New Experimental Limits on Strongly Interacting Massive Particles at the TeV Scale

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We have carried out a search for strongly interacting massive particles (SIMPs) bound to Au and Fe nuclei, which could manifest themselves as anomalously heavy isotopes of these elements. Our samples included gold from the NASA Long Duration Exposure Facility satellite, RHIC at Brookhaven National Laboratory, and from various geological sources. We find no evidence for SIMPs in any of our samples, and our results set stringent limits (as low as $\sim 10^{-12}$) on the abundances of anomalous Au or Fe isotopes with masses up to 1.67 and 0.65 TeV/c^2, respectively.

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Recent theoretical considerations suggest that there may exist in nature heretofore undiscovered electrically neutral strongly interacting massive particles (SIMPs), which can be detected in the laboratory through their interactions with ordinary matter. The theoretical motivation for SIMPs arises from a number of sources: SIMPs have been suggested as candidates for dark matter [1–3], as explanations for cosmic rays with energies exceeding the Greisen-Zatsepin-Kuzmin cutoff [4,5], and as candidates for the lightest supersymmetric particle [4,6,7]. Although the details of SIMP-matter interactions vary from one model to another, there is a prediction common to all models: SIMPs may bind (via strong interactions) to the nuclei of ordinary matter, and, hence, manifest themselves as anomalously heavy isotopes of existing elements.

The present paper reports new results from a high-sensitivity search for SIMPs bound to gold and iron nuclei carried out using the accelerator mass spectrometer (AMS) at PRIME Lab, the Purdue Rare Isotope Measurement Laboratory. Although similar searches have been carried out previously for SIMPs bound to light nuclei [8], for charged SIMPs in Fe [9], and in scattering experiments [10,11], this is the first search for neutral SIMPs bound to heavy nuclei. The present paper expands on the results of Ref. [12] in two significant ways: First, we report results from a wide variety of qualitatively different samples. Second, we extend the range of SIMP masses to which we are sensitive to the TeV scale, where theoretical models suggest that the discovery opportunity for SIMPs may be greater [1,6].

There are several factors motivating searches for SIMPs in gold and iron: (i) Since a heavy nucleus is larger than a light nucleus and, hence, has a larger potential well, it follows from the uncertainty principle that a particle trapped in a heavier nucleus would have a smaller momentum and thus a smaller kinetic energy. As a result, SIMPs should bind preferentially to heavy nuclei [2,12,13]. Moreover, if SIMPs were isoscalars, the forces between SIMPs and nucleons would necessarily be attractive, which would increase the likelihood of SIMPs binding to heavy nuclei [14]. (ii) Gold samples with reasonably well-known long exposure times to cosmic rays are easier to find than would be the case for other elements, since gold is relatively unreactive. (iii) Gold and iron readily form negative ions, which the AMS at PRIME Lab requires in the sample injection stage.

To maximize the possibility of detecting SIMPs, we looked for samples with exposure times to sources (and, hence, to SIMPs) which were both long and reasonably well known. Since likely sources of SIMPs are cosmic rays or a component of dark matter, we obtained several geological samples that were recovered from within ≈15 cm of the surface in regions which were relatively inactive geologically. In such regions, erosion rates can be reliably used to estimate the exposure time of each sample to these sources.

A summary of the samples we studied is given in Table I, where we present the estimated exposure times of each of the geological samples assuming a SIMP penetration depth of ∼1 m. (Other assumed penetration depth exposure times are given in Ref. [15].) The samples denoted by Laverton and Nullagine were obtained from the Leonora District in Australia, and the Arizona sample was obtained from the Mineral Park District. The remaining samples were recovered during placer mining from Golden Valley/McDowell City and Black Run Creek, North Carolina.

We also obtained three samples that came from environments which were very different from those of the geological samples, and, hence, they expand the discovery opportunity for SIMPs. The first was gold from the NASA Long Duration Exposure Facility (LDEF) satellite which was placed into a nearly circular orbit, at an altitude of ≈500 km, for 69 months from 1984 to 1990. During its 32 422 Earth orbits, LDEF experienced one-half a solar cycle, as it was deployed during a solar minimum and retrieved at a solar maximum. (For more details regarding the origin of these samples and the original LDEF experiment, see Hörz *et al.* [16] and Ref. [15].)

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TABLE I. Summary of limits on SIMP abundances in Au and Fe. For each of the geological samples in the left column, we present the estimated exposure time in millions of years (Myr). We also present the mass range for anomalous isotopes X covered by each sample, and the 95% C.L. limits on the abundance ratios, X/Au and X/Fe, for the Au and Fe samples. See text for further details.

Sample	Exposure age [Myr]	Mass range [GeV/c^2]	Limit range
Laverton	1.25	188–1669	$X/\mathrm{Au} < 6.3 \times 10^{-12}$–$1.1 \times 10^{-8}$
Nullagine	1.25	188–647	$X/\mathrm{Au} < 7.5 \times 10^{-11}$–$2.7 \times 10^{-9}$
Arizona	0.02–0.4	188–1669	$X/\mathrm{Au} < 8.9 \times 10^{-12}$–$1.5 \times 10^{-8}$
Golden Valley, NC	0.1–0.2	188–1669	$X/\mathrm{Au} < 6.5 \times 10^{-12}$–$1.1 \times 10^{-8}$
Black Run Creek, NC	0.1–0.2	188–647	$X/\mathrm{Au} < 6.6 \times 10^{-11}$–$2.4 \times 10^{-9}$
LDEF	⋯	188–1669	$X/\mathrm{Au} < 6.6 \times 10^{-12}$–$1.1 \times 10^{-8}$
RHIC	⋯	188–1669	$X/\mathrm{Au} < 6.2 \times 10^{-12}$–$1.0 \times 10^{-8}$
Meteorite	540	188–647	$X/\mathrm{Au} < 5.6 \times 10^{-9}$–$9.7 \times 10^{-9}$

We were also provided with Au from the beam dump of the Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory obtained from experiment E878. In this experiment 3.55×10^{12} gold atoms were incident on an Au target whose thickness corresponded to a 30% interaction length resulting in 7.81×10^{11} inelastic Au + Au interactions [17]. This sample allows us to explore the possibility that SIMPs were created in the Au + Au collisions and remained bound to one of the Au nuclei.

Finally, we obtained a 2995.6 g sample of meteorite which is predominantly iron (92%) and is a fragment of the much larger meteoroid that impacted the earth 50 000 yr before present at Canyon Diablo, Arizona. The meteoroid is estimated to have spent 540×10^6 yr in interstellar space [18] and, hence, has the longest cosmic ray exposure time of all the samples studied in this experiment.

These gold and iron samples were introduced into the ion source where an Au^- or Fe^- beam was formed by 6 keV Cs^+ ions sputtering the exposed surface. Following initial mass selection, the ions were accelerated to the terminal where they passed through argon gas which removed several electrons. This "stripping" stage has two effects on the ion beam: (i) Molecular contaminants in the beam which end up in a charge state $q > +3$ dissociate into individual atoms due to Coulomb repulsion from the partially shielded nuclei. (ii) By changing the sign of the charge, stripping allows the tandem to accelerate atoms both into and out of the accelerator.

The $_{79}\mathrm{Au}$ and $_{26}\mathrm{Fe}$ ions emerging from the accelerator are then passed through magnetic and electric fields which select for ions with predetermined values of ME/q^2 and E/q, respectively. Here M is the ion mass, E is the energy, and q is the final charge state. The net effect of these magnetic and electrostatic components is that ions with a predetermined M/q reach the gas ionization detector.

Since the combined magnetic and electrostatic elements select for M/q, and not for M alone, it is possible for ions with several different masses to enter the detector. These can be used to our advantage by utilizing them as guide beams, and separating them on the basis of their respective energy depositions in the detector [15,19]. A guide beam is an atomic ion beam whose M/q we may anticipate knowing *a priori* which elements are present in the sample. For example, gold ($M = 197$ u) in charge state $q = +5$ is a guide beam to test the tune of the AMS at $M_X = 276$ u running at charge state $q = +7$. These guide beams allowed us to check the tune throughout the scan, while also calibrating the detector.

As the accelerator was tuned to higher masses, the beam energy was reduced so that ME/q^2 remained constant at a value determined by the maximum magnetic field strengths. Eventually the beam energy dropped below 13.7 ± 0.2 MeV which was the minimum energy required to penetrate the 2.5 μm thick Mylar window at the entrance to the detector. It was then necessary to select a higher charge state in order to introduce a beam with a higher energy which would permit us to constrain X/Au at higher masses.

For gold, the quantity of experimental interest is the ratio X/Au, where X denotes the number of hypothetical $_{79}X$ anomalous nuclei (having a mass M_X) and Au denotes the number of $_{79}\mathrm{Au}$ nuclei in the sample. This ratio is experimentally determined by comparing the counting rate (R) of the $_{79}X$ nuclei measured by the detector in counts per minute, cpm, to the $_{79}\mathrm{Au}$ beam current (I_{det}) measured by the detector Faraday cup in nA. X/Au can then be expressed in the form

$$\frac{X}{\mathrm{Au}} = (2.672 \times 10^{-12}) \frac{qR}{I_{\mathrm{det}}} \left(\frac{\eta_{\mathrm{Au}}}{\eta_X} \right). \qquad (1)$$

In Eq. (1), q is the common charge state of the $_{79}\mathrm{Au}$ and $_{79}X$ nuclei selected by the accelerator, and η_{Au} (η_X) is the transmission efficiency for detecting $_{79}\mathrm{Au}$ ($_{79}X$). Since no counts were observed during the 1 min time interval at each mass, R is replaced by $(-\ln \varepsilon_X)/1\ \mathrm{min} = 3.00$ cpm for a 95% confidence limit (C.L.). This was derived using standard Poisson statistics given $\varepsilon_X = (1 - \mathrm{C.L.})$ [20]. Finally, the numerical coefficient in Eq. (1) is the result of converting from cpm to nA, noting that 1 count $= q|e|$, so that X/Au is dimensionless as expected.

Since the transmission efficiencies for X and Au are approximately the same through every element of the AMS with the exception of the Ar gas stripper, $\eta_{\mathrm{Au}}/\eta_X$ is the ratio the stripper yields of Au and X for a given charge state. Since stripping in Ar is a function of ion velocity and nuclear charge (Z) only, the SIMP efficiencies at different masses were modeled by those of an Au beam with the same velocity.

Figure 1 and Table I present the ratios X/Au as a function of M_X for the gold samples that were run up to 1.67 TeV/c^2, along with X/Fe for the iron meteorite sample. Note that for each sample two trends are important: First, the limits become less stringent as M_X increases. This is a consequence of the fact that higher M_X corresponds to a lower beam velocity given that ME/q^2 is fixed. Since a greater difference between the beam velocity and the Bohr velocity results in a lower stripper yield, stripping becomes less efficient with increasing M_X. Second, we note the presence of discontinuous steps which reflect the change from one observed charge state to another. The meteorite data do not exhibit these discontinuities because they were all taken at $q = +9$.

Since the Laverton and Nullagine samples came from the same general locations, we assumed that they had the same exposure, and similarly for the North Carolina samples. In both the Nullagine and Black Creek samples, only $q = +9$ was used which explains why their maximum mass range is lower than for the other samples presented in Table I. The X/Au ratios for the five gold samples along with the X/Fe ratio for the meteorite are shown in Fig. 1. No events corresponding to anomalous nuclei X were found in any of the gold samples or in the iron meteorite, and, hence, the limits shown in Fig. 1 and Table I are the bounds on X/Au and X/Fe at the 95% confidence level. We see from the table that for anomalous nuclei with masses $\approx$1.7 TeV/c^2 the bounds are on the order 1×10^{-8}.

In summary, we have presented in this paper new experimental limits on the abundances of anomalously heavy Au isotopes obtained from a variety of Au samples. We also present similar limits for anomalous Fe isotopes obtained from a meteorite sample. It should be emphasized that, although the limits themselves are model independent, the implications to be drawn from them are not. Our primary objective has been to interpret these limits as constraints

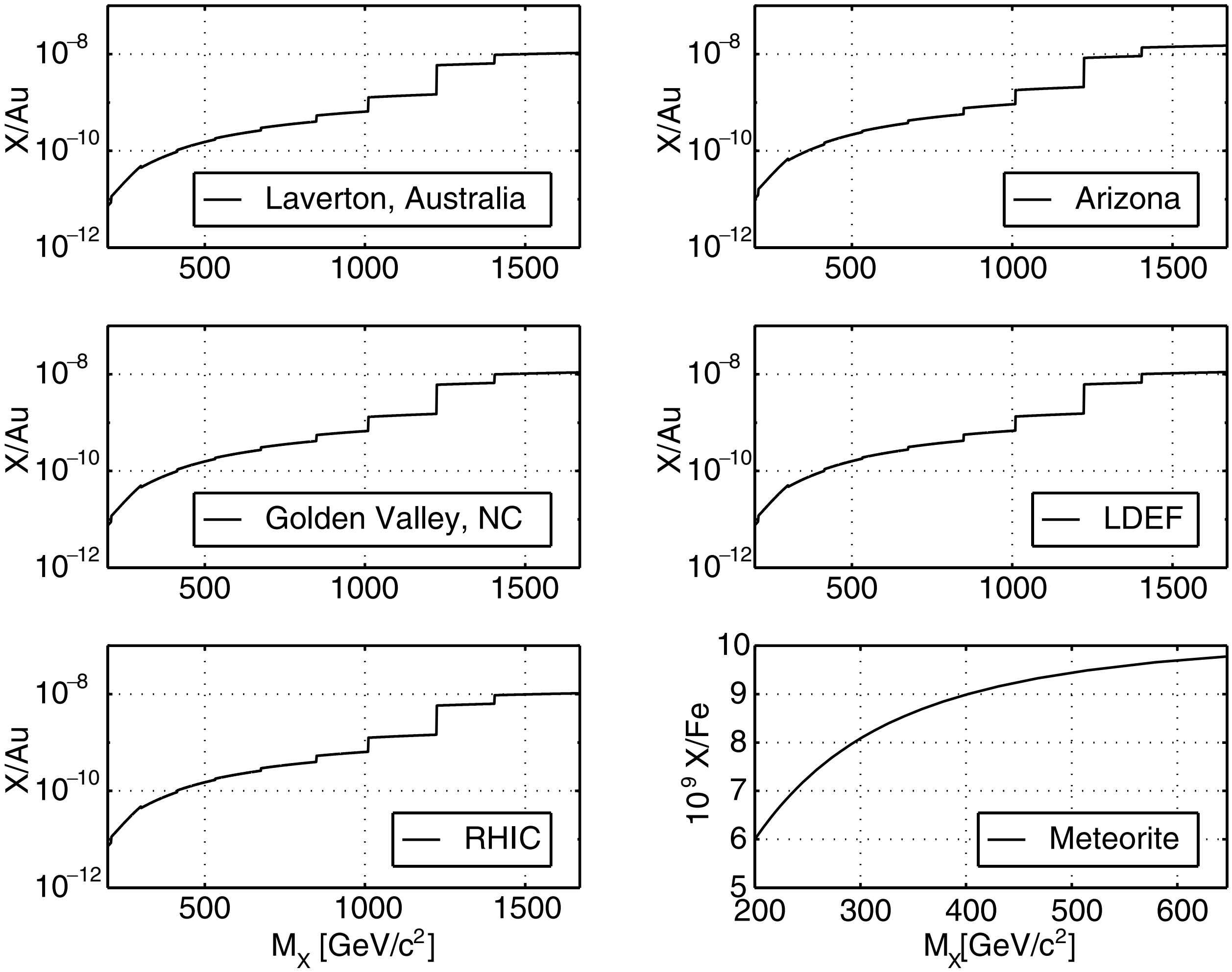

FIG. 1. The X/Au ratios for the five different ${}_{79}\mathrm{Au}$ samples, along with the X/Fe ratio for the ${}_{26}\mathrm{Fe}$ meteorite. Since no evidence for anomalous nuclei was seen in any of the samples, the limits expressed are the bounds on the corresponding ratios at the 95% confidence level. See text and Ref. [15] for further details.

on the mass M_X of a hypothetical massive SIMP bound to an Au or Fe nucleus. Such constraints are model dependent and techniques for their derivation are provided in Refs. [12,13] (see [21]). We note, however, that our results could also be interpreted as setting limits on anomalous stable heavy Au and Fe nuclei containing a large neutron excess.

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[1] G. D. Starkman *et al.,* Phys. Rev. D **41**, 3594 (1990).

[2] R. N. Mohapatra and V. L. Teplitz, Phys. Rev. Lett. **81**, 3079 (1998).

[3] S. Dimopoulos *et al.,* Phys. Rev. D **41**, 2388 (1990); E. Nardi and E. Roulet, Phys. Lett. B **245**, 105 (1990); R. S. Chivukula *et al.,* Phys. Rev. Lett. **65**, 957 (1990).

[4] R. N. Mohapatra and S. Nussinov, Phys. Rev. D **57**, 1940 (1998).

[5] V. S. Berezinskiĭ and B. L. Ioffe, Sov. Phys. JETP **63**, 920 (1986); D. J. H. Chung, G. R. Farrar, and E. W. Kolb, Phys. Rev. D **57**, 4606 (1998); I. F. M. Albuquerque, G. R. Farrar, and E. W. Kolb, Phys. Rev. D **59**, 015021 (1998).

[6] V. Berezinsky and M. Kachelrieß, Phys. Lett. B **422**, 163 (1998).

[7] R. N. Mohapatra and S. Nandi, Phys. Rev. Lett. **79**, 181 (1997); S. Raby, Phys. Rev. D **56**, 2852 (1997); Z. Chacko *et al.,* Phys. Rev. D **56**, 5466 (1997); A. Mafi and S. Raby, Phys. Rev. D **62**, 035003 (2000); Phys. Rev. D **63**, 055010 (2001).

[8] T. K. Hemmick *et al.,* Phys. Rev. D **41**, 2074 (1990).

[9] E. B. Norman, S. B. Gazes, and D. A. Bennett, Phys. Rev. Lett. **58**, 1403 (1987).

[10] J. Rich, R. Rocchia, and M. Spiro, Phys. Lett. B **194**, 173 (1987).

[11] R. Bernabei *et al.,* Phys. Rev. Lett. **83**, 4918 (1999), and references therein.

[12] D. Javorsek II *et al.,* Phys. Rev. D **64**, 012005 (2001).

[13] R. N. Mohapatra *et al.,* Phys. Rev. D **60**, 115013 (1999).

[14] G. Farrar (private communication).

[15] D. Javorsek II, Ph.D. thesis, Purdue University, 2001 (unpublished).

[16] F. Hörz *et al.,* in *LDEF–69 Months in Space: First LDEF Post-Retrieval Symposium,* NASA Conference Publication No. 3134 (1991), p. 487.

[17] S. Aronson (private communication).

[18] D. Heymann *et al.,* J. Geophys. Res. **71**, 619 (1966).

[19] D. L. Knies and D. Elmore, Nucl. Instrum. Methods Phys. Res., Sect. B **92**, 134 (1994).

[20] Particle Data Group, D. E. Groom *et al.,* Eur. Phys. J. C **15**, 1 (2000).

[21] Assumptions are needed as to the $S\overline{S}$ annihilation cross section and the $S - N$ cross section in order to determine the SIMP contribution to the dark matter, the minimum A to which a SIMP will bind, and the depth to which an incident SIMP penetrates into the earth as a function of SIMP mass and energy. In terms of the results of [13], the present experiment rules out SIMPs with low cross sections and low mass (providing these parameters are greater than the minima needed for binding). A detailed discussion of the cosmological constraints implied by our work is given by Javorsek, Fischbach, and Teplitz (to be published).