions, more accurate measurements of cross sections are needed. The necessity of new measurements is well described in [29].

8 Future experiments for CR direct measurements

In this section, few, not exhaustive, examples of future experiments, aiming to continue this prolific era of CR direct measurements, are described. Starting from the near future, a brief description of some experiments with specific relevant goals is presented.

- **GAPS** [30]. This balloon experiment will measure low energy anti-nuclei by exploiting exotic atoms formation in the anti-matter annihilation in the detector. Being based on a completely innovative design, GAPS will have a sensitivity significantly higher with respect to previous experiments. The presence of anti-nuclei in CR is strongly connected to DM physics, thus this experiment will be a unique probe for DM search. The experiment should for the first time be launched in 2023/2024.

- **HELIX** [31]. This is an experiment based on a superconductive magnetic spectrometer, instrumented with drift chambers. It will be installed onboard of a long-duration balloon and it will measure the composition of low energy light CR, providing new information about the isotopic abundance ratios (not describer in this paper).

- **TIGERISS** [32]. This experiment will measure the abundance of CR nuclei from $^3$B to $^{82}$Pb. It is based on the original design of the SuperTIGER balloon instruments and it will improve it’s capability in the identification of heavier nuclei. It will be installed onboard the International Space Station, greatly profiting of a very long term exposure, much larger with respect to balloon experiments.

A future general purpose next generation CR experiment is **HERD** [33]. This is a large acceptance calorimetric experiment. Thanks to a fully 3D design of the detector, it will be able to measure particles coming from every face of the detector (excluding the bottom one). This translates in an acceptance at least ten times larger than the current experiments, with a payload weight of about 4 Tons. The instrument will be installed on-board the Chinese Space Station around 2027. A preliminary design of the detector is shown in Figure 15. The main goal of HERD is the first direct measurement of the CR knee. Differently from the ground based experiments providing up to now information of CR knee, HERD will be able to identify the charge of every detected particle, providing unique information on the composition of CR up to the knee region. Other relevant goals of the mission are the measurement of electron+positron flux up to tens TeV and the observation of gamma ray sky. Furthermore, the
calorimeter will be equipped with two independent readout [34] systems and a TRD will also be employed to validate the energy scale of TeV protons. This innovative design will significantly reduce the energy scale systematic error thanks to unique cross-calibration capabilities, greatly helping to understand the normalization issue of nuclei and electron-positron measurements (described in Section 4 and in Section 6).

The two long term projects for the development of new generation space spectrometer with superconductive magnets currently planned are AMS-100 [35] and ALADInO [36]. Both instruments are designed to operate in the Sun–Earth L2 Lagrangian point, for several years. By following the same base approach of HERD, these detectors will accept particles coming from every directions, to increase the acceptance. Graphical renderings of the two instruments are shown in Figure 16. Thanks to the huge acceptance and to the high Maximum Detectable Rigidity, these projects aim to provide revolutionary observations of electrons, positrons, and antiprotons up to tens TeV. They will also be able to measure nuclear CR up to PeV energies, and investigate the presence of low-energy antideuterium and anti-helium components in CR.

9 Conclusion

Starting from the 2000s, a new golden era of accurate direct cosmic ray observations has been opened. The observational improvements occurred during the past decades allowed to identify in the CR spectra many new unexpected features below the knee, revealing new physics phenomena, that should still properly be incorporated in a coherent model for cosmic ray origin and propagation. Many new open questions have hence appeared and still need to be clarified, e.g.:

• do measurements of secondary and primary nuclei confirm that the hardening is due to propagation effect?

Figure 15. Preliminary schematic design of the HERD experiment. The calorimeter (CALO), the scintillating Fiber Tracker (FIT), the Plastic Scintillator Detector (PSD) and the Silicon Charge Detector (SCD) are shown [33].

Figure 16. Graphical rendering of the baseline design for the ALADInO [36] (top) and AMS-100 [35] (bottom) detectors

• why is the slope of cosmic rays proton and helium spectra different?

• what is the origin of the cutoff observed at ~ 1 TeV in the electron spectrum?

• why do the proton, positron, and antiproton spectra have roughly the same slope for particle energies larger than 10 GeV?

• is the origin of the positron fraction rise above 10 GeV related to the presence of nearby CR sources (e.g. pulsars)?

• why the antiproton/proton ratio is constant above 60 GeV?

The increase in statistics of the existing experiment and the new future experiments (GAPS, HERD, ALADINO, AMS-100, etc...) will allow to significantly extend the current measurements, and will also improve our still quite limited knowledge on cosmic rays. A common effort between experimentalist (in different fields) and theorists is currently nicely under way and it is absolutely necessary to shade light on the many still open intriguing questions connected to the exciting field of Cosmic Rays.
References

[1] A. De Angelis, M. Pimenta, Introduction to Particle and Astroparticle Physics (Springer Cham, 2018)

[34] O. Adriani, M. Antonelli, A. Basti, E. Berti, P. Betti, G. Bigongiari, L. Bonechi, M. Bongi, V. Bonvicini, S. Bottai et al., Journal of Instrumentation 17, P09002 (2022)