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Evading the Current Direct Detection Bound through Metastable Particle-Assisted Freeze-Out

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In this work, we have explored the conversion-driven freeze-out scenario, where the next-to-lightest stable particle (NLSP) sets the dark matter (DM) abundance through
the process "NLSP SM $\leftrightarrow$ DM SM". Although DM is produced via
freeze-out mechanism, its interaction strength with the visible sector can
range from weak-scale to feeble-scale couplings. This leads to a vast,
largely unexplored parameter space that remains beyond the reach of current
direct, indirect, and collider searches with possibility of detection
in near future.
We have studied this mechanism in the context of an alternative $U(1)_{B-L}$ model, where four chiral fermions are required to cancel gauge anomalies, in contrast to the usual case with three right-handed neutrinos. The observed relic abundance,
as measured by Planck, is successfully reproduced within this framework. The viable parameter space can be probed by future direct detection experiments,
while remaining inaccessible to indirect searches in near future.
Our results show that the DM relic density is highly sensitive to both the NLSP's interaction strength with the visible sector and the mass difference between the NLSP and DM but not on the DM interaction strength with the visible sector.
When the NLSP decays to DM via a two-body process involving an extra gauge boson,
the decay can be long-lived, outside the CMS or ATLAS detector at LHC.
In contrast, if the NLSP decays via a CP-odd Higgs, it decays promptly inside the detector.
We have investigated the prospects for detecting such long-lived NLSP signatures
at the proposed MATHUSLA detector, with similar conclusions applying to the ongoing FASER experiment.
Finally, we find that choosing arbitrarily small values for the
gauge coupling and the BSM fermionic mixing angle can violate successful BBN predictions.

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