Optical potentials for the antiproton nucleus interactions

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The nuclear interactions of atomic and low energy antiprotons are studied. Measurements of level shifts and widths in the lightest elements are analyzed and compared with new results obtained in heavy nuclei. Simple geometric properties of \( \bar{p} \) nucleus interactions are demonstrated. Upon this background one finds some anomalies that indicate strong energy dependence in the subthreshold \( \bar{p} \) nucleon interactions. The use of of \( \bar{p} \) in studies of the nuclear surface is briefly discussed.

1. INTRODUCTION

The study of antiprotonic atoms and low energy scattering serves a triple purpose:
(a) to check some properties of \( \bar{p} \) nucleon interactions
(b) to learn about the structure of the nuclear surface
(c) to find some exotic phenomena as \( \bar{p} \) - nucleus quasi-bound states.

(a). In practice this possibility is limited to two simple systems: nucleon and deuterium, nevertheless we argue below that heavier atoms also offer some advantages if there exists a subthreshold \( \bar{N}N \) resonance.

(b). Several methods have been used for this purpose, each of them gives information in regions roughly 1-4 fm beyond the half-density radius. One method studies the X-ray cascade and extracts the atomic level shifts and widths. Until now, the information obtained in this way has been limited to at most one level shift \( \Delta E \) and two level widths \( \Gamma \) for a given atom [1]. The recent CERN experiment [2] detects more transitions, improves the precision, resolves the fine structure and allows for several shifts and widths per atom. In some deformed nuclei, this knowledge may be further extended by E2 excitations.

Other methods to test the nuclear surface with antiprotons detect the products of \( \bar{p} \) annihilation by the nucleus. The first experiment of this type detected charged mesons and in this way could approximately discriminate the captures on protons from captures on neutrons [3]. On the other hand, the recent CERN experiments detect residual nuclei of very low nuclear excitation [4]. Radiochemistry allows to find "cold" nuclei of only one nucleon lost in \( \bar{pn} \) and \( \bar{pp} \) annihilations. In this way one can study the ratio of \( n/p \) densities. The surface nature of the nuclear capture processes arises from the high orbital quantum numbers of the annihilating \( \bar{p} \) and consequently the radiochemical method selects the most peripheral proton or neutron orbits. On average there are five mesons emitted in the annihilation and to leave the final nucleus cold they must all avoid collision with it.

* Representing PS209
This can be achieved only if the annihilation takes place at the extreme nuclear surface around a region 2.5 fm beyond the half density radius.

The advantage of the X-ray studies is that the atomic states in question are known. In the annihilation-product studies this is not the case, and additional knowledge of capture states and final-state interactions is necessary. These two types of atomic experiments complement each other.

2. THE ¯pN AMPLITUDES AT AND BELOW THE ¯pN THRESHOLD

Atomic antiprotons scatter on surface localized nucleons in an almost quasi-free way. However, in the c.m. system of ¯pN pairs the energy momentum relation is not the free one. The energy is determined by the nucleon and antiproton binding $E_B$, while momenta are described by corresponding wave functions. Thus one needs to extrapolate the scattering amplitudes off the energy shell. This may generate tremendous effects in cases of quasi-bound states or resonances in the ¯pN system. The on shell scattering amplitude at low energies may be parameterized in terms of scattering lengths $a_0$ and scattering volumes $a_1$ as $a_0(E) + 3a_1(E)k'k$. Here, $k$ is the c.m. momentum related to the energy $E$. Many spin and isospin states contribute to the scattering and the detailed structure is uncertain and model dependent. Hence, for the few-body and nuclear physics of antiprotons it is convenient to parameterize the data in terms of an averaged effective complex length $a$ defined as

$$a = << a_0(-E_B - E_{rec}) + 3a_1(-E_B - E_{rec})\nabla\nabla >> .$$

The average is to be performed over atomic and nuclear wave functions. Those generate distributions of the total and c.m. momenta of the pair. The total momentum determines recoil energy of the pair with respect to the rest of the nucleus $E_{rec}$. The relative momentum determines the strength of P-wave interactions. The latter are generated by the derivatives $\nabla$ over relative $\bar{p}N$ coordinates. Such effective scattering lengths have been commonly used to parameterize the optical potential

$$V^{opt}(R) = \frac{2\pi}{\mu_{NN}} a \rho(R).$$

Early atomic experiments determined $a$ close to $(-1.5 - i2.5) \text{ fm}$ [1]. The depth of this potential well is $(-120 - i200) \text{ MeV}$ but it has to be stressed that formula (2) refers only to the nuclear surface. The extrapolation to densities exceeding some 15% of the central density is not justified.

In principle $a$ is a function of energy as it depends on the nucleon binding energies. For example in the simplest nuclei $p$, D, $^3$He and $^4$He the nucleon separation energies are roughly: 0, 2, 7 and 21 MeV respectively. In addition the recoil energies amount to several MeV. Thus, $\bar{p}$ atoms built with these nuclei may test the $\bar{p}N$ scattering amplitudes below the $\bar{p}N$ threshold. Typical $(-E_B - E_{rec})$ energies involved in equation (1) are 0, -9, -15 and -30 MeV. This region covers most of the energy range required in heavy $\bar{p}$ atoms.

Now we attempt an extraction of the length parameters $a$ from the recent atomic [3], [4] and scattering [5] experiments. The next task is to disentangle relation (1) to obtain
Table 1
The $\bar{p}N$ scattering parameters extracted from few body systems, $a, a_0$ in [fm], $a_1$ in [fm$^3$].
Sources refer to atomic or scattering experiments (A,S) and calculations (C).

| System | $a$   | $a_0$         | $a_1$         | source |
|--------|-------|---------------|---------------|--------|
| $\bar{p}\bar{p}$ | 0.83 - i0.69 | 0.83(1) - i0.69(3) | -0.4(8)-i0.64(4) | A [3] |
| $N\bar{p}$     | –     | 0.28-i0.59    | 0.02-i0.57    | C [16] |
| $^2\text{D} \bar{p}$ | –     | 0.22-i0.45    | 1.28-i1.25    | A [6], S [8] |
| $^3\text{He} \bar{p}$ | 1.48-i2.81 | –             | 0.68- i1.25   | A [7], C [13] |
| $^4\text{He} \bar{p}$ | 0.77-i2.99 | 0.2(3)-i0.2(1) | 0.3-i 1.0     | A [7], C [13] |

more fundamental scattering parameters $a_0, a_1$ at and below the threshold. The results are collected in table 1.

In protonium, $a_0, a_1$ are just the $\bar{p}p$ scattering length and volume. These are related to atomic level shifts and widths by the Trueman formula $[\Delta E - i\Gamma/2]_l = a_0\omega_l + O(a/B)$. Coefficients $\omega_l$ and higher order terms in the ratio (scattering length / Bohr radius) are known [9]. The same formula holds for deuterium and heavier atoms and in this sense the atomic levels are equivalent to the low energy scattering.

The shifts and widths obtained recently for the 1S and 2P states of $\bar{p}D$ atom [3], [4] allow to calculate the $\bar{p}D$ scattering length $A_0^D = (0.706(17) - i0.39(27))$ fm and volume $A_1^D = (3.15(33) - i3.18(19))$ fm$^3$. The absorptive parts of these are consistent with similar values obtained from the reaction cross sections [8], [10].

To extract the $\bar{p}N$ parameters from deuterium one needs to solve the three body dynamics. Here, the multiple scattering series summation method of Refs. [11] is used for this purpose. For the deuteron, this method has been shown to be very reliable. Its precursor is the Brueckner formula

$$A_0^D = \frac{\mu_{ND}}{\mu_{NN}} \frac{a_0}{1 + a_0 \frac{1}{R_o}},$$

which in the static nucleon limit is obtained from boundary conditions set upon a wave scattered by two centers separated by a distance $R_o$. More careful calculations are needed, and then $\frac{1}{R_o}$ becomes an effective 3-body propagator. It may be expressed in terms of rapidly converging partial sums of the scattering series [11].

The values of $a_0$ and $a_1$ extracted from antiprotonic deuteron and shown in table 1 differ strongly from the threshold values obtained from hydrogen. However, the former pertain to an average $\bar{p}N$ while the latter pertain to the $\bar{p}p$ system. To find the average $\bar{p}N$ lengths at threshold, the missing $\bar{p}n$ amplitudes are calculated. The results obtained with the Paris potential are shown in the second line of table 1. This potential has recently been tested against the $\bar{p}p$ and $\bar{n}p$ interactions [16]. An independent estimate is possible for the S-wave. It follows from the hydrogen 1S width and $\text{Im} a_0(\bar{n}p) = -0.83(7)$ fm extracted from measurements of the $\bar{n}p$ reaction cross section [12]. In this way $\text{Im} a_0(\bar{p}N) = -0.76(5)$ fm is obtained and this number is roughly consistent with the Paris potential calculations. Hence, the S-wave scattering length obtained at the threshold and the length obtained from the deuteron indicate fairly regular energy dependence. On the other hand, a dramatic change of the P-wave scattering volume seems to happen in the region between the threshold and -10 MeV.
An extension of \( a_l \) to lower energies may be performed with the use of 2P and 3D atomic level shifts and widths in \(^3\)He, \(^4\)He, \(^7\)Li. Again, the calculations presented in table 1 involve the partial summation of multiple scattering series. This procedure is rather reliable for the P and D states, \(^{11}\). To obtain \( a_0 \) we use the \( \bar{p}^4\)He scattering length extracted from \( \bar{p}^4\)He absorptive cross sections \(^8\),\(^{10}\). The \( a_0 \) given in table 1 serves essentially as a plausible indication of the real value. It has been calculated with \( A_0^{He} = (1(1-i0.4(4)) \)fm and this figure doubles the error limits given in ref.\(^{10}\). The result for \( a_0 \) indicates a regular behavior of the S-wave amplitude in the subthreshold energy region. Also regular is the result for \( \text{Im} \ a_1 \) in the -15 MeV to -30 MeV region. On the other hand, \( \text{Re} \ a_1 \) tends to fall down. These conclusions are slightly affected by the uncertainty of \( a_0 \) (indicated in the table) that induces a 20% uncertainty in the helium values of \( a_1 \) (not indicated in the table).

Atomic data in light nuclei do not allow to pinpoint the partial wave which is responsible for the dramatic effect in the P wave close to threshold. Models for \( \bar{N}N \) interactions generate fairly narrow P wave resonances just above the threshold and broad quasi-bound states deep below the threshold. In particular the \(^{13}P^0_0\) and \(^{33}P^0_0\) waves are found to resonate in the Paris model, \(^{16}\). We return to this question as similar effects are observed also in heavy \( \bar{p} \) atoms.

3. HEAVY ANTIPROTONIC ATOMS

In this section we discuss some geometric properties of the antiproton nuclear scattering and capture. These are:

i). A saturation of level widths \( \Gamma(Z) \) as the atomic number increases.

ii). A scaling of the ratio \( \Delta E/\Gamma(R) \) as the nuclear radius increases.

iii). An effect of \( \bar{p}N \) force range that increases with the atomic angular momentum.

With some control over these simple properties one finds anomalies and attempts the construction of phenomenological optical potentials. With the potentials one can compare the results of the X-ray measurements with the data on \( \bar{p} \) single nucleon capture. Consistency of these experiments would give a signal that antiprotons make a valid tool to study properties of the distant nuclear surface. Finally the nuclear potentials may offer a check for the underlying \( \bar{p}N \) scattering amplitudes.

3.1. Geometric properties of absorptive interactions

The three related, but different geometric effects are now discussed on the basis of the extended atomic data.

i). The saturation of the scattering length has been recently discovered in light nuclei with the relation of scattering lengths \( \text{Im} \ A(\bar{p}He) < \text{Im} \ A(\bar{p}p), \(^8\),\(^{10}\). A similar effect is seen with the atomic level widths, on a broader Z scale. To obtain an equivalent scattering parameter let us divide the experimental widths by normalization factors for the atomic densities. This prescription normalizes the widths to the same number of antiprotons approaching the nuclear surface. The results for \( n=6, l=5 \) level widths are shown in Fig.1. Most of these atoms have several isotopic states. On average one detects an initial increase and a fall at the heaviest Te atom. The width for this last state has been obtained indirectly by the E2 mixing effect. This state is of independent interest as it reflects the largest atomic-nuclear overlap ever tested and may be interpreted as a Coulomb assisted
nuclear $\bar{p}$ state. For each element the scaled widths display isotopic differences and these reflect a change of the nuclear size. The differences in the Bohr radii of the atomic states have already been accounted for.

\[ \Gamma / w. f. \text{ normalization} \]
\[ \begin{array}{cccccccc}
\text{Ca} & \text{Fe} & \text{Ni} & \text{Y} & \text{Zr} & \text{Mo} & \text{Te} \\
0 & 0.2 & 0.4 & 0.6 & 0.8 & 1 & 1.2 & 1.4 & 1.6 & 1.8 & 2
\end{array} \]

Figure 1. Experimental widths of $n = 6, l = 5$ atomic levels, scaled by the normalization factors of the corresponding wave functions. Arbitrary units. The data: Ca, Fe, Ni, Zr, Te from [3], Fe, Y, Zr from [1] (Roberson), Mo from [14].

The saturation indicated above is due to strong damping of the initial $\bar{p}$ wave in subsequent $\bar{p}N$ collisions. It may be explained in simple terms of the two center formula (3), if $\text{Im} a_0$ is allowed to increase and $R_0$ stays small enough.

The lower level shifts are predominantly repulsive despite the fact that the optical potential may be an attractive one. The repulsion is related to strong damping of the atomic wave function as $\bar{p}$ penetrates the nuclear interior. Such damping results in a large gradient of the wave function and pushes up the kinetic energy i.e. generates an effective repulsion. To see the effect we divide level shifts by level widths. The latter set the scale of the atomic-nucleus overlap. On this scale the shift becomes smaller as the size of the nucleus increases and the gradients become weaker. The result is plotted in Fig.2.

This scaling of $\Delta E / \Gamma$ may be also reproduced in simple terms of formula (3), if the length $a_0$ is dominated by the absorptive part and the size of the system $R_0$ is allowed to increase. Fig.2 indicates an average behavior of this ratio. On top of it some shifts do not follow the trend and become negative. Two effects may contribute to this anomaly: in Cd the overlap (and thus the absorption) is small while in $^{112}\text{Sn}$ and $^{106}\text{Cd}$ one has loosely bound valence protons.

An important geometric effect is related to the $\bar{p}N$ force range. It enters the potential profile in eq.(3) which is usually presented in a folded density form

\[ \rho(R) = \int \rho_o(R - r) v(r) d\rho \] (4)
where \( \rho_o \) is a "bare" nucleon density and \( v(r) \) is a formfactor describing the range in \( \bar{p}N \) interactions. The impact of the force range is determined, essentially, by the m.s. radius of the formfactor \( r_o = \sqrt{< r^2 >} \). To see the effect let us calculate the atomic level width with the formula

\[
\Gamma_s/2 = \text{Im} \int |\Psi_{\bar{p}}(R)|^2 V^{opt}(R)dR \approx \text{const} < R^{2l} > .
\]

In a state of angular momentum \( l \) the wave function at short distances \( \Psi_{\bar{p}}(R) \sim R^l \), hence the width is roughly proportional to the \( 2l \)-th moment of the folded density \( < R^{2l} > \). The latter may be related to the bare nucleon density moment \( < R^{2l}_o > \). To the leading order in \( < r^2 > \) this relation is

\[
< R^{2l} >= < R^{2l}_o > + < R^{2l-2}_o > < r^2 > \lambda_l + ....
\]

Coefficients \( \lambda_l \) rise quickly with \( l \). For \( l=1,2,... \) one has \( \lambda_l = 1, 10/3, 7, 12, 55/3 .. \) and the second term in eq. (6) increases rapidly. The effect of force range becomes more and more important, particularly in the high \( l \) states which may be created in heavy atoms.

### 3.2. The optical potential

Phenomenological potentials that are linear in the nuclear density and the scattering matrix are characterized by at least three parameters: the complex length \( a \) and an
interaction range \( r_o \). Early best-fit potentials assumed \( r_o \) equal to the proton charge radius \( r_{ch} \), which is roughly the \( N\bar{N} \) annihilation radius. The values \( a \approx (-1.5 - i2.5) \) fm were obtained [1]. A recent choice of ref. [17] is the extreme zero range limit. Now this way \( a = (-2.5(2) - i3.5(3)) \) fm becomes larger to compensate for the shorter force range. These values of \( a \) have been determined mostly by the light atoms where the data are more precise. Attempts to extract separate proton and neutron values yield uncertain results [17]. The new data from PS209 [2] offer a chance and a challenge to describe interactions in the whole periodic table, in particular for the neutron rich nuclei.

The old problem in the optical potential studies is that the sign of the effective Re \( a \) differs from the signs of averaged scattering lengths and volumes. The best-fit Re \( a \) are attractive while Re \( a_0 \) and Re \( a_1 \) at the threshold are repulsive. It is seen in table 1 that below the threshold these quantities are also repulsive. The attraction observed in \( \bar{p} \) atoms and in the low energy scattering [18] is due to collective nuclear effects and a more subtle description of the \( \bar{p}N \) scattering amplitudes. The basis to describe these effects exists in the standard approach which generates the optical potential in terms of the half-off shell scattering matrix \( t(r) \). Instead of equation (2) which uses the effective scattering lengths \( a \), one uses \( t(r) \) and folds it over the nucleon density

\[
V_{opt}(R) = \frac{2\pi}{\mu_{NN}} \int \rho_0(R - r)t(r)dr.
\]  

(7)

Since \( a \) and \( t(r) \) are related by \( a = \int t(r)dr \), formula (2) can approximate formula (7) only in a simple case of regular, monotonic \( t(r) \). This does not happen. At large distances \( t(r) \) is given by the \( \bar{p}N \) potential and the average potential in this system is attractive. On the other hand, at smaller distances \( t(r) \) changes sign and becomes repulsive. This sign change is due partly to the annihilation and partly to \( \bar{p}N \) quasibound states. Such a mechanism generates the repulsive on average scattering lengths and volumes. The net result of the folding (7) is that at large distances Re \( V_{opt}(R) \) becomes attractive while at short distances it is repulsive. Several model calculations reproduce such an effect. However, the detailed calculations are uncertain due to strong cancellations involved in the outlined procedure. The problem is aggravated by \( N\bar{N} \) model uncertainties and technical questions: uncertainties in the full off-shell versus half-off shell extension, difficult description of the nuclear surface region and an early onset of nuclear many body effects. Several involved calculations were undertaken in the former decade and all indicate uncertainties due to such effects [15]. One certain conclusion is that Re \( V_{opt} \) is a very complicated, possibly energy dependent and non-local structure. In some states it is attractive while in other states is may be repulsive.

Below a new best-fit potential is presented. It stems from the early best-fit potentials. The basic changes are:

1. Light nuclei are described by two parameter Fermi densities and not by the harmonic oscillator densities which generate incorrect asymptotics. For other nuclei either the electron scattering or muonic atom data are used, whichever yield better fit. For neutrons the \( (r_n - r_p) \) differences are taken from other experiments or interpolated [19] and implemented into a change of the diffuseness parameter.

2. The starting range parameter was \( r_{ch} \). Next, this condition was relaxed.

3. A constant length \( a \) was assumed. Next, some dependence on the separation
energies indicated by the lightest antiprotonic atoms was allowed.

(4) The data base is extended by new results [2]. Some 150 lower shifts, lower widths and upper widths are used in the carbon till uranium region of the periodic table.

The best choice for a constant \( a = (-1.10(5) - i1.85(5)) fm \) is suggested by light atoms. The fit was obtained with \( \chi^2/F = 1.19 \) (for \( Z < 17 \)), \( 1.46 \) (for \( Z < 38 \)), \( 2.72 \) (for \( Z < 53 \)) and \( 3.20 \) (for all \( Z \)). This fit is excellent for the old data and light atoms but the representation of heavy atoms is poor. The improvements were looked for in the energy dependence of \( a \) indicated by results of table 1. In particular an enhancement of absorption on loosely bound nucleons was expected. For the data in existence the separation energies of the valence nucleons span the region from 3.6 MeV to 18.5 MeV. Within this region only minute changes in the neutron \( I_{\text{yn}} \) are allowed by the data. On the other hand a 100 \% increase of \( I_{\text{yp}} \) on weakly bound protons (with separation energies of less than 8 MeV) is allowed and favoured by the data. The best fit \( \chi^2/F = 2.5 \) (for all \( Z \)) is obtained in this way. This shows that the resonance effect indicated by the light atoms is likely to be attributed to the \( \bar{p}p \) system.

With the antiprotonic atoms the interesting region of subthreshold energies of less than 10 MeV cannot easily be reached. The antiproton annihilations involve not only the valence but also other nuclear shells. On the other hand, the single nucleon capture processes, localized at the extreme surface, happen mostly on the valence nucleons. As discussed in next section the energy dependence seen there seems to be more drastic.

What is found with the recent data [2] is that for light nuclei a best fit \( a \) may be obtained for a number of ranges \( r_\infty \), however, a fit over all the periodic table favours \( r_\infty \) slightly larger than \( r_{ch} \). The best fit may be obtained with \( r_\infty = 1 \) fm but the \( \chi^2/F \) is changed only marginally to 2.4.

### 3.3. Relation of the X-ray and the single nucleon capture experiments

The atomic levels test nuclear densities in surface layers of some 2.5 fm in depths. The mean radii correspond roughly to \( R+1.2 \) fm (lower levels widths), \( R+1.5 \) fm (upper level widths) and \( R+2.5 \) fm (single nucleon captures), where \( R \) is a half density radius of the nucleus. The motivation for the radiochemical capture experiments was to study the relative \( \bar{p}n/\bar{p}p \) capture rates \( \sigma_{n/p} \) at far nuclear peripheries. From these rates the ratios of neutron to proton densities were extracted. Results indicated neutron halos in most of the studied medium and heavy nuclei [4]. The \( \bar{p}n/\bar{p}p \) capture ratios may also be obtained from the atomic level widths. These are defined as \( \sigma_{n/p} = \Gamma_{\text{exp}}/\Gamma_{\text{prot}} - 1 \) where \( \Gamma_{\text{prot}} \) is a partial level width that corresponds to the annihilation on a proton. This width has to be calculated with the best-fit potential based on known (in principle) proton density. Few results, and comparison of the two experiments are shown in table 2.

Nuclear physics predicts the neutron/proton density ratios to increase at large distances. This happens predominantly as a result of the Coulomb barrier, subject to differences in the separation energies and centrifugal barriers. Such a behaviour is borne out by the three complementary measurements: the lower level width, the upper level width and the single nucleon capture. These test more and more extreme surface regions. Consistency of the two experiments is indicated in the upper five lines, several additional cases exist in the data. The errors attributed to the atomic values are statistical only. In addition there exists sizable uncertainty due to the calculation of \( \Gamma_{\text{prot}} \). These make a smooth behaviour...
Table 2
The relative capture rates $\sigma_{n/p}$ obtained from the lower and upper level widths $[2]$, $a = (-1.1 - i1.85) \text{fm}$ is used. The last column shows $\sigma_{n/p}$ obtained via the single nucleon captures $[4]$.

| Atom   | lower  | upper  | capture |
|--------|--------|--------|---------|
| $^{48}\text{Ca}$ | $-1.58(28)$ | $2.62(30)$ |         |
| $^{96}\text{Zr}$ | $0.96(9)$  | $1.54(29)$  | $2.6(3)$ |
| $^{116}\text{Cd}$ | $1.64(49)$  | $2.67(61)$  | $5.0(21)$ |
| $^{124}\text{Sn}$ | $1.80(10)$  | $2.46(39)$  | $5.0(6)$  |
| $^{128}\text{Te}$ | $1.03(19)$  | $2.68(56)$  | $4.2(1)$  |
| $^{106}\text{Cd}$ | $1.65(80)$  | $5.13(80)$  | $0.5(1)$  |
| $^{112}\text{Sn}$ | $1.91(13)$  | $2.45(49)$  | $0.79(14)$ |

of the $\sigma_{n/p}$ ratios to be an additional, strong constraint on the nuclear densities and the structure of optical potentials.

The two lowest lines of table 2 indicate a strong disagreement between the two experiments. Again the interesting point is that these results are characterized by low proton separation energies of 7.35 MeV in $^{106}\text{Cd}$ and 7.54 MeV in $^{112}\text{Sn}$. In the upper sector of the table the proton separation energies are close to or larger than 10 MeV.

4. UNSOLVED QUESTIONS

Several new results suggest an interesting physics likely to happen in the antiproton interactions on loosely bound protons. These are: anomalies in the relative neutron/proton single nucleon capture ratios, attractive lower shifts in $^{106}\text{Cd}$, $^{112}\text{Sn}$, the enhancement of $\bar{p}p$ absorption for negative but close to threshold energies and the difference between scattering volumes obtained from the protonium and from the deuteronium.

All these indicate that a particular role in the interaction may be played by the $^{13}P_0$ wave. This state, of vacuum quantum numbers, is characterised by very strong tensor forces generated by the pion exchange. If the annihilation in the spin triplet states is weak these forces generate a fairly narrow resonance just above the threshold and a quasi-bound state well below it. To understand the effects discussed here both these states seem to be required. However, there exists a difficulty in this interpretation and in the related experimental search. Such a resonant state has a large radius of 1-2 fm. It cannot be built in nuclear systems. One has to search for it in very low density situations. Those are met, for instance, in the single nucleon $\bar{p}p$ captures or in the antiprotonic hydrogen. In the latter case, the effect of $^{13}P_0$ state is seen in the fine structure of the 2P states $[5]$, $[6]$. A large scattering volume in this state has been confirmed in this way. Unfortunately the latter is almost independent of the annihilation models. To understand the $^{13}P_0$ resonance better, a few MeV step below the threshold is required. This may be realised in terms of nuclear experiments.

The relation to other recently found, resonant-like phenomena is not transparent as yet. The dip found in the $e^+e^-$ annihilation just below the $\bar{p}p$ threshold $[20]$, might be attributed to the $^{13}S_1$ wave. This effect is at least consistent with the trend of the S wave
absorption found in deuteronium and protonium. Another recent finding of a destructive interference in the $\bar{n}p$ scattering just above the threshold [21] may be attributed to an effect of the $^{33}P_0$ wave. An extrapolation of this effect to the subthreshold region is uncertain, at this moment.

To elucidate these questions, new experiments would be useful: the elastic $\bar{p}D$ scattering at few MeV energies, resolution of the LS splitting in upper atomic levels and studies of hadronic atoms built on nuclei with very loosely bound nucleons.

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