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Death and serious injury from dark matter

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ABSTRACT

Macroscopic dark matter (macros) refers to a class of dark matter candidates that scatter elastically off of ordinary matter with a large geometric cross-section. A wide range of macro masses M_X and cross-sections σ_X remain unprobed. We show that over a wide region within the unexplored parameter space, collisions of a macro with a human body would result in serious injury or death. We use the absence of such unexplained impacts with a well-monitored subset of the human population to exclude a region bounded by $\sigma_X > 10^{-8} - 10^{-7}$ cm^2 and $M_X < 50$ kg. Our results open a new window on dark matter: the human body as a dark matter detector.

1. Introduction

The evidence for dark matter is overwhelming (see, e.g., [1] and references therein), but the nature of dark matter remains one of the great unsolved mysteries of modern cosmology. Recently, Jacobs, Starkman, and Lynn [2] explored the proposition that the dark matter might be macroscopic, in the sense of having a characteristic mass M_X and cross-sectional area in the gram and cm^2 range, respectively. In this model, the macroscopic dark matter objects (dubbed "macros") have a geometric cross section σ_X equal to the cross-sectional area of the macro.

Macros are most likely composites of more fundamental particles. An intriguing possibility is that macros could be made of Standard Model quarks or baryons bound by Standard Model forces. This suggestion was originally made by Witten [3], in the context of a first-order QCD phase transition early in the history of the Universe. A more realistic version was advanced by Lynn, Nelson and Tetradis [4] and Lynn [5] in the context of $SU(3)$ chiral perturbation theory. They argued that "the true bound state of nuclei may have two thirds of the baryon number consisting of strange quarks and that ordinary nuclei may only be metastable." Nelson [6] studied the possible formation of such "nuggets of strange baryon matter" in an early-universe transition from a kaon-condensate phase of QCD to the ordinary phase. Others have suggested non-Standard Model versions of such nuclear objects and their formation, for example incorporating the axion [7].

Once the mass and cross-section of the macros are specified, the internal density of an individual macro is completely determined by the fact that the cross-section is geometric. Macros corresponding to the models mentioned in the previous paragraph would most likely have densities that are comparable to nuclear density (which we take to be $\rho_{nuclear} = 3.6 \times 10^{14}$ g cm^{-3}). This is much higher than ordinary "atomic density" ($\rho_{atomic} = 1$ g cm^{-3}), but much lower than the density of black holes. Although macros of approximately nuclear density are of particular interest, other densities are not excluded at this point, so we will consider the full range of possibilities for M_X and σ_X. Note that macros that form prior to $T \sim 1$ MeV are not subject to the bounds on the baryon density from Big-Bang nucleosynthesis.

Previous work has placed a wide range of constraints on macro masses and cross sections from purely phenomenological considerations, which are displayed in Fig. 1. For macro masses $M_X \leq 55$ g, careful examination of specimens of old mica for tracks made by passing dark matter [8,9] has ruled out such objects as the primary dark-matter candidate (see Fig. 1). For very large macro masses ($M_X \geq 10^{24}$ g), a variety of microlensing searches have similarly constrained macros [10–13]. A large region of parameter space was constrained by considering thermonuclear runaways triggered by macros incident on white dwarfs [14]. For sufficiently large σ_X, scattering between photons and macros will distort the fluctuation spectrum of the cosmic microwave background. Reference [15] utilized the first year release of Planck data to place constraints on σ_X and M_X.

A number of other constraints have been proposed recently. It has been suggested that ultra-high-energy cosmic-ray detectors that exploit atmospheric fluorescence could be modified to probe parts of macro parameter space [16], including macros of nuclear
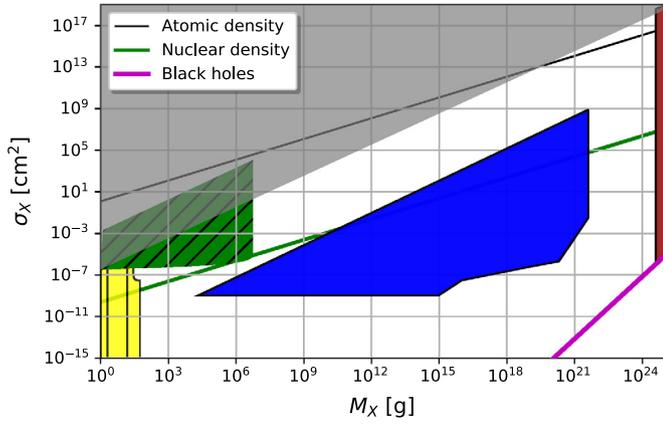
Fig. 1. Constraints for macros over a wide range of masses and cross-sections. Constraints in yellow are derived from a lack of tracks in an ancient slab of mica [8,9], in grey from the Planck Cosmic Microwave Background data considering elastic macro-photon interactions [15], in red from microlensing experiments [11–14] and in blue from thermonuclear runaway in white dwarfs [15]. We have also presented projected regions of parameter space accessible by future searches. The region in green with hatching represents the union of the region accessible using the Pierre Auger Observatory [16], the JEM-EUSO planned experiment [16], and a search of ≈ 100 slabs of commercial granite [17]. The granite-slab search could be scaled up to access much larger macro masses (and smaller fluxes), e.g. through a citizen science program, which is the goal of two of the authors (JSS and GDS) once a preliminary search has been completed.

density and intermediate mass. Macros with $\sigma_x \geq 10^{-6}$ cm^2 were shown to be able to produce an observable fluorescence signal assuming changes to the time binning mechanism of a typical fluorescence detector. It has also been suggested that the approach applied to mica could be adapted to a larger, widely available sample of granite, to search for larger-mass macros [17]. Both these methods have the potential to probe masses exceeding 10^6 g, and the combined parameter space that could be probed is highlighted in green with hatching in Fig. 1.

In this manuscript, we consider the phenomenology of such objects and, in particular, their effects on the human population. We derive a new constraint on some region of the allowed macro parameter space, by noting that for a range of macro masses and cross sections, collisions of macros with the human population would have caused a detectable number of serious injuries and deaths with obvious and unusual features, while there have been no reports of such injuries and deaths in regions of the world in which the human population is well-monitored. (Previously, others [18] have considered the effects of weakly interacting massive particle (WIMP) collisions with the human body, with the conclusion that WIMPs would be essentially harmless.)

2. Derivation of constraints

Consider a macro with cross section σ_X and velocity v_X passing through the human body. The energy per unit length deposited by a macro through elastic scattering on any target is

$$\frac{dE}{dx} = \sigma_X \rho v_X^2, \tag{1}$$

where ρ is the density of the target. As in previous studies, we assume a sufficiently strong interaction between macros and baryonic matter that σ_X is given by the geometric cross section. For human tissue, a good approximation for the target density is the density of water: $\rho \sim 1$ g cm^{-3}.

To determine the amount of damage produced by a macro collision, we make an analogy to gunshot wounds (although there are significant differences, which we will discuss below). Bullets cause injury to the human body from a combination of permanent cavitation, temporary cavitation, and pressure waves [19]. While these

are complex processes, it is generally believed that the overall tissue damage depends primarily on the kinetic energy deposited in the body. This is the key assumption we make in this paper: the amount of damage caused by a macro will scale as the kinetic energy, and the damage produced will be similar to that of a bullet that deposits a similar amount of kinetic energy. Bullets in general have muzzle kinetic energies in the range of 100-10000 J [20], although only a fraction of the muzzle kinetic energy is deposited unless these bullets stop inside the body. As our benchmark for "significant" damage to the human body, we will take the muzzle energy (100 J) from a .22 caliber rifle [20,21]. This is the smallest rifle in common use but is still capable of inflicting serious injury. Hence we will require at least 100 J to be deposited by the macro as it traverses a human body. To determine the total energy deposited, we multiply dE/dx in Eq. (1) by the path length of the macro inside the human body, which we assume to be ~ 10 cm.

Of course, we are working with a very different range of projectile sizes and velocities from typical bullets. Macros have hypersonic velocities but very small geometric cross sections in our parameter range of interest (as small as 1 micron^2). Hence, their destructive effect is likely to be qualitatively different from that of a bullet; a macro impact typically heats the cylinder of tissue carved out along its path to a temperature of 10^7 K [16,17], resulting in an expanding cylinder of plasma inside the body. While some studies have been done on collisions of hypersonic, micronsized projectiles with fixed targets [22], these differed significantly from macro collisions in that the experimental projectiles were of much lower density, and the targets were "hard" rather than "soft." Nonetheless, it is reasonable to take the kinetic energy deposited by a macro as a threshold for significant damage to the human body. Energy conservation requires that the macro energy ultimately be deposited in the body in some form, whether mechanical or thermal, which will result in an equivalent amount of damage. If anything, the unusual form of damage caused by a macro strike is likely to be *more* obvious and easily detected than that of a bullet wound.

We now perform a more detailed calculation. We first require that the energy loss of the macros in traversing the atmosphere be negligible, so that the macros reach their targets on the ground with undiminished velocity. We find that this corresponds to the bound $\sigma_X/M_X \sim 10^{-4}$ cm^2 g^{-1}. Macros above this threshold lose a significant amount of their energy in the atmosphere and are therefore unconstrained by the argument considered here. This consideration produces the diagonal upper bound on the blue excluded region in Fig. 2. Limiting our discussion to macros satisfying this bound allows us to neglect shielding from buildings, automobiles, or similar objects, since the column density of the atmosphere is much larger than the column density of most inhabited structures.

To determine the minimum macro cross section needed to cause significant human injury, we assume macros possess a Maxwellian velocity distribution

$$f_{MB}(v_X) = \left(\frac{1}{\pi v_{vir}^2}\right)^{\frac{3}{2}} 4\pi v_X^2 e^{-\left(\frac{v_X}{v_{vir}}\right)^2}, \tag{2}$$

where $v_{vir} \approx 250$ km s^{-1}. This distribution is slightly modified by the motion of the Earth [23]. We have also truncated this distribution at the galactic escape velocity at the position of the Solar System in the galaxy $v_{esc} \sim 550$ km s^{-1}. Taking into account the distribution (2), multiplying Eq. (1) by a path length of 10 cm and requiring the total energy deposited to be of order 100 J or greater, we obtain the lower bound on σ_X in our excluded region shown in Fig. 2. This lower bound on the excluded region varies slowly with M_X but is roughly $\sigma_X \sim 10^{-7}$ cm^2. Macros with cross sections be-
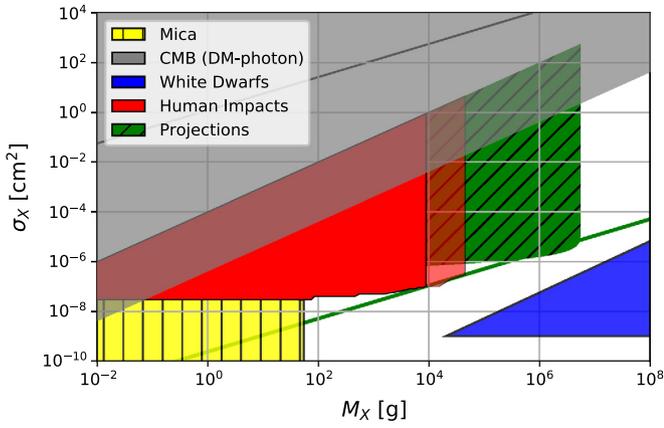
Fig. 2. Constraints in yellow are derived from a lack of tracks in an ancient slab of mica [8,9], in grey from the Planck Cosmic Microwave Background data considering elastic macro-photon interactions [10], in red from a lack of human impacts (this work) and in blue from thermonuclear runaway in white dwarfs [14]. The red excluded region is based on fewer than 10 macro deaths (medium red), and zero macro deaths (light red) over the past 10 years in the population of the US, Canada, and Western Europe. The green hatched region represents projections from other proposed ways of probing macro parameter space [16,17].

low this bound would deposit less than 100 J per human impact, so their interactions with human bodies might not be noticeable.

For macros that have large enough cross sections to cause serious human injury or death, the rate of injuries is proportion to the macro number density. If we assume that the macros constitute the dark matter, the total macro energy density is fixed at $\rho_{DM} \approx 5 \times 10^{-19}$ g m^{-3} [24], and the macro number density is inversely proportional to the macro mass: $n_X = \rho_{DM}/M_X$. Thus, the number of macro-human interaction events scales inversely as M_X, and our excluded region will extend out to some upper bound on M_X. To determine this upper bound, we argue that there have been no unexplained injuries or deaths characteristic of macro collisions among the well-monitored population of the Western countries. Although there are many sudden unexpected deaths daily, and a small fraction of these cannot be explained even following autopsy, a death due to a macro strike would produce a striking signature, most likely a cylinder of vaporized tissue surrounded by a larger cavity, with no projectile in evidence. If the death occurred indoors, there would also have been associated damage to the structure, furnishings, *etc.* We assume that any such deaths would have been easily detected and well reported. Hence, it is reasonable to take the observed number of such deaths in Western countries over the past 10 years to be zero.[1] The expected number of macro passages through a population of N humans depends on M_X as

$$N_{events} = f \frac{\rho_{DM} N A_{human} T_e v_X}{M_X} , \tag{3}$$

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[1] At the low-energy (low cross-section) end of our constrained region, the destruction from a macro would be similar to a gunshot, as we have noted in our paper. Note that deaths in this manner are always investigated by the authorities, with autopsies performed. Furthermore, forensic pathologists go to great lengths to rule out other causes of death, and occasionally discover that what appears to be a gunshot death is, in fact, due to an entirely different cause (see, for example references [25,26]). It is unlikely that a macro injury of this type would not be noted and reported upon autopsy.

The collision with a larger macro would likely produce a much more destructive event. It would be similar, in sheer destructive ability, to a meteor strike. However, it is believed with a high degree of confidence that no one, in modern times, has been killed by a meteorite (see, e.g., references [21,27]). Given that the impact of a large macro would be even more striking than a meteorite and leave even more unambiguous evidence, we feel confident that such an event can be excluded.

where $A_{human} \sim 1$ m^2 is the typical cross-sectional area of a human, $N \approx 8 \times 10^8$ is the population of the US, Western Europe and Canada and T_e is the exposure time, which we take to be 10 years. We also take into account the distribution (2) by adding in an additional factor f accounting for the fraction of macros in the distribution that possess a minimum velocity. Considering the entire distribution, we find that

$$N_{events} \approx \frac{80000g}{M_X} . \tag{4}$$

Since the impact of a macro on a human is a Poisson process, the probability $P(n)$ of n impacts over the exposure time T_e follows the Poisson distribution:

$$P(n) = \frac{N_{events}^n}{n!} e^{-N_{events}} , \tag{5}$$

where N_{events} is the expected number of events per interval, as calculated in equation (4). Having observed no macro-related deaths or serious injuries over 10 years in this population, we may constrain $M_X \leq 5 \times 10^4$ g at the 95% level; this is the vertical line demarcating the right-hand boundary of the excluded region in Fig. 2. To be conservative, we have also considered the possibility of a nonzero number of macro deaths. The corresponding limits are displayed in Fig. 2 for 10 deaths over the past 10 years (medium red). We see that even in this case we can exclude a significant region of parameter space not currently constrained by the geological (mica) limits.

Our excluded region, then, is the roughly triangular region shown in Fig. 2. While it does have some overlap with the mica constraint, it also excludes a wide range of previously-allowed parameter space. One might hope that stronger limits could be derived, e.g., from domestic livestock or wild animals, but this is not the case. The biomass of livestock is roughly twice the biomass of humans [28], but the deaths of domestic animals are considerably less well-monitored. Furthermore, livestock and humans together outmass all wild vertebrates combined, with the exception of fish [28], so it is unlikely that useful constraints could be derived from the deaths of wild animals.

3. Conclusion

We have considered a phenomenological approach and constrained the abundance of macros over the relevant mass range based on the null observation of unique human injuries/deaths. These new limits complement the searches proposed in Refs. [16, 17]. The results presented here constrain macros with physical sizes as small as several microns and masses less than 50 kg (Fig. 2); these are significantly smaller than the cross-sections that we expect to probe in [16,17] over the same mass range. However, the methods outlined in [16,17] will be able to probe larger masses than those constrained in this manuscript. Admittedly, the effect of impacts of hypersonic objects smaller than a few microns on the human body remains an open question, so more detailed analysis might allow constraints on even smaller macro cross sections. Regardless, our results open a new window on dark matter: the human body as a dark matter detector.

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