Probing the ATIC peak in the cosmic-ray electron spectrum with H.E.S.S.


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Cosmic-ray electrons\(^1\) above a few GeV lose their energy rapidly via inverse Compton scattering and synchrotron radiation resulting in short cooling time and hence range. Therefore, they must come from a few nearby sources \([1, 2, 3]\). Recently, the ATIC collaboration reported the measurement of an excess in the electron spectrum \([4]\). The excess appears as a peak in \(E^3 \Phi(E)\) where \(\Phi\) is the differential electron flux; it can be approximated as a component with a power law index around 2 and a sharp cutoff around 620 GeV. Combined with the excess in the positron fraction measured by PAMELA \([5]\), the peak feature of the ATIC measurement has been interpreted in terms of a dark matter signal or a contribution of a nearby pulsar (e.g. \([6]\) and references given there). In the case of dark matter, the structure in the electron spectrum can be explained as caused by dark matter annihilation into low multiplicity final states, while in the case of a pulsar scenario the structure arises from a competition between energy loss processes of pulsar electrons (which impose an energy cutoff depending on pulsar age) and energy-dependent diffusion (which favors high-energy particles in case of more distant pulsars).

The possibility to distinguish between a nearby electron source and a dark matter explanation with imaging atmospheric Cherenkov telescopes has been discussed by Hall and Hooper \([7]\). Imaging atmospheric Cherenkov telescopes (IACTs) have five orders of magnitude larger collection areas than balloon and satellite experiments and can therefore measure TeV electrons with excellent statistics. Hall and Hooper assume that a structure in the electron spectrum should be visible even in the presence of a strong background of misidentified nucleonic cosmic rays. However, the assumption of a smooth background is oversimplified; in typical analyses the background rejection varies strongly with energy and without reliable control or better subtraction of the background, decisive results are difficult to achieve.

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\(^1\) The term electrons is used generically in the following to refer to both electrons and positrons since most experiments do not discriminate between particle and antiparticle.

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The measurement of an excess in the cosmic-ray electron spectrum between 300 and 800 GeV by the ATIC experiment has - together with the PAMELA detection of a rise in the positron fraction up to \(\approx 100\) GeV - motivated many interpretations in terms of dark matter scenarios; alternative explanations assume a nearby electron source like a pulsar or supernova remnant. Here we present a measurement of the cosmic-ray electron spectrum with H.E.S.S. starting at 340 GeV. The H.E.S.S. data with their lower statistical errors show no indication of a structure in the electron spectrum, but rather a power-law spectrum with spectral index of \(3.0 \pm 0.1\text{(stat.)} \pm 0.3\text{(syst.)}\) which steepens at about 1 TeV.

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In a recent publication, the High Energy Stereoscopic System (H.E.S.S.) Collaboration has shown that such a subtraction is indeed possible, reporting a measurement of the electron spectrum in the range of 700 GeV to 5 TeV \([8]\). Here an extension of this measurement towards lower energies is presented, partially covering the range of the reported ATIC excess. H.E.S.S. \([9]\) is a system of four imaging atmospheric Cherenkov telescopes in Namibia. While designed for the measurement of \(\gamma\)-ray initiated air-showers, it can be used to measure cosmic-ray electrons as well. The basic properties of the analysis of cosmic-ray electrons with H.E.S.S. have been presented in \([8]\). For the analysis, data from extragalactic fields (with a minimum of \(7^\circ\) above or below the Galactic plane) are used excluding any known or potential \(\gamma\)-ray source in order to avoid an almost indistinguishable \(\gamma\)-ray contribution to the electron signal. As the diffuse extragalactic \(\gamma\)-ray background is strongly suppressed by pair creation on cosmic radiation fields \([10]\), its contribution to the measured flux is commonly assumed to be negligible. For an improved rejection of the hadronic background a Random Forest algorithm \([11]\) is used. The algorithm uses image information to estimate the electron likeness \(\zeta\) of each event. To derive an electron spectrum, a cut on \(\zeta\) of \(\zeta > 0.6\) is applied and the number of electrons is determined in independent energy bands by a fit of the distribution in \(\zeta\) with contributions of simulated electrons and protons. The contribution of heavier nuclei is sufficiently suppressed for \(\zeta > 0.6\) as not to play a role. For an extension of the spectrum towards lower energies, the analysis has been modified to improve the sensitivity at low energies. In the event selection cuts, the minimum image amplitude has been reduced from 200 to 80 photo electrons to allow for lower energy events. In order to guarantee good shower reconstruction, only events with a reconstructed distance from the projected core position on the ground to the array center of less than 100 m are included. Additionally, only data taken between 2004 and 2005 are used. The reason is that the H.E.S.S. mirror reflectivity degrades over time and a reduced light yield corresponds to an increased energy threshold. The new data and event selection
reduces the event statistics but enables to lower the analysis threshold to 340 GeV. The effective collection area at 340 GeV is $\approx 4 \times 10^5$ m$^2$. With a live-time of 77 hours of good quality data, a total effective exposure of $\approx 2.2 \times 10^7$ m$^2$ sr s is achieved at 340 GeV. Owing to the steepness of the electron spectrum, the measurement at lower energies is facilitated by the comparatively higher fluxes. The $\zeta$ distribution in the energy range of 340 to 700 GeV is shown in Fig. 1.

The low-energy electron spectrum resulting from this analysis is shown in Fig. 2 together with previous data of H.E.S.S. and balloon experiments. The spectrum is well described by a broken power law $dN/dE = k \cdot (E/E_b)^{-\Gamma_1} \cdot (1 + (E/E_b)^{1/\alpha})^{-\Gamma_2/\alpha}$ with a normalization $k = (1.5 \pm 1.1) \times 10^{-4}$ TeV$^{-1}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$, and a break energy $E_b = 0.9 \pm 0.1$ TeV, where the transition between the two spectral indices $\Gamma_1 = 3.0 \pm 0.1$ and $\Gamma_2 = 4.1 \pm 0.3$ occurs. The parameter $\alpha$ denotes the sharpness of the transition, the fit prefers a sharp transition, $\alpha < 0.3$.

The shaded band indicates the uncertainties in the modeling of hadronic interactions and in the atmospheric model, and are derived in the same fashion as in the initial paper [8]. The band is centered around the broken power law fit. The systematic error on the spectral indices $\Delta \Gamma_1$, $\Delta \Gamma_2$ is $\Delta \Gamma$ (syst.) $\lesssim 0.3$. The H.E.S.S. energy scale uncertainty of 15% is visualized by the double arrow.

The H.E.S.S. data show no indication of an excess and sharp cutoff in the electron spectrum as reported by ATIC. Since H.E.S.S. measures the electron spectrum only above 340 GeV, one cannot test the rising section of the ATIC-reported excess. Although different in shape, an overall consistency of the ATIC spectrum with the H.E.S.S. result can be obtained within the uncertainty of the H.E.S.S. energy scale of about 15%. The deviation between the ATIC and the H.E.S.S data is minimal at the 20% confidence level (assuming Gaussian errors for the systematic uncertainty dominating the H.E.S.S. measurement) when applying an upward shift of 10% in energy to the H.E.S.S. data. The shift is well within the uncertainty of the H.E.S.S. energy scale. In this case the H.E.S.S. data overshoot the measurement of balloon experiments above 800 GeV, but are consistent given the large statistical errors from balloon experiments at these energies. A model calculation of how a Kaluza-Klein (KK) signature with a mass of 620 GeV [4] and a flux approximated to fit the ATIC data would appear in the H.E.S.S. data is shown in Fig. 3. Due to the limited

FIG. 1: The measured distribution of the parameter $\zeta$, compared with distributions for simulated protons and electrons, for showers with reconstructed energy between 0.34 and 0.7 TeV (the energy range of the extension towards lower energies compared to the analysis presented in [8]). The best fit model combination of electrons and protons is shown as a shaded band. The proton simulations use the SIBYLL hadronic interaction model. Distributions differ from the ones presented in Fig. 1 of [8] because of the energy dependence of the $\zeta$ parameter.

FIG. 2: The energy spectrum $E^2 dN/dE$ of cosmic-ray electrons as measured by ATIC [4], PPB-BETS [12], emulsion chamber experiments [9] and H.E.S.S. Previous H.E.S.S. data [8] are shown as blue points, the result of the low-energy analysis presented here as red points. The shaded bands indicate the approximate systematic error arising from uncertainties in the modeling of hadronic interactions and in the atmospheric model in the two analyses. The double arrow indicates the effect of an energy scale shift of 15%, the approximate systematic uncertainty on the H.E.S.S. energy scale. The fit function is described in the text.
An improved measurement of the electron spectrum over a wide range of energies from 10 GeV to 1 TeV can be expected from FERMI [13].

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