Indirect Dark Matter Search with Antideuterons: Progress and Future Prospects for General Antiparticle Spectrometer (GAPS)

J. E. Koglin[a], T. Aramaki[a], W. W. Craig[b], L. Fabris[b], F. Gahbauer[ac], C. J. Hailey[a], F. J. Jou[a], N. Madden[b], K. Mori[d], H. T. Yu[a] and K. P. Ziock[b]

[a]Columbia Astrophysics Laboratory, Columbia University, New York, NY

[b]Lawrence Livermore National Laboratory, Livermore, CA

[c]University of Latvia, Riga, Latvia

[d]Canadian Institute of Theoretical Astrophysics, Toronto, Canada

We report on recent accelerator testing of a prototype general antiparticle spectrometer (GAPS). GAPS is a novel approach for indirect dark matter searches that exploits the antideuterons produced in neutralino-neutralino annihilations. Many supersymmetry models, as well as other models based on extra dimensions, predict a primary antideuteron flux from dark matter annihilation that is much greater than the secondary and tertiary background sources at low energies. The GAPS method involves capturing antiparticles in a target material into excited energy states. The X-rays that are emitted as the antiparticle cascades to lower energy states before the exotic atom decays serve as a fingerprint that uniquely identifies the mass of the captured antiparticle. This approach provides large area and field of view in addition to excellent background rejection capability. Analysis of the performance of a prototype GAPS tested in an antiproton beam at the KEK accelerator in Japan in 2004 and 2005 are presented.

1. Introduction

The General Antiparticle Spectrometer (GAPS) is a novel concept for detection of antimatter and is particularly well suited for antideuteron searches. Antideuterons provide an indirect signature of neutralino pair annihilation, as first pointed out by Donato and collaborators [1]. While the antideuteron production is not as copious as other dark matter annihilation products such as antiprotons, the astrophysical background is much more significantly suppressed. Thus, especially at very low energies, antideuterons provide an essentially background free technique for detecting dark matter.

Indirect antideuteron signatures of Cold Dark Matter (CDM) have also been explored within the context of other models such as minimal supergravity [2] as well as more complicated SUSY models [3,4]. Other studies have focused on CDM detection outside SUSY, namely universal extra-dimensions (UED) Kaluza-Klein and warped extra-dimensional dark matter models [5]. In some regions of these models, antideuterons are the only viable detection method, while in other regions antideuterons are competitive with direct detection or indirect detection of neutrinos from neutralino annihilation in the Sun. In general, antideuteron searches are complementary to direct and other indirect detection methods in that they probe different portions of the allowed parameter space for a given model. Alternatively, an antideuteron detection could also signal black hole evaporation [6].

The operating principles, designs and sensitivity calculations for potential balloon and satellite-based GAPS experiments have been previously reported in Mori et al. [7,8]. Interim progress has also been reported on the performance of a GAPS prototype exposed to an antiproton beam, as well as various beams representative of cosmic backgrounds, at the KEK accelerator facility in Japan [9]. In this paper we describe the GAPS concept, the GAPS prototype experiment and analysis, along with the implications of this prototype experiment and plans for the future.

2. Operating Concept of the General Antiparticle Spectrometer

An antiparticle that passes through a time of flight (TOF) system (which measures energy) is slowed down by dE/dx losses in a degrader block. The thickness of this block is tuned to select the sensitive energy range of the detector. The antiparticle is stopped in a target, forming an excited, exotic atom with probability of order unity. The exotic atom deexcites through both autoionizing transitions and radiation producing transitions with three or more well-defined X-rays typically emitted. The target is selected such that the X-rays have energies in the 20-200 keV range so that the X-rays can escape with low losses and be efficiently detected in common X-ray detectors. After the emission of the X-rays the antiparticle annihilates in the nucleus producing a shower (star) of pions. The X-ray/pion emission takes place within nanoseconds. The fast timing coincidence between the characteristic decay X-rays of precisely known energy (dependent only on antiparticle mass and charge) and the energy deposition induced by the pion star is an extremely clean antiparticle signature. The GAPS concept is only practical at extremely low energies ($\lesssim$ 0.3 GeV/n), where particles can be ranged out with low mass degraders (essential for balloon or satellite missions where low mass is paramount).

3. Experimental Setup of 2004 and 2005 Prototype Experiments at the KEK Accelerator

The GAPS prototype was tested at the KEK accelerator facility in Tsukuba, Japan in two separate experiments done in 2004 and 2005. The experiments were performed using the Pi2 secondary beamline of the 8 GeV proton synchrotron. The Pi2 beamline is unseparated such that copious quantities of kaons, pions and electrons are transported to the experimental area along with antiprotons. Pions are the dominant background event type with four orders of magnitude higher rate than the antiprotons. A momentum of 1 GeV/c was chosen to optimize antiproton flux.

The experimental setup is illustrated in Fig. 1. The detectors highlighted and labeled from above were added for the KEK05 run to provide additional information to more accurately normalize event types and rates. Since all of the particles initially have the same momentum, they can be identified by time of flight (TOF) due to their difference in mass using P0-P2.

The P3 and P4 counters provide redundant timing and energy deposit information to tag the antiprotons that have survived passage through the degrader and enter the target. The P5 counter is used to veto antiprotons that did not stop in the target. The S1-S4 plastic scintillators interspersed with lead form a shower counter used to confirm the passage of a valid antiproton through its dE/dx loss signature. Six charged particle veto counters (V1-V6) consisting of thin scintillating fiber bundles were added in front of the scintillator crystals to completely surround the target cell. These counters identify beam particles that scatter directly into the crystals.

The target has a cylindrical geometry (12 cm diameter, 48 cm length). The GAPS detector consists of sets of 2x4 NaI crystals (25mm diameter, 5 mm thick) housed in 16 panels arranged in a hexagonal array. Each of the 128 crystals is coupled to a Hamamatsu RM1924a photomultiplier tube (PMT). The system achieves sufficient energy resolution to resolve the X-ray transitions of interest and 200 ns time resolution for coincidence rejection of background. The level of detector segmentation was chosen to balance cost with the desire to limit the occurrence of multiple X-rays or annihilation products entering the same crystal. A custom 128-channel data acquisition system was constructed to directly handle signals from the NaI detector phototubes.

4. Experimental Results of Accelerator Experiments

A variety of solid (S, CBr4, Al, C aerogel), liquid (CCl4) and gas (C2F6 and N2) targets were used in KEK04 and KEK05, with the intention of

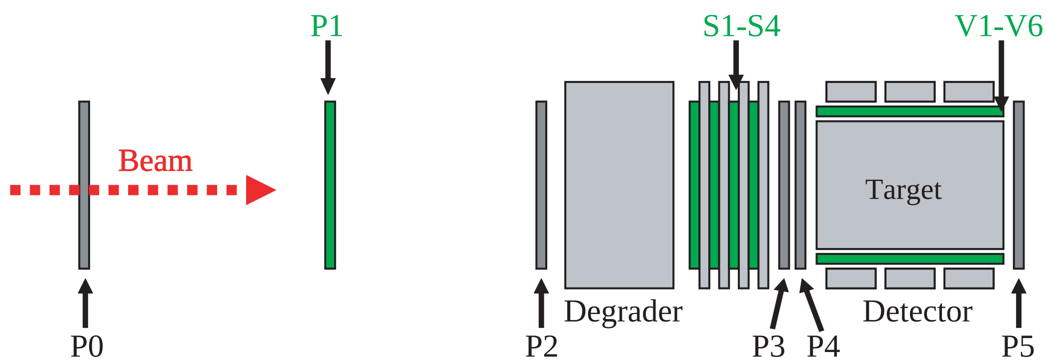

Figure 1. KEK Experimental Setup. The detectors labeled from above were only included in the 2005 experiment.

evaluating candidate targets for real space experiments. A major result of the two KEK runs was to demonstrate successful detection of multi-X-ray events from solid and liquid targets. This is a substantial improvement over the GAPS baseline of high pressure gaseous targets. Solid and liquid targets substantially ease handling and design requirements for space-based systems and reduce dead area in the detector.

As an example of the KEK results, Fig. 2a shows a carbon tetrabromide integrated X-ray spectrum. This spectrum was produced solely using cut criteria intrinsic to GAPS. In this case the cut required more than two ladder X-ray transitions and more than four total energy deposits. The spectrum of Fig. 2a clearly shows the bromine X-rays (whose capture probability is large compared to the carbon). Again correcting for accidentals, the X-ray ladder transition rates are consistent with high effective X-ray yield – comparable to those in the corresponding kaonic system. More detailed analysis is underway.

Fig. 2b shows the signature of a carbon tetrabromide antiproton annihilation in the GAPS detector (four X-rays with energies consistent with the expected Br transitions given the NaI resolution) with independent event verification from beamline identification. The boxes surrounding the segmented crystal display give data on the upstream and downstream diagnostics. In particular, displays P1-P4 for the plastic scintillators indicate the timing deviation at each piece of plastic compared to that expected for an antiproton. In each case the timing deviation is within the timing resolution of the system (~1 ns). The counters S1-S4 show the monotonic increase in deposited energy whose magnitude in each counter is consistent with that expected for slowing down of an antiproton of proper incident momentum. And finally there is no signal in the downstream plastic P5 (indicating a stop in GAPS).

5. Experimental Implications and Future Directions for GAPS

The most important result of the KEK04 and KEK05 runs was to verify the basic GAPS concept. Simultaneous atomic ladder X-ray transitions and pion stars have been used, for the first time, to specifically identify antiparticles. GAPS provided near unity efficiency in identifying antiproton stops, which were confirmed with a completely independent array of experiment detectors that identify stopped events by particle type.

Two results of great importance to future design work were obtained. Firstly, solid (and liquid) targets have been successfully utilized. This enormously simplifies the design challenges of GAPS. With no need for high pressure gas, as in the original concept, GAPS is easier to operate and it is lighter and more efficient because of the removal of the dead mass of the gas handling system. GAPS efficiency also increases because solid and liquid targets provide more design

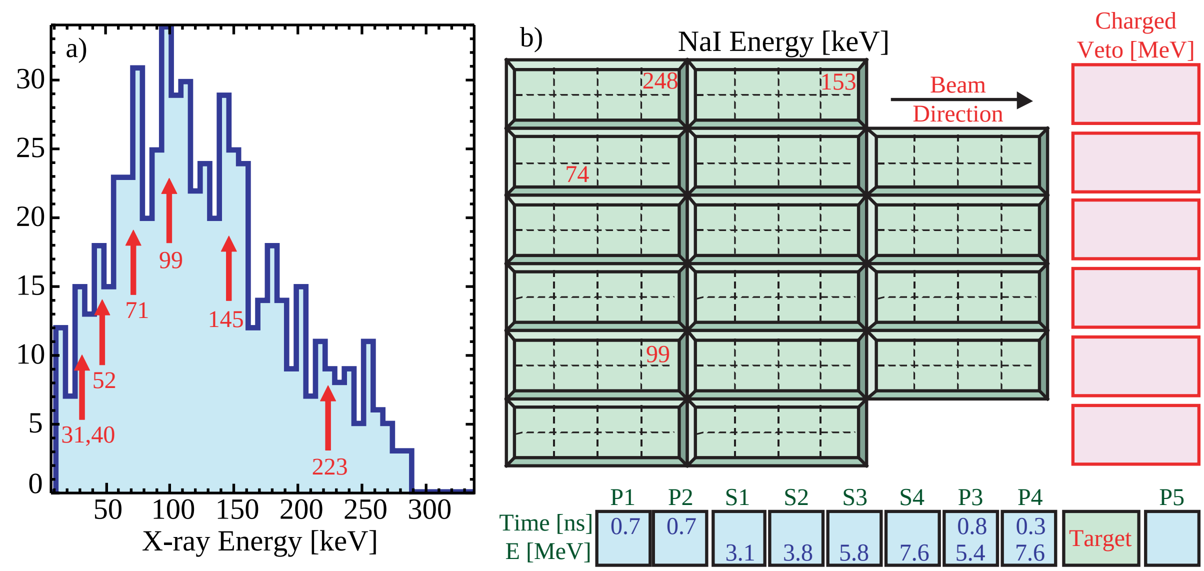

Figure 2. a) The carbon tetrabromide (CBr_4) integrated X-ray spectrum for events with $\geq$2 ladder X-ray transitions and $\geq$4 total energy deposits. b) An example of a four ladder X-ray event.

options. And secondly, the preliminary estimate of effective X-ray yield gives numbers consistent with the $\gtrsim 30\%$ used in the original GAPS sensitivity calculations.

Our conclusion from the experiments is that the GAPS concept is sound and that the sensitivity numbers of Mori et al. [7] are basically correct. Thus the theoretical implications of a GAPS experiment, discussed in numerous papers, will not be meaningfully altered when exact effective X-ray yields are produced from our detailed analysis. The experimental program at KEK in Japan has been sufficiently successful to move on to a flight test of GAPS. We are currently evaluating advanced flight detector and readout concepts. While much work remains to be done, it is realistic to envision flying a GAPS instrument that can detect antideuterons with sufficient sensitivity to probe well into the CMSSM and other SUSY parameter spaces on a timescale of five years or less.

Acknowledgments

We thank J Collins and the electronics shop staff at LLNL for the development and construction of the GAPS electronics, and T Decker, R Hill and G Tajiri for mechanical engineering support. We gratefully acknowledge the support of M Ieiri and the KEK staff before and during the accelerator experiments. This work was supported in part by a NASA SR&T grant, NAG5-5393.

REFERENCES

1. Donato F, Fornengo N and Salati P, 2000 *Phys. Rev. D* **62** [hep-ph/043003]
2. Edsjo J, Schelke M and Ullio P, 2004 *JCAP* **09** 004 [astro-ph/0405414]
3. Profumo S and Ullio P, 2004 *JCAP* **0407** 006 [hep-ph/0406018]
4. Masiero A, Profumo S and Ullio P, 2005 *Nucl. Phys. B* **712** 86 [hep-ph/0412058]
5. Baer H and Profumo S, 2005, *JCAP* **12**, 008 [astro-ph/0510722]
6. Barrau A et al, 2003 *A&A* **398**, 403 [astro-ph/0207395]
7. Mori K et al, 2002 *ApJ* **566**, 604 [astro-ph/0109463]
8. Hailey C J et al, 2004 *NIM B* **214** 122 [astro-ph/0306589]
9. Hailey C J et al, 2006 *JCAP* **0601** 007 [astro-ph/0509587]