

## REJECTION OF THE HYPOTHESIS THAT MARKARIAN 501 TeV PHOTONS ARE PURE BOSE-EINSTEIN CONDENSATES

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Received 2000 June 8; accepted 2000 August 4; published 2000 October 11

### ABSTRACT

The energy spectrum of the blazar-type galaxy Markarian 501 (Mrk 501), as measured by the High-Energy Gamma-Ray Astronomy (HEGRA) air Cerenkov telescopes, extends beyond 16 TeV and constitutes the most energetic photons observed from an extragalactic object. A fraction of the emitted spectrum is possibly absorbed in interactions with low-energy photons of the diffuse extragalactic infrared radiation, which in turn offers the unique possibility to measure the diffuse infrared radiation density by exact TeV spectroscopy. The upper limit on the density of the extragalactic infrared radiation derived from the TeV observations imposes constraints on models of galaxy formation and stellar evolution. One of the recently published ideas to overcome severe absorption of TeV photons is based on the assumption that sources like Mrk 501 could produce Bose-Einstein condensates of coherent photons. The condensates would have a higher survival probability during the transport in the diffuse radiation field and could mimic TeV air shower events. The powerful stereoscopic technique of the HEGRA air Cerenkov telescopes allows us to test this hypothesis by reconstructing the penetration depths of TeV air shower events: air showers initiated by Bose-Einstein condensates are expected to reach the maximum of shower development in the atmosphere earlier than single photon events. By comparing the energy-dependent penetration depths of TeV photons from Mrk 501 with those from the TeV standard-candle Crab Nebula and simulated air shower events, we can reject the hypothesis that TeV photons from Mrk 501 are pure Bose-Einstein condensates.

*Subject headings:* BL Lacertae objects: individual (Markarian 501) — diffuse radiation —  
gamma rays: observations — intergalactic medium

### 1. INTRODUCTION

The propagation of multi-TeV photons through extragalactic space is hindered by pair-production processes that are due to interactions of TeV photons with photons of the diffuse extragalactic background radiation (DEBRA; Gould & Schröder 1966; Biller 1999; Bullock et al. 1999; Stecker & de Jager 1998). The opacity for TeV photons depends on the spectral energy distribution of the DEBRA roughly between wavelengths of 10 and 100  $\mu\text{m}$ . Direct measurements of this weak background radiation is a challenging task because of the orders-of-magnitude higher fluxes of foreground radiation of

Galactic and solar system origin. The good spectroscopy of TeV radiation combined with simultaneous X-ray observations from blazars gives us a tool at hand to determine the level of DEBRA independently (Coppi & Aharonian 1999). The recent High-Energy Gamma-Ray Astronomy (HEGRA) and Cerenkov Atmospheric Telescope (CAT) results on the energy spectrum of Markarian 501 and its interpretation yield consistent results on the flux of the DEBRA up to wavelengths of 50  $\mu\text{m}$  (Aharonian et al. 1999a; Guy et al. 2000; Konopelko et al. 1999b; Krawczynski et al. 2000).

Recently, however, Finkbeiner, Davis, & Schlegel (2000) claimed a tentative detection of the DEBRA at 60  $\mu\text{m}$  with the DIRBE instrument on board the *COBE* satellite. The cited flux level would translate into a large optical depth ( $>10$  for 20 TeV photons), as mentioned by Finkbeiner et al. (2000), and would result in unreasonable reconstructed source spectra (Protheroe & Meyer 2000).

A possible solution to this apparent contradiction was previously put forward by Harwit, Protheroe, & Biermann (1999). Assuming that powerful sources could produce Bose-Einstein condensates (BECs) of photons with energies in the GeV regime, such condensates could be erroneously detected as TeV air shower events by air Cerenkov telescopes. Due to the strong energy dependence of the pair-production cross section, the mean free path length for a condensate of, e.g., ten 1 TeV

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photons would increase by a few 100 Mpc in comparison with the mean free path length for a single 10 TeV photon. This would reduce the influence of absorption on the measured energy spectrum of Mrk 501 (with a distance of 157 Mpc, assuming  $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ) considerably. In this Letter, we present the results of a search for signatures of BECs in air shower events with the HEGRA-imaging air Cerenkov telescopes.

## 2. SIGNATURES OF BOSE-EINSTEIN CONDENSATES

When impinging on Earth's atmosphere, the photons of the condensate would arrive almost simultaneously and simulate higher energy air shower events. Since the BECs behave like a superposition of  $N$ -independent photons (Harwit et al. 1999) with a total energy  $E_0$ , the resulting air shower reaches its maximum earlier [ $X_{\text{max}} = \lambda \times \log(E_0/N) + \text{const}$ , for the Crab Nebula:  $\lambda = (74.1 \pm 0.8^{\text{stat.}} \pm 6^{\text{syst.}}) \text{ g cm}^{-2}$ ] and fluctuates less in its longitudinal development. Since differences in the penetration depth with regard to normal photon-induced showers are comparable to those due to the regular shower fluctuations of  $\approx 60 \text{ g cm}^{-2}$ , a discrimination on an event-by-event basis is not possible. However, the distribution of penetration depths allows us to distinguish easily between different scenarios for the existence of BECs in TeV air shower events:

1. For a pure BEC, there would be a constant shift of greater than  $24 \text{ g cm}^{-2}$  to smaller penetration depths depending on the multiplicity of the photons in the condensate.
2. For a given constant fraction of BECs, the mean value of the distribution of penetration depths would be shifted to smaller values. In addition, the shape of the distribution would be asymmetric toward smaller penetration depths because of the superposition of a BEC component.
3. An energy-dependent relative content of BECs (due to the energy-dependent absorption of TeV photons, for example) would reduce the rate with which the mean penetration depth increases with increasing energy (elongation rate) and would show an observable change in the shape of the distribution of penetration depths.

These characteristic signatures, as already suggested in Harwit et al. (1999), have been searched for in the HEGRA data gathered on Mrk 501 during the 1997 flaring period. By comparing the energy-dependent penetration depth of events from the direction of Mrk 501 with the ones from the Crab Nebula and with simulated data, the existence of a pure condensate with  $N \geq 2$  can be tested (case 1), and the relative content of condensates with  $N = 10$  can be probed to a level of 20%–30% (case 2). The sensitivity is limited by the systematic error on the energy scale. Independent of this systematic uncertainty on the energy scale, changes in the elongation rate would be an obvious signature for case 3.

## 3. DATA SELECTION AND ANALYSIS

The HEGRA Collaboration operates a system of six imaging air Cerenkov telescopes on the Canary Island of La Palma at 2200 m above sea level ( $800 \text{ g cm}^{-2}$  mass overburden). Five telescopes operate in a stereoscopic mode, registering simultaneously the images of extended air showers in the light produced by the air Cerenkov effect from different viewing angles (Daum et al. 1997; Bulian et al. 1998; Konopelko et al. 1999a). One telescope observes in a stand-alone mode (Mirzoyan et al. 1994). The stereoscopic imaging allows for the complete

geometrical reconstruction of the shower axis. In addition, the position of the maximum of particle numbers in the shower development can be inferred geometrically from the position of the image centroid. The method described in Hofmann et al. (2000) has been extended to cover different energies and zenith angles. The average resolution of the reconstruction of the position of the shower maximum is better than one radiation length, including all experimental uncertainties. For the reconstruction of the mean penetration depths in bins of energy, an energy reconstruction method based on Hofmann et al. (1999) has been used. The relative energy resolution obtained is smaller than 20%. The absolute calibration of the energy scale is known to within an accuracy of 15%.

The data have been taken in a nodding mode, where the ON and OFF regions are shifted by  $\pm 0.5^\circ$  in declination with respect to the center of the camera, changing sign every 20 minutes. Data processing and the reconstruction of the shower geometry follow the standard analysis described in Aharonian et al. (1999a).

The data on Mrk 501 used in this analysis have been gathered during 1997 with a four-telescope setup. In 1997, Mrk 501 underwent a very strong flaring activity, with a peak flux reaching 40 times the intensity of the quiescent state as measured in 1995 and 1996 (Quinn et al. 1996; Bradbury et al. 1997). The mean flux of the source was approximately 3 times as high as the flux measured from the Crab Nebula (Aharonian et al. 1999a).

The data taken on the Crab Nebula have been accumulated during the observation periods of 1997/1998 and 1998/1999. The observations of 1998/1999 were partially carried out with the five-telescope setup. The energy spectrum derived from a subset of these data is published in Aharonian et al. (2000).

The data have been selected to ensure good quality, details are given in Aharonian et al. (1999a, 1999b). Events with a distance to the zenith angle exceeding  $30^\circ$  have been excluded in order to reduce systematic uncertainties. The data sample amounts to 81 hr (Mrk 501) and 98 hr (Crab Nebula) of data under small zenith angles and excellent conditions.

The selection of gamma-ray events is based on an image cut on the quantity *mean scaled width*  $\langle \tilde{w} \rangle < 1.1$  rejecting 90% of the hadronic background and 40% of the photons (Konopelko et al. 1999a). In this procedure, the image width of each telescope is scaled according to the expectation for a photon-induced shower of a given image size, the impact point distance, and the zenith angle. The scaled widths  $\tilde{w}$  from individual telescopes are combined to obtain  $\langle \tilde{w} \rangle$ . In addition to the cut on the image shapes, the direction of accepted events were constrained to be within a half-angle of  $0.2^\circ$  of the source direction, and the reconstructed impact point of the shower has to be within 200 m of the central telescope.

Simulations of air showers have been carried out using CORSIKA (Heck et al. 1998) with a complete and detailed simulation of the atmosphere (Bernlöhner 2000) and the detector, including Rayleigh and Mie scattering, single-photon ray-tracing, detailed modeling of signal digitization, and threshold behavior (K. Bernlöhner 1998, internal report). The simulated data are processed and analyzed in the same way as actual data.

## 4. RESULTS AND INTERPRETATION

The resulting distribution of penetration depths are obtained within equally sized logarithmic bins of reconstructed energy. The distributions of reconstructed penetration depths for photons from Mrk 501 and from the Crab Nebula are displayed

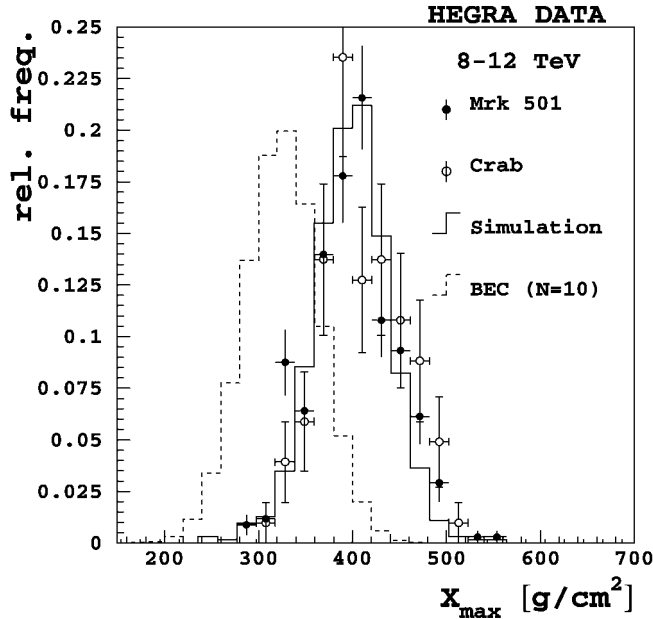


FIG. 1.—Reconstructed distributions of penetration depths for photons from Mrk 501, the Crab Nebula, and from simulated photon-induced air shower events in comparison with one of the energy bins from 8 to 12 TeV. For details on the distribution of condensates with  $N = 10$ , see text.

in Figure 1 for one of the energy bins from 8 to 12 TeV. The distributions of background events constituting a relative fraction of less than 10% have been subtracted. The distribution for photons derived from simulated air showers, including a complete detector simulation and the data processing chain, is superposed. The distributions of penetration depths of the simulated and actual data are in good agreement ( $\chi^2$  and Kolmogorov tests of the distributions give probabilities ranging from 70% to 98%). For comparison, the expected distribution for a BEC with  $N = 10$  is overlaid. The expectation is derived from simulated data by parameterizing the histogram with a Gaussian distribution and by changing the width and the mean value according to the occupation number, taking the experimental resolution into account.

Figure 2 displays the mean values of  $X_{\max}$  for eight energy bins, comparing the ones from Mrk 501 with the ones from the Crab Nebula. The error bars indicate the  $1\sigma$  statistical uncertainty on the mean value. The given elongation rate for  $N = 1$  is derived from the simulated data. The gray region indicates the systematic error that is due to the 15% uncertainty on the energy scale.

An additional systematic error in the elongation rate is expected because of the different spectral shapes of the TeV spectra from the Crab Nebula and Mrk 501 combined with the finite-energy resolution. This is expected to change the mean penetration depths in the exponential cutoff region beyond 10 TeV by  $\approx 5 \text{ g cm}^{-2}$ . Other sources of systematic errors (e.g., the deviation in the alignment of the telescopes and the changes in the atmospheric conditions) affect both data sets in the same way but will not be discussed any further in this Letter. From a comparison with the simulated data, the contribution of these systematic errors is estimated to be less than  $\approx 10 \text{ g cm}^{-2}$ .

The prediction for the elongation rate in the case of a condensate of 2 and 10 photons is illustrated by lines in Figure 2, assuming that *all* photons are produced in a condensate state (case 1). The prediction is derived by shifting the elongation

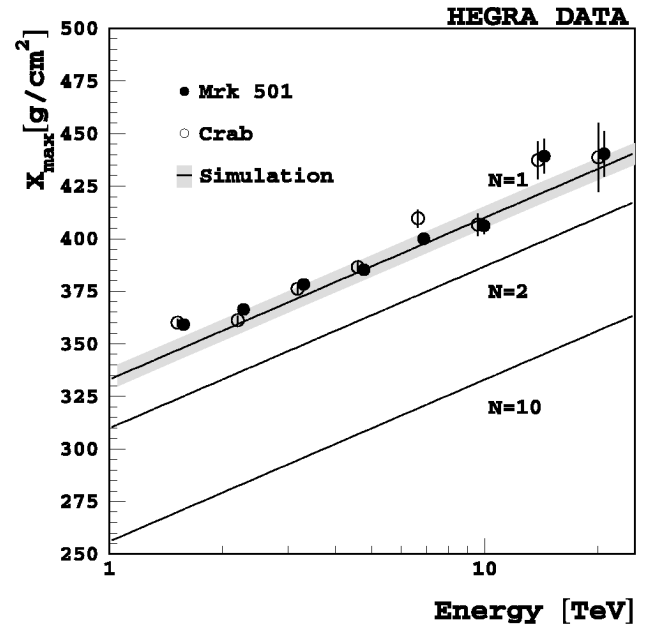


FIG. 2.—Mean values of the penetration depths for eight energy bins. The  $1\sigma$  statistical error is given by the error bars. The systematic error due to uncertainties in the absolute energy calibration is indicated by the gray region. The predictions for different occupation numbers  $N$  in the condensate are illustrated by a set of lines derived from the elongation rate from the simulated air showers (see text).

rate for the simulated photon showers according to the expectation for a given occupation number. Besides an overall shift in the mean value, the condensates would change the fluctuations in the position of the shower maximum, causing a smaller rms value of the distributions.

The mean penetration depths of the photon-induced showers from Mrk 501, the Crab Nebula, and from simulated air shower events are in good agreement with each other but are not compatible with the expectation for a pure beam of BECs with  $N \geq 2$  for all considered energies. Furthermore, focusing on the events with reconstructed energy  $\geq 10$  TeV, a  $\chi^2$  test of the distributions of penetration depths from Mrk 501, with simulated data adding a relative fraction of  $N = 10$  (2) condensate, sets an upper limit for the relative content of 30% (65%) on the 90% confidence level (case 2).

## 5. CONCLUSION

The precise reconstruction of the shower geometry with the stereoscopic technique has been used to determine the penetration depth and the energy for individual photon induced air showers with the HEGRA system of imaging air Cerenkov telescopes.

The distributions of penetration depths of TeV air showers from the extragalactic source Mrk 501 have been compared with those from simulated data and with those from the Crab Nebula to search for BECs. The analysis rules out a pure beam of condensates with occupation numbers  $N \geq 2$ . The relative content of  $N = 10$  (2) condensates is limited to below 30% (65%) with 90% confidence for energies  $\geq 10$  TeV. The allowed relative content of BECs would change the optical depth for TeV photons only marginally.

The support of the German ministry for research and tech-

nology BMBF and the Spanish Research Council CYCIT is gratefully acknowledged. We thank the Instituto de Astrofísica de Canarias for the use of the site and for supplying excellent working conditions at La Palma. We gratefully acknowledge

the technical support staff of the Heidelberg, Kiel, Munich, and Yerevan Institutes. The air shower simulations have been carried out using CORSIKA v5.91, and it is a pleasure to thank its authors for their support.

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