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Antinucleon–nucleus interaction near threshold from the Paris $\bar{N}N$ potential

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Abstract

A general algorithm for handling the energy dependence of hadron–nucleon amplitudes in the nuclear medium, consistently with their density dependence, has been recently applied to antikaons, eta mesons and pions interacting with nuclei. Here we apply this approach to antiprotons below threshold, analyzing experimental results for antiprotonic atoms across the periodic table. It is also applied to antiproton and antineutron interactions with nuclei up to 400 MeV/c, comparing with elastic scattering and annihilation cross sections. The underlying $\bar{p}N$ scattering amplitudes are derived from the Paris $\bar{N}N$ potential, including in-medium modifications. Emphasis is placed on the role of the P-wave amplitudes with respect to the repulsive S-wave amplitudes.

Keywords: Antiproton–nucleon in-medium interaction; Energy dependence; Antiprotonic atoms; Antiproton scattering; Antiproton and antineutron annihilation; Paris $\bar{N}N$ potential

1. Introduction

The connection between hadron–nucleus empirical potentials near threshold and the underlying hadron–nucleon interactions has been studied for years by analyses of strong-interaction

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effects in exotic atoms and in studies of elastic scattering of hadrons by nuclei [1,2]. It was recognized in the early 1970s that the $\bar{K}$-nucleus interaction near threshold was determined by the $\bar{K}$-nucleon scattering amplitude at subthreshold energies [3–5]. Recently an algorithm was devised to account for the subthreshold energy dependence of the meson–nucleon amplitude in evaluating the meson–nucleus strong-interaction potential in kaonic atoms and for strongly-bound $\bar{K}$ and η mesons in nuclei [6–12]. Pionic atoms and elastic scattering of 22 MeV $\pi^{\pm}$ by nuclei have also been studied using this approach [13].

In the present work we apply this approach to the interaction of antiprotons with nuclei near threshold. As in previous works, we are not interested in any single nuclear species but rather in global behavior. Therefore we handle only large data sets within 'global' comparisons between calculation and experiment, as was done for kaonic atoms [10] and for pionic atoms and pion scattering [13]. Nevertheless, in order to assess the validity of the model, some annihilation cross sections are also considered. Due to the much stronger absorption of antiprotons in nuclei compared to pions, and even to antikaons, it is inevitable that ambiguities may exist in some of the conclusions.

An extensive data-base for strong interaction effects in antiprotonic atoms is available from the PS209 Collaboration at CERN [14]. Results for elastic scattering of 48 MeV antiprotons on C, Ca and Pb nuclei are available from the pioneering experiments of the 1980s [15]. For the free-space $\bar{p}N$ interaction near threshold we used the 2009 version of the $\bar{N}N$ Paris potential [16]. This potential consists of a long-range one-pion and correlated two-pion exchange terms, plus a short-range phenomenological term that includes an absorptive component representing $\bar{p}N$ annihilation. The potential parameters are fitted to some 4300 scattering data plus scattering lengths and scattering volumes extracted from antiprotonic hydrogen levels. This qualifies the 2009 version of the $\bar{N}N$ Paris potential as a realistic potential. Other realistic, and 'microscopic' as well, $\bar{N}N$ potential models that have become available recently could, in principle, be used in $\bar{p}$-nucleus calculations near threshold. These include (i) the Zhou–Timmermans model [17] which is also based on a long-range one-pion and correlated two-pion exchange terms, but uses a boundary condition description for its short-range term; and (ii) a Bonn–Jülich NNLO chiral EFT potential model [18] with a similar long-range behavior that is subject, however, to a strict power counting hierarchy, and in which the short-range behavior is given by suitably determined contact terms. The present work is not intended to compare between different microscopic $\bar{N}N$ potential models, nor to study possible $\bar{N}N$ quasi-bound states near threshold (*e.g.* with quantum numbers ${}^{11}S_0$ [19], or ${}^{13}P_0$ [20], or ${}^{31}S_0$ [21]), but rather to apply a microscopic model in the context of antiproton–nucleus interactions below threshold and at very low energies. As our handling of in-medium scattering amplitudes assumes some rather general properties of nuclei, we do not consider very light nuclei in the present work.

$\bar{N}N$ potentials are found to be strongly attractive and absorptive in all the microscopic models known to us, including the various versions of the Paris potential and the recently published potentials mentioned above. This results, generally, in *repulsive* $\bar{N}N$ S-wave scattering amplitudes at low energies. Hence, the simple impulse-approximation $t_{\bar{p}N}\rho$ optical potential, with $t_{\bar{p}N}$ the corresponding free-space $\bar{p}N$ t matrix and ρ the nuclear density, is repulsive at and near threshold. However, past global analyses of antiprotonic atoms [22,23] achieved good agreement with experiment when using an empirical (as opposed to 'microscopic') local *attractive* and absorptive optical potential, related to nuclear densities through a folded-in finite-range interaction of rms radius about 1.1–1.2 fm. A strong density dependence of the effective, in-medium $\bar{p}N$ t matrix is apparently required in order to reverse the sign of the free-space $\bar{p}N$ t matrix in the medium and inflate its size, or a significant contribution from P-wave amplitudes is able to achieve it. This