BRANON DARK MATTER: AN INTRODUCTION*

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This is a brief introduction to branon physics and its role in the dark matter problem. We pay special attention to the phenomenological consequences, both in high-energy particle physics experiments and in astrophysical and cosmological observations.

1. Introduction
Most of the works done in the context of the brane-world scenario consider our world brane as a rigid object which is placed at a given position in the extra dimensions. However, rigid objects are incompatible with Relativity and we should consider instead branes as dynamical objects which can move and fluctuate along the extra dimensions. In such a case, apart from the Kaluza-Klein (KK) modes of the gravitons propagating in the bulk space, new fields appear on the brane which parametrize its position in the extra dimensions. This fields are the branons which we will study in this work.

2. Branon dynamics
Let us consider our four-dimensional space-time $M_4$ to be embedded in a $D$-dimensional bulk space whose coordinates will be denoted by $(x^\mu, y^m)$, where $x^\mu$, with $\mu = 0, 1, 2, 3$, correspond to the ordinary four dimensional space-time and $y^m$, with $m = 4, 5, \ldots, D-1$, are coordinates of the compact

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extra space of typical size $R_B$. For simplicity we will assume that the bulk metric tensor takes the following form:

$$ds^2 = \tilde{g}_{\mu\nu}(x)W(y)dx^\mu dx^\nu - g_{mn}^{\prime}(y)dy^m dy^n$$

where the warp factor is normalized as $W(0) = 1$. The position of the brane in the bulk can be parametrized as $Y^M = (x^\mu, Y^m(x))$, and we assume for simplicity that the ground state of the brane corresponds to $Y^m(x) = 0$.

In the simplest case in which the metric is not warped along the extra dimensions, i.e. $W(y) = 1$, the transverse brane fluctuations are massless and they can be parametrized by the Goldstone boson fields $\pi^\alpha(x)$, $\alpha = 4, 5, \ldots D - 1$, associated to the spontaneous breaking of the extra-space translational symmetry. In that case we can choose the $y$ coordinates so that the branon fields are proportional to the extra-space coordinates: $\pi^\alpha(x) = f^2 \delta^\alpha_m Y^m(x)$, where the proportionality constant is related to the brane tension $\tau = f^4$.

In the general case, the curvature generated by the warp factor explicitly breaks the translational invariance in the extra space. Therefore branons acquire a mass matrix which is given precisely by the bulk Riemann tensor evaluated at the brane position: $M_{\alpha\beta}^2 = \tilde{g}^{\mu\nu} R_{\mu\alpha\beta\nu}|_{y=0}$.

The dynamics of branons can be obtained from the Nambu-Goto action. In addition, it is also possible to get their couplings to the ordinary particles just by replacing the space-time by the induced metric in the Standard Model (SM) action. Thus we get up to quadratic terms in the branon fields:

$$S_{Br} = \int_{M_4} d^4x \sqrt{g} \left[ \frac{1}{2} \left( \tilde{g}^{\mu\nu} \partial_\mu \pi^\alpha \partial_\nu \pi^\alpha - M_{\alpha\beta}^2 \pi^\alpha \pi^\beta \right) + \frac{1}{8f^4} \left( 4\partial_\mu \pi^\alpha \partial_\nu \pi^\alpha - M_{\alpha\beta}^2 \pi^\alpha \pi^\beta \tilde{g}_{\mu\nu} \right) T_{\mu\nu}^{SM} \right]$$

We can see that branons interact with the SM particles through their energy-momentum tensor. The couplings are controlled by the brane tension scale $f$. For large $f$, branons are therefore weakly interacting particles. In the case of a three-brane, branons are pseudoscalar particles. Parity on the brane then requires that branons always couple to SM particles by pairs, which ensures that they are stable particles. This fact means that branons are natural dark matter candidates.
3. Limits from colliders

Collider experiments can be used to set bounds on the parameters of branon physics, i.e. the brane tension scale $f$ and the branon mass $M$. The L3 collaboration at LEP experiment has recently obtained very stringent limits from the analysis of single-photon processes in $e^+e^-$ collisions (see Fig. 1). In addition, we have also estimated the limits coming from mono-jet and single-photon processes at Tevatron (see Fig. 1).

4. Cosmological and astrophysical limits

The potential WIMP nature of branons means that these new particles are natural dark matter candidates. In the relic branon abundance has been calculated in two cases: either relativistic branons at freeze-out (hot-warm) or non-relativistic (cold), and assuming that the evolution of the universe is standard for $T < f$ (see Fig. 2). Furthermore, if the maximum temperature reached in the universe is smaller than the branon freeze-out temperature, but larger than the explicit symmetry breaking scale, then branons can be considered as massless particles decoupled from the rest of matter and radiation. In such a case, branons can act as nonthermal relics establishing a connection between the coincidence problem and the existence of large extra dimensions.

If branons make up the galactic halo, they could be detected by direct search experiments from the energy transfer in elastic collisions with nuclei of a suitable target. From Fig. 3 we see that if branons constitute the
dominant dark matter component, they could not be detected by present experiments such as DAMA, ZEPLIN 1 or EDELWEISS. However, they could be observed by future detectors such as CRESST II, CDMS or GENIUS.

Branons could also be detected indirectly: their annihilations in the galactic halo can give rise to pairs of photons or $e^+e^-$ which could be detected by $\gamma$-ray telescopes such as MAGIC or GLAST or antimatter detectors (see for an estimation of positron and photon fluxes from branon annihilation in AMS). Annihilation of branons trapped in the center of the sun or the earth can give rise to high-energy neutrinos which could be detectable by high-energy neutrino telescopes such as AMANDA, IceCube or ANTARES. These searches complement those in high-energy particle colliders (both in $e^+e^-$ and hadron colliders) in which real (see Fig. 1) and virtual branon effects could be measured. Finally, quantum fluctuations of branon fields during inflation can give rise to CMB anisotropies through their direct contribution to the induced metric (work is in progress in these directions).
Figure 3: Elastic branon-nucleon cross section $\sigma_n$ in terms of the branon mass. The thick (red) line corresponds to the $\Omega_{Br} h^2 = 0.129 - 0.095$ curve for cold branons in Fig. 2 from $N = 1$ to $N = 7$. The shaded areas are the LEP-II and Tevatron-I exclusion regions. The solid lines correspond to the current limits on the spin-independent cross section from direct detection experiments. The discontinuous lines are the projected limits for future experiments. Limits obtained from $^9$.

References

1. N. Arkani-Hamed, S. Dimopoulos and G. Dvali, *Phys. Lett.* B429, 263 (1998) and *Phys. Rev.* D59, 086004 (1999); I. Antoniadis et al., *Phys. Lett.* B436 257 (1998)
2. R. Sundrum, *Phys. Rev.* D59, 085009 (1999); A. Dobado and A.L. Maroto *Nucl. Phys.* B592, 203 (2001)
3. M. Bando et al., *Phys. Rev. Lett.* 83, 3601 (1999)
4. J.A.R. Cembranos, A. Dobado and A.L. Maroto, *Phys. Rev.* D65, 026005 (2002) and hep-ph/0107155
5. J.A.R. Cembranos, A. Dobado and A.L. Maroto, *Phys. Rev. Lett.* 90, 241301 (2003); T. Kugo and K. Yoshioka, *Nucl. Phys.* B594, 301 (2001); J.A.R. Cembranos, A. Dobado and A.L. Maroto, *Phys. Rev.* D68, 103505 (2003); hep-ph/0307015; hep-ph/0402142; hep-ph/0405165 and hep-ph/0406076; AMS Collaboration, AMS Internal Note 2003-08-02
6. L3 Collaboration,(P. Achard et al.), *Phys.Lett.* B597, 145 (2004)
7. J. Alcaraz et al. *Phys. Rev.* D67, 075010 (2003); J.A.R. Cembranos, A. Dobado, A.L. Maroto, hep-ph/0405286 and *AIP Conf.Proc.* 670, 235 (2003)
8. A.L. Maroto, *Phys. Rev.* D69, 043509 (2004) and *Phys. Rev.* D69, 101304 (2004)
9. R. Gaitskell and V. Mandic, http://dmtools.berkeley.edu