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RECENT RESULTS FROM ANTIPROTONIC ATOMS AT LEAR

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ABSTRACT

The first-generation experiments at LEAR investigating X-ray spectra of antiprotonic atoms have accumulated a substantial amount of new data. These are summarized and discussed.

The study of X-ray spectra of $\bar{p}$ atoms is an alternative to cross-section measurements, aiming at establishing a conclusive model of the $N\bar{N}$ interactions at low energies where potential models are applicable. The $\bar{p}$ atoms provide data on $\bar{p}$ interactions practically at rest.

In this paper emphasis is put on outlining the coherence of the experimental programme at LEAR attacking unresolved problems of $N\bar{N}$ physics. The particular role of the $\bar{p}$ -atom studies is pointed out and the intercorrelation with other experimental work is shown.

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INTRODUCTION

One of the primary reasons for constructing LEAR was to get a better picture of $N\bar{N}$ interactions at low energy. The description of the NN force in terms of boson exchange models is very successful. This microscopic theory allows the same treatment for the $N\bar{N}$ system since both systems are related through a G-parity transformation. In the latter case, however, the annihilation as yet unexplained by a quantitative microscopic theoretical model has, in addition, to be taken into account. The unknown role of the annihilation gave rise to many speculations. In particular, a variety of narrow resonances and bound states in the $N\bar{N}$ system was predicted. Experimental evidence for such phenomena has come and gone. Today there is no convincing signature for such states, only indications. We are rather left with a puzzle and have to find many pieces to establish a clear picture of the $N\bar{N}$ interaction. Moreover, we have to find means to distinguish between the various $N\bar{N}$ models through dedicated and conclusive experiments questioning particular and controversial predictions. Some of the pieces for this mosaic can be provided by the results of the $\bar{p}$ -atom studies. The X-ray spectra of the following antiprotonic atoms were recently studied at LEAR: ^1H (PS171, PS174, PS175); ^2H (PS175); ^3He (PS175); ^4He (PS175, PS174); $^6/7\text{Li}$, ^{14}N , $^{16/17/18}\text{O}$, ^{19}F , ^{23}Na , ^{40}Ca , $^{58/64}\text{Ni}$ (PS176); $^{92/94/95/98/100}\text{Mo}$ (PS186); ^{138}Ba (PS176); $^{146/148}\text{Nd}$, ^{165}Ho (PS186); ^{208}Pb , ^{232}Th (PS176).

Theoretically the $p\bar{p}$ interaction at rest (antiprotonic hydrogen) is to some extent one of the simpler cases. Experimentally, however, the study of the X-ray spectrum of this system is very demanding. In heavier systems the experiments are easier; the interpretation of the data in terms of a microscopic model is more difficult.

In the following we will first discuss the situation for the antiprotonic hydrogen atom and then continue with heavier atoms. At the end, the outcome of these measurements is compared with the results of other experiments done at LEAR.

ANTIPROTONIC HYDROGEN

The main interest in the antiprotonic hydrogen atom system, as far as it concerns the overall features of the $p\bar{p}$ interaction, lies in the determination of the $p\bar{p}$ scattering length $a(p\bar{p})$ through the measurement of the energy shift and hadronic width of the 1s levels (spin and isospin multiplets). There are three experiments¹⁾ on the floor at LEAR to determine this crucial quantity. The s-wave scattering length is a check point for any $N\bar{N}$ potential. The predicted scattering length of various models is shown in Table 1.

The common features of all these predictions is the negative real part reflecting a strong repulsion of the boson exchange potential. The values in Table 1 also show the required accuracy in order to distinguish between the different models.

Frequently a relation (Trueman formula) between the s-wave scattering length and the shift and width of the 1s level is used²⁾:

$$\epsilon + i\Gamma/2 = 2(\hbar c)^2 / \mu \alpha_B^3 a(p\bar{p}) = 0.866 a(p\bar{p}) \quad .$$

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Table 1

s-wave scattering lengths predicted by various potential models

a(I,S)	Re (a) (fm)	Im (a) (fm)	ϵ (eV)	Γ (eV)	$q(p\bar{p})$	Ref.
a(1,1)	-0.77	0.68	- 667	1178	- 1.13	BP (3)
a(1,0)	- 1.01	0.51	- 875	883	- 1.98	BP (3)
a(0,0)	-0.35	1.18	- 303	2044	-0.30	BP (3)
a(0,1)	- 1.44	0.76	- 1247	1316	- 1.90	BP (3)
a(p $\bar{p}$)	-1.00	0.75	- 866	1301	- 1.33	BP (3)
a(p $\bar{p}$)	-0.92	0.68	- 797	1178	- 1.35	DR1 (4)
a(p $\bar{p}$)	-0.96	0.73	- 831	1264	- 1.32	DR2 (4)
a(p $\bar{p}$)	- 1.03	0.79	- 890	1365	- 1.31	PA (5)

The shift and width thus calculated are shown in columns 4 and 5 of Table 1³⁻⁵⁾. For illustration, the spin S and isospin I decomposed scattering length are given in the first four rows for the Bryan-Phillips (BP) potential³⁾.

In our opinion this formula should, however, be applied to $\bar{p}$ atoms only with care since the interaction is of finite range and so strong that the underlying procedure for its use is not necessarily justified. The strong absorptive part leads to such a deformation of the wave function that a purely imaginary potential leads already to a sizeable repulsive shift unexplained by the Trueman formula. Adding then a real part may lead to an oscillating behaviour of the level width as a function of the strength of the real part. This was already shown more than ten years ago by Krell⁶⁾ and by Koch et al.⁷⁾. The correct procedure is to solve the Schrödinger or Dirac equation using the full potential.

The ratio of the real-to-imaginary part of the scattering length is equivalent to the ratio of the real-to-imaginary part of the $(p\bar{p})$ forward scattering length $q(p\bar{p})$ at zero energy. This fact provides a direct link between $\bar{p}$ -atom and scattering data since every phase-shift analysis, or the extrapolation of the $q(p\bar{p})$ parameter determined from Coulomb interference and continued to zero energy, should lead to the value derived from $\bar{p}$ atoms. The value of $q(p\bar{p})$ at rest calculated from the ratio of the real-to-imaginary part of the scattering length is shown in column 6 of Table 1. All theories predict a negative $q(p\bar{p})$ around - 1.3 for zero energy.

Tentative experimental results from LEAR are available now, and they all indicate a repulsive shift^{8,9)}.

ANTIPROTONIC ATOMS BEYOND ANTIPROTONIC HYDROGEN

As soon as the nucleus is composed of more than one nucleon, the $\bar{p}A$ interaction is a combination of elementary $\bar{p}N$ interaction and nuclear-matter effects. As in other hadronic atoms one attempts to derive the $\bar{p}A$ potential from the free t-matrix, taking into account the Fermi motion of the nucleons and their distribution within the nucleus. Pre-LEAR data, summarized elsewhere¹⁰⁾, were so scarce that they did not allow for a conclusive test of these attempts. A simple optical potential model gave a satisfactory overall description of the data. With the availability of very precise measurements from LEAR the situation has changed considerably.

The primary goal of the new experiments was the accurate determination of hadronic level shifts and widths in a variety of nuclei ranging from $\bar{p}\text{He}$ to $\bar{p}\text{Pb}$. Combined with $\bar{p}A$ scattering data, it is aimed at the construction of a universal $\bar{p}A$ potential in terms of the elementary $N\bar{N}$ interaction.

In systems heavier than $\bar{p}\text{H}$ the antiproton annihilates before it reaches the 1s state. The atomic level from which the antiproton is absorbed depends on the nuclear charge. In helium, for instance, it annihilates in the 2p level while in lead it reaches at most $n = 9$ states. The shift and width of the last level are, however, not always measurable simultaneously. On the one hand, they have to be large enough compared to the detector resolution in order to be measurable and, on the other hand, the transition feeding this level has to be intensive enough to be observable. Table 2 shows the windows where level shifts and widths in $\bar{p}$ atoms can be measured simultaneously with solid-state detectors.

Table 2

Accessible levels for simultaneous measurement of shift and width in $\bar{p}$ atoms

Nuclear charge	1	2-4	7-11	15-20	26-30	40-45	55-59	70-74	90-92
Atomic level	1s	2p	3d	4f	5g	6h	7i	8j	9k

Though the $\bar{p}A$ interaction takes place in high partial waves, the elementary $\bar{p}N$ interaction is dominated mostly by s- and p-waves, since the Fermi momentum of the nucleons in the nucleus hardly exceeds 300 MeV/c. In Fig. 1 a typical X-ray spectrum is shown (^{40}Ca). In this example the lowest atomic level that the antiproton reaches is the 4f state. The strong absorption manifests itself in a broad line (5 $\rightarrow$ 4) feeding this level.

Fig. 1 Spectrum of antiprotonic ^{40}Ca .

Fig. 2 Part of the X-ray spectrum of antiprotonic ${}^6\text{Li}$ and ${}^7\text{Li}$ showing the isotope effect in the $3 \rightarrow 2$ transition. Note that the energy of the X-rays in ${}^7\text{Li}$ is higher than in ${}^6\text{Li}$ by a factor of 1.0210 (ratio of the reduced masses).

In contrast to the investigation of the general features of $\bar{p}A$ force, a part of the experimental programme was devoted to the study of particular dependences of the $\bar{N}N$ interaction. Specifically it was aimed at the determination of the dependence on spin and isospin of the $\bar{N}N$ potential. The latter can be found out by comparing hadronic widths and shifts of the same atomic level in different isotopes of the same element and also by determining the relative strength of antiproton absorption on protons and on neutrons. Figure 2 shows the spectrum for such a case (${}^6/{}^7\text{Li}$).

Spin-orbit effects should produce different shifts and widths for fine structure levels. In Fig. 3 a part of the X-ray spectrum of $\bar{p}{}^{174}\text{Yb}$ is displayed, showing the resolved fine structure components of the $9 \rightarrow 8$ transition. This fortunate situation is used to determine the spin-orbit dependence of the $\bar{p}N$ force through the measurement of hadronic shifts and widths in the two fine structure levels (usually the fine structure components cannot be resolved experimentally).

Moreover, particular terms of the $\bar{p}$ interaction with the nucleus can be studied through $\bar{p}$ -induced nuclear excitations. This is shown in Fig. 4, giving an example of the degeneracy of $\bar{p}$ -atomic levels with nuclear levels (${}^{100}\text{Mo}$), which leads to an excitation of the nucleus through an internal E2 transition.

Ultimately also spin-spin effects should be detectable through the measurement of hadronic shifts and widths of hyperfine levels.

The quantum numbers of the nucleus play an important role in this sense, as they allow one to filter out particular components of the $\bar{N}N$ force. For example, in $\bar{p}$ atoms with a nucleus of vanishing isospin the pion exchange is not present.

Fig. 3 Part of the X-ray spectrum of antiprotonic ^{174}Yb , showing the resolved fine structure components of the $9 \rightarrow 8$ transition.

Fig. 4 X-ray spectrum of antiprotonic $^{92/94/95/98/100}\text{Mo}$, displaying the excitation of the ^{100}Mo nucleus showing up through an attenuation of the $7 \rightarrow 6$ transition.

DISCUSSION OF RESULTS

a) Strong interaction in general

Traditionally, strong-interaction effects in baryonic atoms are analysed by solving the Schrödinger (Dirac) equation for a Coulomb and a hadronic potential. The hadronic part is constructed from the free t-matrix or, in the simplest case, from an optical potential where the real and imaginary parts of the potential are considered to be the 'effective' hadron-nucleus s-wave scattering length A :

$$V(r) = -(2\pi/\mu)[1 + m_{\bar{p}}/M_A] [A_{p\bar{p}} \rho_p(r) + A_{p\bar{n}} \rho_n(r)].$$

This ansatz is extremely simplified as it completely neglects all the details of the interaction and its dependence on quantum numbers. However, it is surprising how well this optical model reproduces the data so far. An interesting feature of this ansatz is shown in Fig. 5, where the pairs of $\text{Re}(A)$ and $\text{Im}(A)$ give a certain 3d width or shift in $\bar{p}^{16}\text{O}$. There is a strong dependence of ϵ on $\text{Im}(A)$ and of Γ on $\text{Re}(A)$ visible [a weak perturbative potential would give $\epsilon \propto \text{Re}(A)$ and $\Gamma \propto \text{Im}(A)$]. Furthermore, at first glance, it seems surprising that an attractive potential [$\text{Re}(A) > 0$] gives repulsion ($\epsilon < 0$). This can, however, be explained by the strong damping of the $\bar{p}$ -wave function from the surface on to the interior of the nucleus which produces a net repulsion. One notes that through a precise measurement of the hadronic width and shift the optical potential is well determined for fixed nuclear matter distributions. These results can be compared with $\bar{p}A$ scattering data¹¹⁾ which are also analysed in terms of an optical potential. In fact, the study of the $\bar{p}A$ interaction at LEAR was coordinated such that a number of nuclei were investigated in scattering and $\bar{p}$ -atom studies. The outcome of the scattering experiments was presented in the talk by Lemaire¹¹⁾.

The data confirm that there is no room for a family of potentials which would reproduce $\bar{p}$ -atom data as claimed earlier¹²⁾. The findings of Ref. 12 may rather reflect the oscillatory behaviour of strong-interaction effects with increasing potential strength, as mentioned earlier^{6,7)} and as shown in Fig. 6. An analysis based on a rather limited sample of less precise pre-LEAR data is misleading and it has been shown recently¹³⁾ that the inclusion of the full set of pre-LEAR data excluded already these ambiguities. Moreover, it can be shown that the accurate measurement of strong-interaction effects in a single nucleus determines a unique optical potential (cf. Fig. 5).

Fig. 5 Plot of lines of equal shifts and equal widths in the complex $\bar{p}A$ potential plane for the 3d level of $\bar{p}O$.

Fig. 6 Width of the 3d level in $\bar{p}^{16}\text{O}$ calculated with an optical potential as a function of the real part of the potential for various imaginary potential strengths.

Recently, microscopic $\bar{p}A$ theories based on the Dover-Richard⁴⁾ or the Paris⁵⁾ potential, have been applied to the $\bar{p}$ atom and the $\bar{p}A$ scattering results. Their predictions¹⁴⁻²⁰⁾ are shown in Table 3, together with earlier phenomenological approaches, pre-LEAR¹⁰⁾ and the tentative LEAR [PS174⁹⁾, PS176²¹⁾, PS186²²⁾] experimental results. Regarding the values given in Table 3, we will not draw any conclusions now, as one should await the results from the data still under evaluation and an eventual refinement of the theoretical approaches.

Table 3

Shifts and widths of the same atomic levels for $\bar{p}$ atoms.
First value: negative shift; second value: width (all in eV).

Nucleus	Level	Experimental		Theoretical						
		Pre-LEAR	LEAR	Ref. 14	Ref. 15	Ref. 16	Ref. 17	Ref. 18	Ref. 19	Ref. 20
^4He	2p	50(18), 105(65)	7.4(5.3), 35(15)			4.8, 21		5, 36		
^6Li	2p	205(66), 410(170)	*) *)					230, 444		
^7Li	2p	312(48), 277(113)	*) *)					203, 570		
^{12}C	3d	4(10), 42(18)				14, 52		8, 76		
^{14}N	3d	18(36), 179(31)	*) 100(50)	51, 141	71, 175	53, 167	31, 148			-, 163
^{16}O	3d	124(36), 480(110)	120(20), 480(30)	148, 367	116, 547	161, 444	134, 578	125, 652	90, 554	-, 532
^{17}O	3d		150(50), 550(50)					155, 858		
^{18}O	3d	189(42), 550(240)	200(20), 620(30)			195, 503		181, 750	158, 688	-, 646
^{19}F	3d		470(20), 1490(50)							
^{23}Na	3d		2200(260), 4700(1400)							
Si	4f	38(39), 110(190)				41, 171				
P	4f	65(23), 446(69)				91, 332				-, 797
^{32}S	4f	60(40), 650(100)		130, 457	97, 734	165, 561	120, 800		151, 514	
^{40}Ca	4f		*) *)						1440, 3520	
Fe	5g	10(310), 540(320)				139, 550				
Y	6i	150(160), 800(320)				159, 680				
Zr	6i	450(100), 700(210)				222, 900				
^{92}Mo	6i		480(90), 1800(400)			254, 1180				
^{94}Mo	6i		400(310), 2100(900)			270, 1170				
^{95}Mo	6i		630(110), 2300(400)			279, 1200				
^{96}Mo	6i		630(150), 2700(800)			306, 1270				
^{138}Ba	7j		350(150), 1800(450)							
^{174}Yb	8k	-260(460), 1480(660)	*) *)							
^{232}Th	9l		*) *)							

^{*)} Data under evaluation.

The preliminary conclusions that can be drawn from the optical model analysis of all evaluated data is that the $\bar{p}A$ force has a much deeper imaginary than real part both for atoms and scattering experiments ($\text{Re } V/\text{Im } V$ about 1/2). This is a universal feature. The interaction is strongly peripheral (as expected). The strength of the potential is well defined at the nuclear surface with little sensitivity to the interior of the nucleus. This is not surprising when regarding the depth of the annihilation potential. It is unlikely that information can be extracted about the behaviour of the $\bar{p}A$ potential in the interior of the nucleus through this kind of measurements. Moreover, an optical model is highly inappropriate for the interior of the nucleus. The nucleus is essentially black to the antiproton beyond a certain radius. This has the advantage that internal nuclear structure effects do not matter and only the configuration of the outer nucleons counts, which means that the $\bar{p}A$ interaction can be separated from the bulk and reduced eventually to the interaction of the antiproton with the outer nucleons. By choosing the right nucleus, we may then come close to the situation where we have essentially elementary antiproton-nucleon interactions. This opens the possibility to study more details of the $N\bar{N}$ force with the technique of $\bar{p}$ atoms, which are in some cases easier to perform than in experiments on the $N\bar{N}$ system itself. This leads us to the next point.

b) Isotope effects

Isotope effects have been measured in order to study the isospin dependence of the $N\bar{N}$ force. Changes of hadronic shifts and widths within a chain of isotopes should indicate the strength of the $\bar{p}n$ interaction (pure isospin triplet state). Care has to be taken in order to account for the change of the nuclear-shape parameter from one isotope to another.

Clear isotope effects have been observed in the stable oxygen isotopes⁸⁾. Also the recent measurements (PS176) of ${}^6\text{Li}/{}^7\text{Li}$ and ${}^{58}\text{Ni}/{}^{64}\text{Ni}$ indicate a pronounced effect. The final evaluation of the data aims at the determination of the strength of the isospin $I = 1$ component. Ultimately the $\bar{p}n$ scattering length should be deducible.

The simple optical model may give, however, a first indication of the strength of the $\bar{p}n$ interaction. In contrast to the calculation of the total strong-interaction effects, which requires a full solution of the Schrödinger equation, a perturbation calculation of the relative changes of hadronic level widths and shifts in isotopes may suffice to determine the effects of the $\bar{p}n$ interaction. If this can be proved to be applicable then the changes in width and shift can be directly related to the $\bar{p}n$ potential:

$$\Delta\epsilon + i \Delta\Gamma/2 \propto \int V(I = 1) \psi^2(r) dr$$

Decomposition into a real and an imaginary part on either side of the potential and forming ratios in order to get rid of common factors yields:

$$2\Delta\epsilon/\Delta\Gamma = \text{Re}(V)/\text{Im}(V)$$

In the case of pure s-wave interaction this is equivalent to the ratio of the real-to-imaginary part of the $\bar{p}n$ forward scattering amplitude nearly at zero energy. The experimental value for this ratio derived from the isotope effects in ${}^{16}\text{O}/{}^{18}\text{O}$, is around negative unity; this value is close to $\text{Re } a(p\bar{p})/\text{Im } a(p\bar{p})$ at rest predicted by the various potential models (see Table 1). This is remarkable since the determination of $\rho(p\bar{p})$ from Coulomb interference measurements in low-energy scattering experiments^{23, 24)} gives values close to zero at lowest $\bar{p}$ momenta (Fig. 7). Our suspicion is that the opening of the charge-exchange channel at 100 MeV/c may strongly influence this parameter. Since the nucleons may have a large Fermi momentum it is, however, the contribution of higher partial waves which is as yet unclear. If their contribution is significant, the above ratio is only a limit for $\rho(\bar{p}n)$ at rest.

Dalkarov and Karmanov²⁵⁾ have analysed the $\bar{p}$ - ${}^{12}\text{C}$ scattering data of Ref. 11 in a Glauber treatment. They derived a ρ parameter of zero for 300 MeV/c and of +0.2 for 600 MeV/c. It would be interesting to see whether a similar approach could be applied to the $\bar{p}$ -atom data.

Fig. 7 The real-to-imaginary part of the $\bar{p}p$ forward scattering amplitude as a function of $\bar{p}$ momentum.

c) Spin-orbit dependence

The NN potential is known for its strong spin-orbit term. The situation should be similar for the real part of the $N\bar{N}$ force; however, the annihilation potential is very deep and its dependence on the spin is unclear. The determination of L-S effects in the $N\bar{N}$ interaction is a crucial point, as they provide deeper insight into the details of the potential. Their magnitude also determines whether polarized $\bar{p}$ beams can be produced through scattering unpolarized antiprotons from a target.

Theoretically large spin-orbit effects for the total hadronic shifts were predicted¹⁵⁾ for light nuclei on the basis of a 20 MeV deep L-S term. Recently, Suzuki and Narumi¹⁶⁾ calculated these effects in more detail for $\bar{p}^{16}\text{O}$. More recently Dumbrajs et al.¹⁸⁾ constructed a $\bar{p}A$ potential from the Dover-Richard model. They predict effects of similar magnitude, but opposite in sign for oxygen. In Table 4, the calculated spin-orbit effects for

Table 4

Predicted spin-orbit effects in $\bar{p}$ atoms.
First value: $\epsilon_{\uparrow\uparrow} - \epsilon_{\uparrow\downarrow}$; second value: $\Gamma_{\uparrow\uparrow} - \Gamma_{\uparrow\downarrow}$ (in eV).

Nucleus	Level (n, l)	Ref. 15 ⁾	Ref. 16 ⁾	Ref. 18
^{14}N	3, 2	23, -		
^{16}O	3, 2	50, -	20, 50	-33, -50
^{32}S	4, 3	65, -		

⁾ Sign of $\Delta\epsilon$ not given.

light $\bar{p}$ atoms are shown. Although with present techniques these effects are unmeasurable in light nuclei, they should be even stronger in higher angular momentum states of heavier atoms where their determination is possible.

The PS176 experiment has investigated this question by measuring shift and width separately in resolved fine structure levels of $\bar{p}$ atoms. This is possible only in a few even-even nuclei since firstly the nucleus should have zero spin to avoid confusion with hyperfine interactions; and secondly the hadronic level width should be large enough to allow a precise determination of the effect but, on the other hand, it should be smaller than the fine structure splitting. Owing to limited statistics, a first measurement of L-S effects on ^{138}Ba resulted only in a lower limit of about 30%; recent measurements of PS176 on ^{174}Yb , however, indicate a significant difference of strong-interaction effects in different fine structure levels, particularly showing up in the absorption.

These results have to be compared with the outcome of a double scattering experiment on ^{12}C at 550 MeV/c recently performed by the SING Collaboration at LEAR (PS172, Ref. 26). They measured the asymmetry parameters at small scattering angles and found practically a null result. Theoretical models predict, however, sizeable effects at higher angles, where no data are available yet. If there are strong spin-orbit effects they should show up in $\bar{p}$ atoms as here an integration is done over all angles and they enter directly into the differences of shifts and widths for fine structure levels.

d) Nuclear excitations

There are a few cases where the energy difference between atomic levels coincides with the energy required to populate the first excited state of a nucleus. For the energy scale present in hadronic atoms this concerns mostly the excitation of rotational states involving E2 transitions. This means that during the atomic cascade of the antiproton the nucleus is excited (mostly $0^+ \rightarrow 2^+$ transitions) and the antiproton is absorbed from an atomic level while the nucleus is in an excited state. This effect has been identified through the attenuation of atomic transitions studied by experiment PS 186²²⁾. The measured attenuation is in good agreement with the predictions of Leon²⁷⁾, who first pointed out this technique. However, a full exploitation of this effect requires a rather advanced theoretical model. On the other hand, this method is very appealing as it opens up the possibility of studying the $\bar{p}$ interaction with an excited nucleus and, in this way, to probe in a different manner the NN force. This is of particular interest when inelastic scattering data from such a nucleus should also be available.

SUMMARY AND CONCLUSIONS

The study of the NN interactions at low energy is one of the main goals of the LEAR programme. Investigations are made, starting from different directions and applying various experimental techniques. In this paper we tried to outline the link between the different experiments, in particular between $\bar{p}$ -atom studies, and $p\bar{p}$ and $\bar{p}\text{A}$ elastic scattering. In view of the complexity of the NN force all available data are needed for a refinement and a better judgement of the quality of the potentials. This is, in particular, true for the test of spin-orbit, isospin, and spin-spin dependent terms and equally important for the annihilation. Data from $\bar{p}$ atoms can contribute significantly to the solution of these questions through the application of specific techniques.

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