MESONIC EFFECTS IN ANTIPROTONIC ATOMS*†

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A short review of recent measurements with antiprotonic atoms is given. It concentrates on results related to mesonic interactions: spin dependence of $N\bar{N}$ forces and measurements of neutron haloes in heavy nuclei. The latter involve nuclear interactions of mesons produced in antiproton annihilation.

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Motivation for this talk is twofold. First, the COSY research is to be partly devoted to pionic atoms. It may be of interest to compare it to a related field. Secondly, the nuclear absorption of antiprotons involve final state pions. The antiprotons may become a tool to study nuclear surface structure provided the mesonic final state interactions are well understood. In Section 1 of this report the simplest atoms are introduced and consistency with theoretical models is analyzed. In Section 2 we concentrate on the measurements of the neutron haloes in heavy antiprotonic atoms.

1. The lightest atoms, spin effects

Protonium — an atomic state of $p\bar{p}$ — has been intensively studied at CERN. Its energy levels are known by measurements of the X-ray transitions. By the same method the lifetimes of the lowest $1S$ states are extracted from the line shapes. The binding energies due mainly to Coulomb forces are sizably shifted by strong $p\bar{p}$ interactions. These shifts ε and accompanying widths Γ are linked to the $p\bar{p}$ scattering length a by formula

$$\varepsilon - \frac{i\Gamma}{2} = \frac{2\pi}{\mu_{NN}} |\psi_s(0)|^2 a , \tag{1}$$

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that involves atomic wave function at the origin and is accurate up to $o(a/\text{Bohr radius, effective radius/Bohr radius})$. This and similar relations for higher partial waves indicate an equivalence of atomic X-ray measurements to low energy scattering. Atomic studies have some advantages over the latter when the resolution of spin states is possible. It was achieved in protonium 1S states for the spin triplet and spin average shifts and widths, [1]. The results

TABLE I

1S protonium shifts and half-widths, keV

		Spin-triplet		Spin average	
Experiment	[1]	0.850 (50)	$-i.385(80)$	0.727 (23)	$-i.580(39)$
DR	[2]	0.760	$-i.360$	0.720	$-i.400$
KW	[2]	0.750	$-i.440$	0.690	$-i.490$
Paris	[3]	0.710	$-i.390$	0.750	$-i.500$

indicate reasonable consistency with theoretical models. This is not surprising, however, as the latter contain free parameters fitted to the low energy $p\bar{p}$ total, elastic and charge exchange scattering. The spin experiments at low energies are not feasible, and atoms supply equivalent data. The triplet states live longer and the triplet shifts are more repulsive. The differences may be understood, partly, in terms of $\vec{\sigma}\vec{\sigma}$ potentials due to meson exchanges. These enter triplet with a repulsive $V_\sigma = V_\pi + V_\eta - V_\omega - V_\rho$ and singlet with an attractive $-3V_\sigma$ combinations. The repulsive, in the triplet state, long range pion force keeps baryons away from the annihilation region and pushes the level up. Results of calculations with the Dover-Richard and Kohno-Weise potentials are shown in Table 1. The spin-average is approximately a 3 : 1 combination. Both models consist of single meson exchange potentials fitted to the NN data and transformed according to $(-1)^G$ parity rule. The $p\bar{p}$ annihilation is described by local and spin independent potentials. The full extent of experimental splitting is not reproduced. The right trend is due to the spin dependence of pion exchange, effects of heavier mesons are strongly suppressed by the absorption. One concludes that there is some spin dependence of the annihilation. The latter is built in the Paris [3] model. Although semi-phenomenological in practice it is inspired by a baryon exchange mechanism of annihilation. Strong $\vec{\sigma}\vec{\sigma}$ term exists in the absorptive potential of this model. It makes singlet absorption and the singlet width sizably larger than the triplet one [3]. However, the same absorptive potential generates repulsive effects that are much stronger in the singlet states. This is not supported by data. Similar results follow from the Paris potential supplemented with quark rearrangement annihilation model [4].

Next in complication — the $\bar{p}$ deuterium atom — has been observed, [5, 6]. In involved experiments a dependence of the X ray intensities on molecular effects (Stark mixing) has been detected and the width of $3d$ level was extracted. Serious discrepancy with the calculated level widths occurs and origin of this difficulty is not understood. Other measurements of the $3d$ level widths and $2p$ level widths and shifts were obtained from the X ray cascade in ^{3}He and ^{4}He, [7]. Attempts to understand the results with an antiproton optical potential fitted to atomic data in the oxygen region were not successful, [7]. The problem, apparently, is not related to anomalous $\bar{p}$ behaviour in dense systems but to shortcomings of the first order optical potential that double-counts some multiple scattering events and neglects the NN correlations. These effects are of significance in the few body systems. To improve calculations one may use a formula that sums part of the multiple scattering series, [8]. In this way one obtains

$$\Delta\varepsilon - \frac{i\Gamma}{2} = \langle T\rangle \left[1 - \frac{\langle TDT\rangle}{\langle T\rangle} + \frac{\langle TDT\rangle^2}{\langle T\rangle^2} - \frac{\langle TDTDT\rangle}{\langle T\rangle^3} + \cdots\right]^{-1}, \tag{2}$$

where T denotes scattering matrix, D is a propagator for a free $\bar{N}$ and interacting nucleons and the brackets $< \ldots >$ mean an average over atomic and nuclear ground state wave functions.

In particular, when one sets

$$T = \frac{2\pi}{\mu} t A\rho(r), \qquad D = -\frac{m}{2\pi|r - r'|}, \tag{3}$$

Eq. (2) becomes a partial sum of the multiple scattering expansion for the standard local optical potential

$$V = \frac{2\pi}{\mu} t A\rho(r), \tag{4}$$

where A is the number of nucleons and ρ is the density profile. This potential fits the antiprotonic widths and shifts in the oxygen region with the phenomenological value of $t = -1.0(.5) - i2.5(.5)$ fm [9]. The latter value of t fails however in He, while the values fitted to the data have relation neither to theoretical models nor to the positonium. On the other hand an understanding of the He data is obtained with simple improvements in Eq. (2). In particular, one needs to put proper number of double $A(A-)$ and triple $A(A-1)(A-1)$ collisions instead of A^2 and A^3 given by V in the multiple scattering series. These corrections may be supplemented with the

NN correlations. Calculations [8] indicate necessity of proper treatment of the off-shell effects in the scattering matrices, that reflect the range of NN bar forces. In particular the strong pion exchange force in the $^{13}P_0o$ state of the range longer than the helium radius is seen in the $3d$ states.

The expansion (2) is advertised here as a simple and effective method to calculate the low energy scattering on few body systems. With relatively weakly interacting particles (π, η) it may be used in S and higher waves. For kaons, antiprotons, hyperons it is applicable in P and higher waves.

2. Heavy atoms, isotope effects, neutron haloes

Precise measurements of atomic level widths were made for the $4f$ levels, [10]. These include isotope effects in $^{16,17,18}O$ and other well studied nuclei. The results may be used as a check for our understanding of the nuclear absorption mechanism. Assuming an S wave $\bar{p}$ nucleon absorption one obtains [11] the atomic width

$$\Gamma(S) = \frac{4\pi}{\mu_{NN}} \int\int |\Psi(x)|^2 \rho(r) \,\mathrm{Im}\, t_s(x-r) P\,, \tag{5}$$

expressed in terms of atomic wave function that includes strong interaction effects, nuclear density ρ and absorptive part of the $N\bar{N}$ t matrix extended off the energy shell. A corrective factor P ($\simeq .9$) represents some manipulations necessary to bring the underlying optical potential into a local form with a folded nuclear density. A similar expression for the P wave $N\bar{N}$ absorption is more complicated

$$\begin{aligned}\Gamma(P) = &\frac{4\pi}{\mu_{NN}}\frac{3}{4} \int\int \Big[|\Psi(x)|^2 \rho_p(r) \\ &+ \Big[\Psi_r'(x)^2 + \frac{L(L+1)}{x^2}\Psi_r^2(x)\Big]\Big] \rho(r)\,\mathrm{Im}\, t_p(x-r)P \\ \rho_p = &\sum \left[\phi_{mr}'(x)\right]^2 + \frac{l(l+1)}{x^2}\phi_{mr}(x)^2\,,\end{aligned} \tag{6}$$

as it involves derivatives of the radial atomic and nuclear wave functions ϕ. In these expressions L, l are the atomic and nucleon angular momenta, the summation extends over single particle states. Detailed calculations [11] indicate consistency of the model $N\bar{N}$ t matrices with the isotopic differences of the atomic widths. These concern mainly neutrons. The neutron/proton capture ratio of about .75 given by the Dover Richard $N\bar{N}$ potential cannot be precisely verified. Extraction of this number is of interest in the studies of neutron haloes in heavy nuclei to be discussed later. Calculations of the relevant t matrices are not trivial as one needs to extrapolate in energies below the $N\bar{N}$ thresholds into the region dominated by quasi-bound states.

The atomic wave functions follow the $x \times L$ barrier factor. Thus in the first approximation $\Gamma(S)$ of Eq. (5) reflect magnitudes of the $x \times 2L$ moments of the nuclear density distributions. The $\Gamma(P)$ of Eq. (6) reflect mainly the $x \times (2L-2)$ moments. The folding range in $\mathrm{Im}\, t(x-r)$ makes the moments involved still smaller. As the contributions of $\Gamma(S)$ and $\Gamma(P)$ are comparable, the atomic widths test essentially the $2L-2$ moments. In the capture states the L values are high. The absorption is thus located at extreme nuclear periphery not accessible in other experiments, with the exception of subcoulomb stripping or pick-up reactions.

Antiprotonic studies of the neutron/proton ratio at nuclear peripheries were undertaken long time ago. The initial method was based on detection of charged pions produced in the $N\bar{p}$ annihilation [12]. The same question has recently been revived, now with the detection of final state nuclei [13]. The radiochemical method used finds also the final $A-1$ nuclei which are left intact or weakly excited. These are used to identify capture on protons and on neutrons. The first measurement done in ^{232}Th yields the n/p ratio of 7.8(2.2). Full understanding of this result requires calculations of the final state pionic elastic scattering amplitudes. Multiplicity of the pions produced is 2-8 with an average of about 5 and an average momentum of about 380 Mev/c. It locates the interaction slightly above the Δ in the strongly absorptive and repulsive region. Calculations were done in the eikonal approximation with the pionic optical potential given by the forward scattering P wave amplitudes that span over the Δ and N^* resonances. The square of f.s. mesonic wave functions averaged over f.s. phase space determine the probability for pions to miss nuclear collisions. It is inserted into Eqs (5), (6) as $P(r)$ and plotted as P_{miss} in Fig. 1. Similar values of $P(r)$ are obtained in the internal cascade model [14]. The nuclear absorption scenario is also plotted in this Figure. The capture takes place from $L=8$ and $L=9$ circular atomic states. The absorption densities given by integrands in Eqs (5), (6) are plotted as $W_{\mathrm{n}}, W_{\mathrm{p}}$ for neutrons and protons separately ($P=1$). These represent nuclear regions tested by the atomic level widths. Because of the $P(r)$ cut-off at small distances the capture leading to $A-1$ final states is even more peripheral. The nuclear densities used are calculated with a standard, non-deformed, shell model [15]. Nucleon separation energies and the electric charge radius are used as an input. With the experimental neutron capture/proton capture cross section ratio of .63 obtained in Carbon [12], one obtains very good agreement with the experimental n/p density ratio in the capture region in Th. It is not clear yet, how many single particle nuclear levels are involved in the process. In this calculation the last highly populated orbits took about half of the absorption strengths. It seems that most of the absorptions occur on levels that lead to final nuclear excitations below the neutron separation threshold. It is a vital condition for the proper determination of the n/p density ratios with this new technique. Both experimental and theoretical work is still required to see clearly the advantages and shortcomings of this promising method.

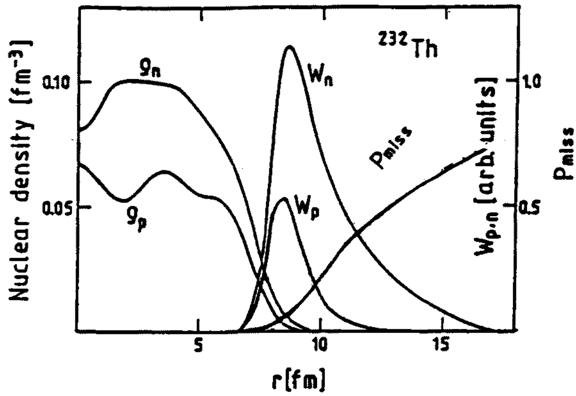

Fig. 1. The scenario of the antiproton absorption in Thorium nucleus

The calculated rate of the $A-1$ capture events is higher than the experimental 13% by about 50%. An important parameter in the calculation is the range of the pion-nucleon interactions in the Δ region. This range, usually put into the Δ formfactor is in fact poorly known. Another uncertainty is related to intermediate states of the $N\bar{N}$ annihilations. Small fraction passes the final nucleus as η and ω mesons. These apparently are absorbed less than the pions [14]. On the other hand, most of annihilation channels involve intermediate short lived ρ. Including the latter one reduces the probability of $A-1$ final states by about 10%. These calculations are not very reliable, as yet, but we hope some consensus will be established soon.

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