BALLOON-BORNE DIRECT SEARCH FOR IONIZING MASSIVE PARTICLES AS A COMPONENT OF THE GALACTIC HALO DARK MATTER

(The Arizona-IMAX Collaboration)

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ABSTRACT

A dark matter (DM) search experiment was flown on the IMAX balloon payload, to search for a possible minor component of the dark matter in the Galactic halo: ionizing massive particles (IMPs) ($m_x > 10^4$ GeV/c^2) that cannot penetrate the atmosphere due to their low-velocities and high energy-loss. The DM search experiment consisted of a delayed coincidence between four large plastic scintillation detectors arranged in a vertical stack. In order to search for ultra-slow particles which do not slow down in the IMAX telescope, the experiment contained TDCs which measured the time-delays $T_{i,i+1} \in [0.3, 14.0]$ μs between hits in successive counters to $\sim 2\%$ precision. We present IMP flux limits for non-slowing IMPs and also for IMPs which slow down significantly within the IMAX telescope. This experiment effectively closes much of a previously unconstrained 'window' in the mass/cross-section joint parameter space for massive particles as the dominant halo DM.

1. INTRODUCTION & MOTIVATION

A whole host of different 'elementary' particles have been hypothesized as solutions to the dark matter problem[1](e.g. a small neutrino rest mass, WIMPs, monopoles, CHAMPs, very massive neutrinos, SIMPs, strange quark nuggets, axions); and novel particle detectors are required to detect each different dark matter candidate. Weakly Interacting Massive Particles (WIMPs) are considered to be a likely dark matter particle candidate. In the early universe, the low WIMP cross-section might allow enough WIMPs to survive annihilation from anti-WIMPs, so as to be abundant enough to solve the missing matter problem today. However, Ionizing Massive Particles (IMPS), which presently have a much higher interaction cross-section with ordinary matter, might have a primodial annihilation cross-section that is similar to the WIMP primordial annihilation cross-section. Therefore, IMPs *might* have a relic abundance that is large enough to constitute all the dark matter in the universe and be unnoticed in past experiments[2]. Examples of IMPs include: CHAMPs (electrically CHArged Massive Particles), SIMPs (Strongly Interacting Massive Particles), monopoles and "strange" quark nuggets. If IMPs have antiparticles, the range of IMP masses for which IMPs could be the dominant (halo) dark matter (DDM) includes $m_x \in [6 \times 10^2, 3 \times 10^5]h$ GeV, where $h \sim 1$ is the Hubble constant[2]. Since the high interaction cross-section of IMPs with ordinary nuclei should have easily observable consequences, many experiments have been completed[3] or clever arguments invented[2] to rule out different hypothetical IMPs as the DDM, within the theoretically most favored ranges of IMP mass, m_x, number density, n_x, and interaction cross-section with ordinary nuclei σ_{xN}. However, Starkman *et al.* have found that for a significant range of the joint mass and interaction cross-section parameter space, generic IMPs have *not* been ruled out as the dominant halo dark matter, as previously thought.

Despite the fact that the IMAX dark matter search is similar in spirit and technique to the ground-based experiment by Barish *et al.*, our work was unprecedented for several reasons. First and foremost, dark matter hunters have rarely searched for dark matter particles at balloon or satellite altitude. Second, usually when a search for dark matter particles at balloon or satellite altitude has been performed, the experimenters have been unable to reject the background with flux ~ 1 cm^{-2}s^{-1}sr^{-1} from ordinary cosmic rays, which deposit energies of > 2 MeV/g/cm^2. Our search for IMPs with a four-fold delayed coincidence between the four scintillation detectors in the IMAX stack was the first dark matter particle search experiment flown at balloon altitude which could reject the cosmic ray background to a flux level of $\sim 10^{-5}$ cm^{-2}s^{-1}sr^{-1} and have a relatively small energy-loss threshold ($dE/dx\,(\mathrm{THR}) \sim 3.5$ MeV/g/cm^2). This article briefly discusses the results of our balloon-borne dark matter search — for more details, see Ref.[4].

2. THE IMP SEARCH EXPERIMENT & RESULTS

The parameters of the IMAX balloon flight opportunity are listed in Table 1. In order to search for IMPs over a wide range of velocities, $\beta = (0.33$ to $3.3) \times 10^{-3}$, triggering is accomplished in a specially designed detector module with a series of delayed coincidence gates. All 4 time intervals and 3 pulse heights are readout by an ORTEC 811 ADC CAMAC module.

Number of scintillation counters	4
Total thickness of counters	5 g/cm^2
Total thickness of material above counter telescope (including 5 g/cm^2 atmosphere)	6 g/cm^2
Total thickness of material between counters	8 g/cm^2
Total thickness to reach and traverse experiment	19 g/cm^2
Geometry factor	$\Omega = 100$ cm^{2}sr
Time at float altitude (for high quality DM data)	$t = 1.8 \times 10^4$ seconds
IMP velocity range	$\beta = (0.33$ to $3.3) \times 10^{-3}$
Trigger thresholds in 1 cm plastic scintillators: $\beta \approx 1, Z = \pm 1$, 35% of Landau peak of MIPs in 1 cm; $dL/dx = 0.018$MeV/cm $Z = +1$ IMPs (e.g. X^+ and $X^- - \alpha$ CHAMPs), monopoles, dyons,(1/5)e superstring particles are all above threshold over full IMP velocity range listed above	

Table 1: Parameters of IMAX Balloon-Borne Experiment

The wide coincidence timing gates (μs instead of ns) ensured a steady stream of accidental coincidences uniformly distributed in each time gate, the principal background for the IMP search. The accidental rate $A(n)$ for n counters is proportional to each counter's singles rate and to the gatewidths for each of the delayed coincidences. At float altitude, $R_i \approx 3500$ Hz for each counter, and with the gate widths as given in Ref. [4], $A(3) \approx 4$ Hz; about 44×10^3 events were recorded (reduced somewhat by deadtime) during the five hours of excellent IMP search data at float altitude. The time-interval distributions are uniform, as expected, except for the peaks in T_{12} and T_{23} which are due to anomalous events, of unknown origin, which are eliminated from the data set when the velocity limits, $v_{\min} = 0.1\mathrm{m}/\mu\mathrm{s}$, $v_{\max} = 0.67\mathrm{m}/\mu\mathrm{s}$, corresponding to the limits of the T_{34} distribution, are applied to T_{12} and T_{23}. Since $A(4) \approx 0.055$ Hz, 653 four-fold accidental coincidences were observed during the five hour observation period. However, if the three independent time measurements must be consistent in the data analysis with the time delays of an IMP traversal within, say, $\pm 1\sigma$, where $\sigma = 2\%$, then two of the timing gates are effectively narrowed; one of the gates is not narrowed since the IMP is allowed to have any velocity consistent with the gate widths. Then the effective accidental rate is $A(4) = 2.6 \times 10^{-4}$ Hz, corresponding to $N_{\mathrm{IMP}} \sim 5$ accidental events which mimic IMP traversals in the 5 hours of analysed data. Thus the IMAX time-of-flight IMP search has a minimum detectable flux, $\phi_{\mathrm{IMP,\ min.\ det.}}$, at the 4σ level using $N_{\mathrm{IMP}} + N_{\mathrm{ACCID}} \geq 14$ as well as the geometry factor Ω and time t from Table 1, of $\phi_{\mathrm{IMP,\ min.\ det.}} = 5 \times 10^{-6}\ \mathrm{cm^{-2}s^{-1}sr^{-1}}$(see Tables 2 and 3 for our actual results).

When we assume a specific IMP-nucleus interaction model to parametrize the different IMP scattering cross-sections with different nuclei, we indeed find that our IMP search does place useful *new* constraints on IMP parameter space, closing a wide-open window in parameter space ($10^6 < m_x < 10^8$ GeV; see Figure 1). The windows shown here are from the Starkman *et al.* interpretation, adapted from and including the results of the recent BPRS publication. We eliminate a large fraction of the remaining window W_2 for the coherent IMP-nucleus interactions. The remaining portion of the window W_2 can be constrained by a sea level IMP search with low thresholds and a significant background rejection capability.

Search	$\frac{dE}{dx}(THR)$	$\sigma_{\min}(\mathbf{cm^2})$	$a_1^{\max}\ (\frac{\mathrm{cm}^2}{g})$	$(\frac{\sigma}{m_x})^{\max}\ (\frac{\mathrm{cm}^2}{\mathrm{GeV}})$	$\mathbf{A\Omega}$ **($\mathbf{cm^2sr}$)**
$\Delta v \approx 0$	3.0	6.2×10^{-21}	0.013	2.31×10^{-26}	100
small Δv	3.0	6.2×10^{-21}	0.07	1.2×10^{-25}	100
large Δv	3.0	6.2×10^{-21}	0.123	2.1×10^{-25}	100
Triples	3.0	6.2×10^{-21}	0.123	2.1×10^{-25}	135
Singles Rate	0.9	1.6×10^{-21}	0.38	3.3×10^{-25}	9120

Table 2: Summary of IMAX Results, part 1. For each IMP search, we tabulate the energy loss detection threshold ($dE/dx(THR)$($\mathbf{MeV/g/cm^2}$)), the corresponding threshold cross-section including the β^2-dependence of dE/dx ($\sigma_{\min}$), the maximum slowing down rate ($a_1^{\max}$), the corresponding maximum elastic cross-section to mass ratio ($(\sigma/m_x)^{\max}$), and the geometry factor ($\mathbf{A\Omega}$) for the search.

Search	**N**	**B**	$n_{s,\max}$	$\phi_{\max}(\frac{1}{\mathrm{cm^2 s\ sr}})$	$m_{\max}$ **(GeV)**
$\Delta v \approx 0$	5	4.0 ± 0.3	9.1	6.5×10^{-6}	1.5×10^{11}
small-Δv	5	7.5 ± 0.1	6.9	4.9×10^{-6}	2.0×10^{11}
large-Δv	16	18.3 ± 2.1	11.1	7.9×10^{-6}	1.3×10^{11}
Triples	4 Hz	0 Hz	4 Hz	3×10^{-2}	3.3×10^{7}
Singles	4000 Hz	0 Hz	4000 Hz	0.44	2.27×10^{6}

Table 3: Summary of IMAX Results, part 2. For each IMP search, we tabulate the number of signal (**N**) and background (**B**) events observed, the 95% C.L. Poisson upper limit ($n_{s\max}$) on the number of IMP events, the upper limit on the flux ($\phi_{\max}$), and the maximum mass detectable ($m_{\max}$) (assuming IMPs are all the dark matter).

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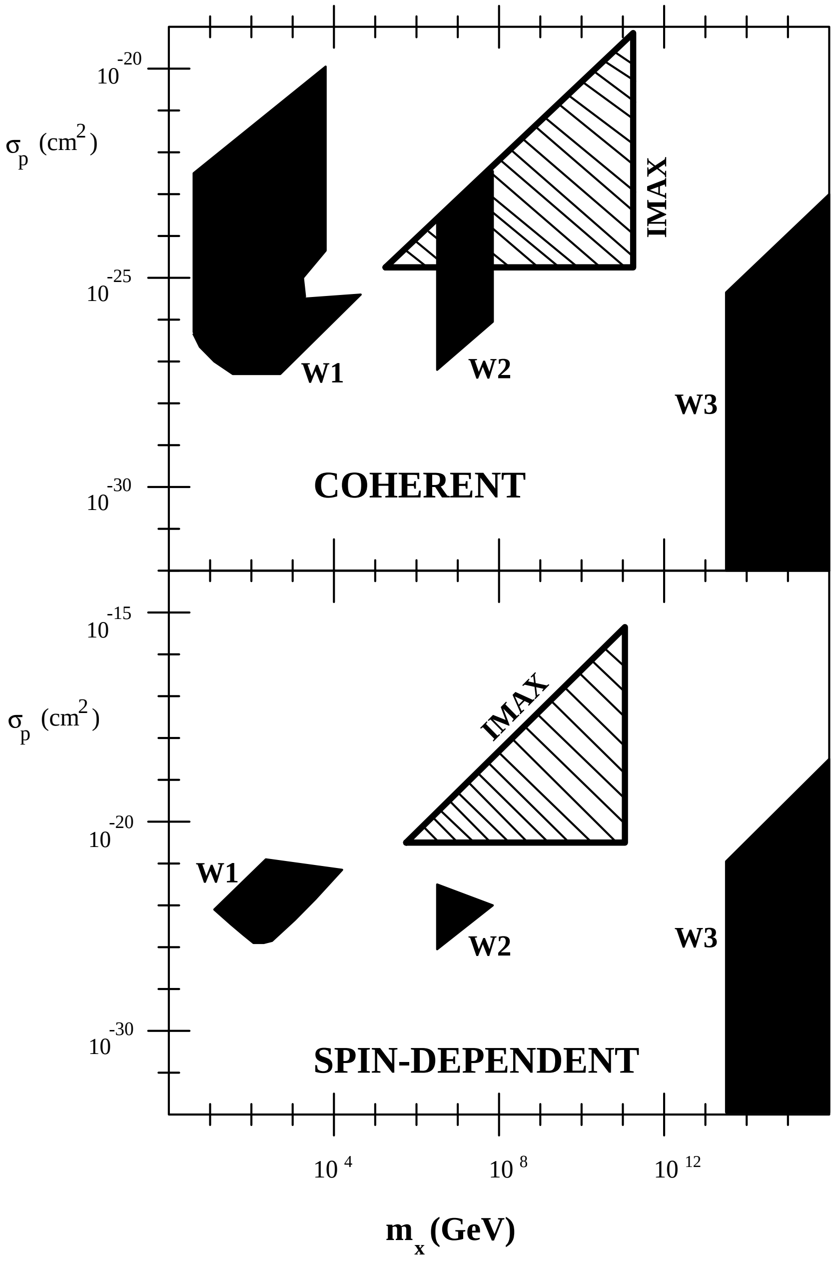

Figure 1: We show the IMAX constraints on the SIMP mass/cross-section parameter space for coherent interactions and for spin-dependent interactions. Without the IMAX results, there are three different non-excluded windows in each parameter space W_1, W_2, and W_3. The hatched areas are the IMAX excluded regions, assuming that SIMPs are all the galactic halo dark matter ($f_d = 1$).