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Protonium Formation in a Collision Between Slow Anti-Proton and Muonic Hydrogen Atom

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Recent progress in creation of ultra-slow anti-protons, $\bar{p}$, [1] is of considerable scientific interest, because of possible formation of low-energy anti-hydrogen atoms $\bar{H}$: a bound state of $\bar{p}$ and a positron e+. The main goal of the anti-hydrogen/antimatter research is to check and confirm (or not confirm) certain fundamental laws and theories of modern physics. For example, one of the most important subjects in the field is to check the charge conjugation, parity, and time reversal (CPT) symmetry of quantum electrodynamics. In other words: a charged particle and its antiparticle should have equal and opposite charges, equal masses, lifetimes, and gyromagnetic ratios. The CPT symmetry predicts that the H and $\bar{H}$ atoms should have identical spectra. In order to test these fundamental laws of physics, new experiments are in progress in the field. Together with the $\bar{H}$ physics there is a significant interest in the protonium Pn atom too: Pn is a bound state of p and $\bar{p}$. For example, Pn formation is related to charmonium - a hydrogen-like atom ($c\bar{c}$), which is a bound state of a c-quark and c-antiquark. The $p\bar{p}$ annihilation can produce ($c\bar{c}$) in the ground and excited states. It would be interesting to study how charmonium interacts with other nuclear particles. It is interesting, because charmonium is composed of quarks, which are not parts of the nuclei. Charmonium interacts with nuclear particles through exchange of gluons. It provides the strong interaction. Gluons are usually manifested in processes at high energies, but in the interaction with nuclear particles charmonium gluons can be studied at low energies. In this work, a few-body system with Coulomb and nuclear forces is considered. Specifically we compute the cross-sections and rates of the ultra-low energy collision between $\bar{p}$ and a muonic hydrogen atom, i.e. a bound state of p, i.e a proton p+, and a muon, μ−: $\bar{p} + (p\mu)_{1s} \longrightarrow (p\bar{p})_\alpha + \mu^-$. (1)
Here, α=1s, or 2s/2p is Pn's quantum atomic state. In the low-energy muonic reaction (1) protonium is formed in a very compact, small size ground and "almost"ground states α, in which the hadronic nuclear force between p and $\bar{p}$ should be extremely pronounced. For example, in the atomic case of the reaction (1), i.e. $\bar{p} + (pe)_{1s} \longrightarrow (p\bar{p})_{\alpha'} + e^-$, Pn would be formed at highly excited "crumbly"states with $\alpha' \approx 30$. In the current work, a detailed few-body approach based on a Faddeev-Hahn-type equation formalism [2] is applied.

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[2] R.A. Sultanov, S.K. Adhikari, Phys. Rev. A 61 (2000) 022711; R.A. Sultanov, D. Guster, J. Phys. B: At. Mol. Opt. Phys. 46 (2013) 215204; Hyperfine Interactions (2014) DOI 10.1007/s10751-013-1005-4.

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