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doi: 10.15940/j.cnki.0001-5245.2020.05.013　　博士学位论文摘要选登

暗物质粒子探测卫星的能量重建和宇宙线质子能谱的分析

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宇宙线的观测研究和暗物质粒子的间接探测是高能天体物理领域两个重大研究课题. 自1912年V. Hess发现宇宙线开始, 人类对宇宙线的观测历史已经超过了一个世纪, 传统理论模型预言“膝”区以下能段的宇宙线能谱应服从单一幂率分布, 而近些年的空间和高空气球实验表明10 GeV–100 TeV的宇宙线质子能谱可能存在偏离单一幂律谱分布的重要结构, 这对研究银河系内宇宙线的起源、传播和加速机制具有重要意义. 另一方面, 得益于宇宙线和伽马射线观测精度的提高和观测能段的拓宽, 暗物质粒子的间接探测在国际上受到越来越多的关注, 暗物质粒子可能会发生湮灭或衰变产生稳定的普通高能粒子, 包括正负电子对、正反质子对、伽马射线和中微子等, 进而在宇宙线或伽马射线留下可探测的信号.

暗物质粒子探测卫星悟空号(DAMPE)是中国发射的第1颗空间天文卫星, 也是目前国际上最为先进的空间高能粒子探测器之一, 可以实现对高能宇宙线和伽马射线的精确探测, 并在此基础上开展暗物质信号搜寻和其他高能天体物理课题的研究. 伴随悟空号的发射和在轨运行, 作者参与了卫星在轨标定、科学数据分析软件和探测器模拟程序的开发与测试、物理事例重建和宇宙线粒子能谱分析等诸多方面的工作.

探测器模拟不仅对研究数据重建方法和理解实验结果具有重要意义, 同时也是获取探测器对不同入射粒子的仪器响应(如能量分辨、角度分辨)的重要途径. 本文第2章介绍了DAMPE探测模拟程序开发过程中的相关问题, 包括探测器的几何建模、探测单元响应信号的读出、模拟信号数字化(电子学噪声添加)过程等. 此外, 本文利用卫星在轨数据对探测器模拟程序进行了对比验证.

在完成探测器模拟程序的基础之上, 本文利用大量的模拟数据研究了针对不同粒子的能量重建方法. 粒子在量能器中的簇射发展可分为电磁簇射和强子簇射两种, 两种簇射在量能器中的发展过程和能量沉积行为有很大不同. 针对电磁簇射型粒子(电子、光子), 本文研究了一种基于簇射发展形状的参数化能量修正算法, 能够逐事例对入射电子或光子的泄露能量进行补偿修正, 并可以有效提高能量分辨率; 针对强子簇射型粒子(质子、重核), 本文研究了能谱反卷积的算法, 利用量能器的沉积能量分布重建出入射粒子的原初能量分布. 我们利用电子和质子束流实验数据, 分别对两种算法进行了检验. 这些工作分别在第3、4章进行了介绍.

第5章系统介绍了宇宙线质子能谱的分析工作, 主要包括在轨质子事例的挑选、选择效率的标定、本底的估算、能谱反卷积、质子流量的计算和误差分析. 基于悟空号两年的在轨飞行数据, 本文得到了50 GeV–20 TeV的宇宙线质子能谱的初步测量结果, 结果显示在该能量范围内质子能谱明显偏离单一幂律分布, 能谱在约400 GeV能量出现变硬的结构, 这与空间磁谱仪实验PAMELA (Payload for

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Antimatter Matter Exploration and Light-nuclei Astrophysics)和阿尔法磁谱仪2号(AMS-02)得到的观测结果一致.

Energy Reconstruction of Dark Matter Particle Explorer and Analysis of Cosmic-ray Proton Flux

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The observation of cosmic rays and indirect detection of dark matter particles are two important topics in high-energy astrophysics. In 1912, V. Hess discovered the cosmic rays. Since then, the observation of cosmic rays has lasted for more than a century. Traditional theories suggest that the cosmic-ray flux follows a single power-law below the so called "knee" at a few PeV energies. Recent measurements of cosmic-ray proton flux from space-based observatories and balloon-borne experiments have revealed some unexpected structures in the energy range of 10 GeV–100 TeV, which provided important clues for the study of the origin, propagation, and acceleration mechanism of galactic cosmic rays. On the other hand, thanks to the improvement of observational accuracy and the extending of observational energy range for cosmic-rays and gamma-rays, the indirect detection of dark matter particles (DM) has attracted more and more attentions in the past few years. DM annihilation/decay may produce $e^{\pm}$, protons, and anti-protons, gamma-rays, or neutrinos, which can potentially lead to observable signals in cosmic-rays or gamma-rays.

The DArk Matter Particle Detector Explorer (DAMPE) is the first astronomical satellite of China. DAMPE is one of the most advanced space-based particle detectors for the observation of high-energy cosmic-rays/gamma-rays and the detection of DM signals. Since the launch of DAMPE, I have been deeply involved in the calibration, simulation, and scientific data analysis for this project.

Detector simulation plays a crucial role not only for the studies of analysis methods, but also for the understanding of the detector response (e.g. energy resolution and angular resolution) for different particles. In the second chapter, several issues about the detector simulation of DAMPE are introduced, including the geometric modelling of the detector, the readout of the response signals from sensitive units, and the digitization process. The detector simulation program is then verified by comprehensive comparisons between simulation data and flight data.

Based on the simulation data, we studied the energy reconstruction method for different kinds of incident particles. In the calorimeter, there are two kinds of showers related to different interaction mechanisms between incident particles and the detector. One is the electromagnetic shower induced by an electron/positron or a gamma-ray photon, the other is the hadronic shower induced by a proton or heavy ion. For the electromagnetic shower produced by $e^{\pm}/\gamma$, we proposed a parameterized correction method using the lateral and longitudinal information of shower development to estimate the primary energy event by event. This method is verified with data of electron beam test at CERN, which shows significant improvements for both the energy linearity and resolution. For the hadronic shower produced by proton/heavy ion, we studied an unfolding method based on the Bayes' theorem to directly estimate the primary energy distribution instead of the event-by-event level correction of the energy.

The final part is the analysis of the cosmic-ray proton spectrum. The whole procedure is introduced, including event selection, particle identification, background estimation, efficiency validation, spectral deconvolution, acceptance calculation, and uncertainty analysis. Based on two years of data recorded by DAMPE, the preliminary cosmic-ray proton spectrum from 50 GeV to 20 TeV is obtained. The cosmic-ray proton spectrum of DAMPE is not consistent with a featureless power-law model, but exhibits a spectral hardening at hundreds of GeV, which confirms the results reported by PAMELA (Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics) and AMS-02 (Alpha Magnetic Spectrometer-2).

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