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A balance for dark matter bound states

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ABSTRACT

Massive particles with self interactions of the order of 0.2 barn/GeV are intriguing Dark Matter candidates from an astrophysical point of view. Current and past experiments for direct detection of massive Dark Matter particles are focusing to relatively low cross sections with ordinary matter, however they cannot rule out very large cross sections, $\sigma/M > 0.01$ barn/GeV, due to atmosphere and material shielding. Cosmology places a strong indirect limit for the presence of large interactions among Dark Matter and baryons in the Universe, however such a limit cannot rule out the existence of a small sub-dominant component of Dark Matter with non negligible interactions with ordinary matter in our galactic halo. Here, the possibility of the existence of bound states with ordinary matter, for a similar Dark Matter candidate with not negligible interactions, is considered. The existence of bound states, with binding energy larger than ~ 1 meV, would offer the possibility to test in laboratory capture cross sections of the order of a barn (or larger). The signature of the detection for a mass increasing of cryogenic samples, due to the possible particle accumulation, would allow the investigation of these Dark Matter candidates with mass up to the GUT scale. A proof of concept for a possible detection set-up and the evaluation of some noise sources are described.

1. Introduction

There is experimental evidence, in nature, for the existence of particle bound states for three out of four known interactions and, in general, occurrence of bound states can be expected for a large variety of attractive potentials. In particular, apart from the details of the potential behavior, it is expected that a bound state should exists for a particle of mass M in a potential of range $< r >$, if the coupling satisfies the relation: $\alpha \gg \frac{\hbar c}{<r>M}$. Despite the expected tiny interaction, the possibility of having bound states with Dark Matter particles was already considered in literature for a quite large variety of scenarios. We report some of them for reference:

– Monopolonium [1], that is a long living bound state of a Magnetic Monopole with its antiparticle. In general, it is expected that a Magnetic Monopole itself can form bound states also with nuclei [2,3].
– Terafermion Dark Matter or "Dark Atoms" [4–6], where the bound state of heavy charged fermions and the Helium nucleus are proposed as Dark Matter in the SU(3) × SU(2) × SU(2)' × U(1) extension of SM or in walking Technicolor models.
– WIMPonium [7–9], where the phenomenology of a bound state, composed by two WIMP Dark Matter particles, is considered for the indirect detection or for production at colliders [10,11], with particular interest in the possible existence of a new light massive particle mediator of the interaction [12,13].
– Atomic Dark Matter [14,15], composed by particles interacting in the Dark Sector as, for example, in the case of millicharged Dark Matter [16–20], that naturally arises in the mirror matter scenario [21,22].

We note that most of the proposed scenarios are focusing on the consequences of bound states, between two Dark Matter particles [23]. In this framework it is important to note that, recently, some astrophysical/cosmological hints, for a self interacting nature of the Dark Matter particles, have been reported, such as: gravitational lensing measurement of the galaxy cluster Abell 3827 [24] or the improved fit of Cosmic Microwave Background measurements with Large Scale Structure, when considering Dark Matter particles interacting with dark radiation [25]. Moreover, self-interacting Dark Matter, with mass M_W and cross section $\sigma_W/M_W \sim 0.2$ barn/GeV, seems to be compatible with cosmological N-body simulations of the halo structure, from the scale of spiral galaxies to galaxy clusters [26,27]. On the other hand, the measurement of gravitational lensing in galaxy cluster collisions offers an upper

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limit $\sigma_W/M_W < 0.83$ barn/GeV for the possible Dark Matter self interaction cross section [28].

Regarding the possibility of the existence of large elastic scattering cross section of Dark Matter with Baryons, strong limits arise from cosmology (see e.g. [29]). However these limits cannot exclude that a small subdominant fraction of the Dark Matter in the Universe could experience large scattering cross sections with ordinary matter.[1] Therefore in case of Dark Matter candidates with large elastic scattering with Baryons, we assume in the following that they represents only a small subdominant component of the Dark Matter in the Universe and cannot account for all the expected Dark Matter.

In the particular case of a strong interaction model for the large cross section with the ordinary matter, various experimental limits, from satellites, balloons and Gravitational wave bar detectors, exclude nucleon cross sections below ~ 0.01 barn/GeV, for M_W up to few 10^{18} GeV [33–35]. Lower cross sections can be excluded by underground detectors and study of ancient Mica samples [36]. Since strong interaction usually implies also self interaction, assuming a similar cross section for the two processes, the aforementioned limits for self-interaction cross section should be also considered. In this framework, it is interesting to note that the window for cross sections in the range $0.01 < \sigma_W/M_W < 0.83$ barn/GeV and for $M_W > 10^5$ GeV, that would be compatible with the above mentioned astrophysical and cosmological hints for self-interacting Dark Matter, is also very difficult to test in laboratory, since the Dark Matter particles would lose most of their kinetic energy crossing the atmosphere or, also, crossing a relatively small thickness of soil.

It is possible to derive some additional constraints for these Dark Matter candidates (ruling out the scenario where Strongly Interacting particles are the dominant form of Dark Matter) paying the price of some additional assumptions on the cross section, as the possibility of annihilation in the core of the celestial bodies like the Sun or the Earth [37], or considering the production of a diffuse γ ray excess in the space, because of π^0 produced by cosmic ray proton inelastic scattering on Strongly Interacting Dark Matter. In the latter case, Dark Matter particles with energy independent cross section are practically excluded, whereas $1/v$ or steeper cross section scaling are allowed [38]. All these limits are somehow model dependent. As a simple example, some of them could be loosen in case of a Dark Matter candidate with dominant Leptophilic/Protophobic interaction [13]; therefore, they cannot prevent interest in further experimental investigation of Dark Matter candidates in this large cross section region.

In this paper, the phenomenology of possible occurrences of bound states, for Dark Matter particles with ordinary matter (nucleus, electron or molecule) in a hypothetical detector, will be described in a model independent approach.[2] Some new signatures could be considered for the experimental investigation of these particular Dark Matter models.

As suggested also in [3,6], bound states, with very large binding energy with nuclei, could be detected searching for the existence of anomalous heavy isotopes or anomalous atomic transitions or it could lead to sizable effects in atomic and material physics. Therefore, in the following we will focus mainly on the existence of states with small binding energy $\Delta E \ll 25$ meV, i.e. bounds that would be not stable at room temperature and that would escape the traditional detection techniques. In this case, on our planet, a similar bound state could form and survive only within cryogenic samples of low enough temperatures and it would melt when the sample is reheated to room temperature, releasing all the condensed Dark Matter particles. An interesting feature of this process would be its reproducibility by varying the final temperature of the sample.

2. Survival conditions for dark matter bound states

Since the exact nature of the Dark Matter particle, its mass and its interactions are unknown, we will evaluate the survival condition of a bound state of a Dark Matter particle with ordinary matter in a wide framework. In particular, we will simply assume that a Dark Matter particle of mass M_W will experience an attractive potential with the target particle of mass M_A, that allows the formation of a bound state of energy ΔE. The target particle could be either a nucleus, the whole atom or even a molecule, since we are not making assumptions on M_W and its interactions. For the formation of the bound state, we have also to consider the existence of some energy dissipation mechanism: this role could be easily fulfilled by the target particle that could radiate a photon or could transfer energy in collisions. It is not necessary to model this process in detail and in the following it will be described by the velocity dependent capture cross section parameter[3] σ_c. Once the Dark Matter particle is captured in the bound state, the target particle will experience collisions with the other particles in the hosting material, gaining enough velocity to break the bond. Thermodynamically, the bound state is melting at a temperature over the critical temperature T_c. In the following, we can evaluate the order of magnitude of T_c in the classical approximation. Assuming Maxwellian velocity distributions of the target in the material, after a collision, the average target velocity is $< v_A > \simeq \sqrt{3kT/M_A}$, therefore, considering the Dark Matter - target pair center of mass frame, the bond will not break if:

$$\Delta E > \frac{M_A}{2} < v_A >^2 \frac{M_W}{M_W + M_A} \quad (1)$$

Therefore a bound state of energy ΔE would survive if:

$$kT < kT_c \simeq \Delta E \frac{M_W + M_A}{M_W} = \Delta E \frac{M_A}{\mu} = \Delta_{eff} \quad (2)$$

where μ is the reduced mass. This imply that for the same ΔE a bound with "light" DM particles will melt at higher temperatures w.r.t. to "heavy" DM particles.

2.1. Condensation of Dark Matter in cryogenic samples

Let us consider a macroscopic detector, made of targets of mass M_A, with a total mass M_D, surface S and thickness $h \ll S$, the probability for a capture of a DM particle in the time interval dt is:

$$dP = dtS\left\langle \Phi\left(1 - e^{-h\sigma_c \rho_D/M_A}\right)\right\rangle_v = \frac{dt}{\tau} \quad (3)$$

where ρ_D is the detector density, Φ is the Dark Matter flux that is a function of the Dark Matter velocity v as well as the capture cross section σ_c.

In general, an increase of the capture cross section is expected for low velocity, therefore it is possible that, for high enough cross sections, the Dark Matter particle at ground has already lost most of the initial kinetic energy, by multiple capture/scattering in the

[1] In this last case, the large interactions are expected to modify the galactic distribution for this subdominant Dark Matter component giving rise to a rotationally supported Dark Disk [30,31]. The presence of a Dark Disk has sizable consequences in the local density and local velocity distribution of Dark Matter as well as in the interpretation of the results of the direct detection experiments [32].

[2] The strong interaction nature of the dark matter interaction is not required. In A.1, as an example, the parameter space probed by this approach, for the particular model of millicharged particles, is shown.

[3] In A.1, the radiative atomic capture cross section, for the simple case of millicharged Dark Matter, is given as an example.