ANTIPROTON-NUCLEUS INTERACTION

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Abstract

We present a general overview of the physics issues associated with the antiproton-nucleus experiments at low energy. This includes antiprotonic atoms, antiproton-nucleus elastic and inelastic scattering, proton emission measurements, charge-exchange reactions and the study of the antiproton annihilation on nuclei. Antiprotons prove to be useful and accurate tools for developing conventional nuclear physics. They also provide unique tests of speculative new aspects of strong interactions.

Introduction

The antiproton-nucleus interaction has received considerable attention during recent years. This can be seen by the number of papers published on this subject; the list of references will give only a rather arbitrarily chosen selection (with my apologies to the authors whose papers have been omitted). The discussions on these topics were also numerous at Tignes [1] and at specialized meetings [2,3].

There are several reasons for being interested in the antiproton-nucleus ($\bar{p}$-A) interaction. The first of these belong to the modern frontier of Nuclear Physics : $\bar{p}$-A provides rich information on the "elementary" nucleon-antinucleon (N-$\bar{N}$) amplitude whose spin and isospin dependence is not measured completely in direct 2-body experiments, due to the lack of intense antineutron beams and of polarized $\bar{p}$'s. The study of how a nucleus reacts to excitation by antiprotons also provides interesting tests of nuclear dynamics.

A second motivation is reminiscent of baryonium physics : it has been speculated on the basis of plausible models, that a $\bar{p}$ can be attached at the periphery of a nucleus by the attractive tail of the real potential without being immediately absorbed by the imaginary potential of shorter range. These are, for instance, the "orbiting resonances" of Ref. [4], to be seen in backward $\bar{p}$ scattering or in the proton spectrum of the ($\bar{p}$-p) reactions. In a different context, it was also proposed that the 1S level of the $\bar{p}$-A system is not fully washed out by annihilation : for A = ^{16}O, a width of only 0.1 - 0.2 MeV was calculated [5].

In a third category may be mentioned the study of $\bar{p}$-A annihilation. New reactions are likely to occur [6] (and appear to have already been seen [7]), such as the genuine 3-body process $\bar{p}NN \to \Lambda X$, not to be confused with "ordinary" $\bar{p}N \to K\bar{K}$ followed by the $\bar{K}$ rescattering on a nucleon. Also, it is of great interest to study how a nucleus reacts to a sudden and localized energy release of 2 GeV provided by annihilation. A detailed study of the fragments emitted helps to reconstruct the time and temperature evolution of the nucleus in such a process. Even if the conditions for a genuine "quark-gluon plasma" are not reached, we have here nuclear matter in a quite unusual state [8].

Finally, as already underlined by Brodsky [9], when energy increases, it will be worth studying $\bar{p}A \to hX$ inclusive reactions, where h = π, K, Λ, ... as well as the Drell-Yan process $\bar{p}A \to \ell^+\ell^-X$, as a probe of the quark distributions in nuclei and of our understanding of this basic QCD process. Coming back to low energy, one may recall that the phenomenon of neutron-antineutron oscillations, predicted in certain GUT or SUSY-GUT, occurs in nuclei at a rate which depends on the nuclear potential felt by the antineutron [10].

Experimental Results

The LEAR results have been reweived by K. Kilian [11], while the future was outlined by R. Landua [12]. H. Poth's talk [13] contains more details on antiproton atoms. Data have also been taken at BNL and KEK. Let me summarize what is available now :

antiprotonic atoms [13] : shifts and widths have been measured for a variety of atoms as different as $\bar{p}$-p (protonium) and ^{208}Pb. In particular, a comparison of isotopes has been made for Lithium and Oxygen. The collaboration PS 186 has observed an interesting mixing of nuclear and atomic excitations in Molybdenum [14].

$\bar{p}$ elastic scattering [15] : The differential cross-section of $\bar{p}$-^{12}C at 50 MeV was the first measurement performed at LEAR. Other targets and energies have been used. In particular, the ^{16}O and ^{18}O isotopes have been compared.

$\bar{p}$ inelastic scattering, i.e. $\bar{p}\ A \rightarrow \bar{p}\ A^*$ is limited by the energy resolution which is necessary to disentangle the various nuclear levels A* in the final state. Interesting data have been provided by the PS 184 collaboration [16].

$\bar{p}$ reaction cross-section, as well as differential cross-sections in the forward region are shown in Ref. [17]. This concerns the following nuclei : C, Al, Cu and Pb.

The ($\bar{p}$,p) reaction was studied on ^{12}C, , ^{63}Cu and ^{208}Pb, to search for antiproton-nucleus states [18]. Although the result is negative, the measured proton spectrum gives interesting information on the mechanism of annihilation and subsequent intranuclear cascades.

The ($\bar{p}$-$\bar{n}$) charge-exchange has been compared to the elementary process $\bar{p}p \rightarrow n\bar{n}$ in Ref. [19]. Experiments have also been performed [20] or proposed [21] at LEAR or at "BNL and beyond" [22].

Annihilation products have been analyzed by different techniques such as residual radioactivity [14], emulsion pictures [23] (see also [24]), not to mention the delayed fission of heavy hypernuclei [25]. Systematic studies are planned using the "Obelix" facility [26].

The antiproton-nucleus potential

As the accuracy of the data is improved, their theoretical description becomes more elaborate and reaches the point where the microscopic dynamics is tested. Let me describe the successive steps :

1. The black sphere model describes the forward amplitude but completely fails at larger angles, as seen in Fig. 1, taken from Ref. [27]. This means that the antiproton does not penetrate much inside the nucleus without being absorbed but enjoys non trivial interactions at the surface of the nucleus.

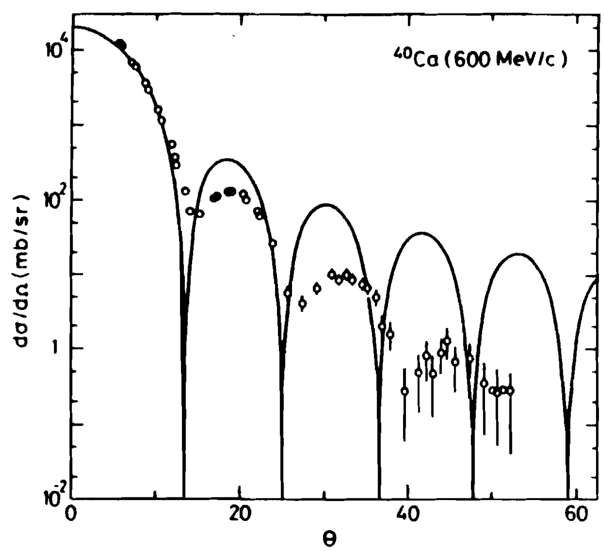

Fig. 1 : Experimental differential cross section as a function of angle for 600 MeV/c antiproton elastic scattering on ^{40}Ca. The curve is the black-sphere prediction for the radius R = 1.3 fm x $40^{1/3}$.

2. A slight variant, apparently more successful, is the boundary condition model used by Kaufmann and Pilkuhn [28] for the antiprotonic atoms. At a certain radius R, a value is imposed to the logarithmic derivative f'/f of the wave-function, corresponding to a strong absorption for r < R. For r > R,f(r) is driven by the Coulomb force and the tail of the meson-exchange interaction.

3. The zero-range approximation was used for a while. See, for instance, the pre-LEAR review by Batty [29]. It reads, in terms of the nuclear density ρ(r)

$$V_{\bar{p}A} \propto (a + ib)\, \rho(r) \qquad (1)$$

In principle, a + ib is the 2-body scattering length. The problem was that, while any "realistic" two-body potential [30,31] produces a repulsive real scattering length a, antiprotonic atoms require, on the basis of eq. (1), an attractive a [29]. This is due to the neglect of the range of the N-$\bar{N}$ forces (a few fermis for the real part).

4. The range problem can be cured in a <u>phenomenological potential</u> which is allowed to extend beyond the nuclear density. A standard choice is the Wood-Saxon shape

$$V_{\bar{p}-A} = \frac{-V^\circ}{1+\exp(r-c)/\gamma} - \frac{i\, W^\circ}{1+\exp(r-d)/\delta} \qquad (2)$$

The pre-LEAR data were compatible with two types of optical potential [32] :

i) S-type, with a shallow imaginary part $W^\circ \simeq 100$ MeV, and a deep real part $V^\circ \simeq 200$ MeV.

ii) D-type with deeper imaginary part $W^\circ \simeq 200$ MeV and shallower real part $V^\circ \simeq 100$ MeV.

The χ^2 plot for ^{12}C is shown in Fig. (2).

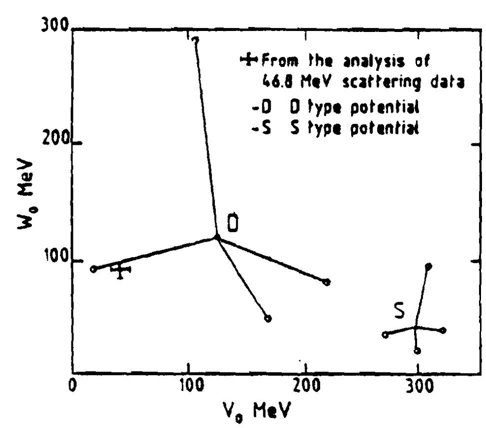

Fig. 2 : Comparison between the real (V_0) and imaginary (W_0) potential depths which reproduce the 46.8 MeV $\bar{p}$-^{12}C scattering data to the results deduced from the analysis of pre-LEAR antiprotonic atom data (S and D) (from ref. 16).

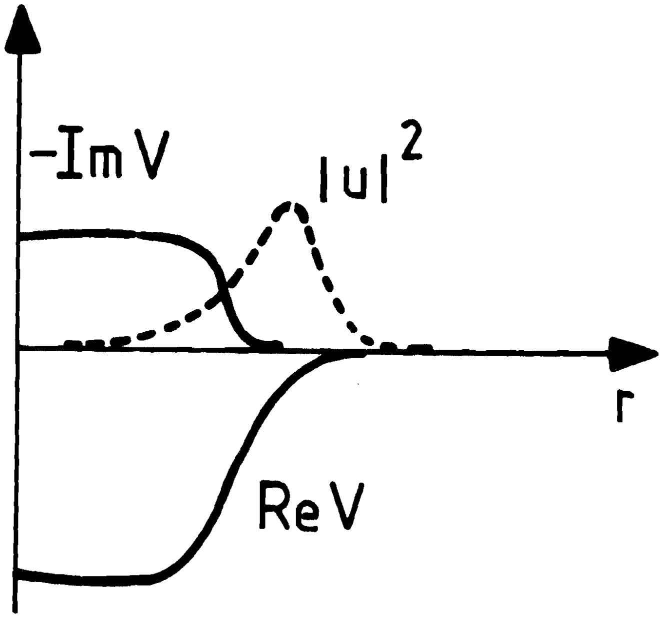

Fig. 3 : Schematic representation of a metastable antiproton-nucleus state in a S-type potential

When LEAR came into operation, it took only two hours to rule out the S-type of potential for ^{12}C , thanks to the PS 184 experiment [15]. This is clearly seen in Fig. (3). More detailed phenomenological analysis have been done by several groups [27,33].

It is important to notice that the real potential V° needs to be attractive, but, since only the surface region is really experienced by the antiprotons, the inner part of the potential is not determined by this phenomenological analysis.

5. With the Glauber approximation, the $\bar{p}$-A amplitude is now related to the elementary $N\bar{N}$ scattering, through the total cross-section σ and the real-to-imaginary ratio ρ = Re F/Im F. This is described, e.g., in Ref. [34], where a good agreement with the data is obtained.

6. In the impulse approximation, one performs a folding of the elementary amplitude T with the nuclear wave-function, as given by standard nuclear models and constrained to fit the electron scattering data. T is produced by semi-phenomenological $N\bar{N}$ potentials with meson-exchange and empirical complex core [30,31].

A good agreement with the data is generally obtained. In fact, the corresponding potential coincides with the empirical form (2) near the surface, whereas inside the nucleus the real part becomes repulsive. This is shown in Fig. 4a.

The data are accurate enough to constrain the 2-body potential. For instance, the study of antiprotonic atoms in Ref. [35] gives the following results :

Nucleus	J	l	j	F	Central part		Central + spin-orbit	Central + tensor	Experiment
					Model 1	Model 2			
^{4}He	0	1	3/2	3/2	(-6,-19)	(-6,-17)	(-6,-19)	(-6,-19)	(-7.4±5.3, -17.5±7.5)
		1	1/2	1/2	(-6,-19)	(-6,-17)	(-4,-18)	(-6,-19)	
^{6}Li	1	1	3/2	1/2	(-190,-261)				(-230±72,-222±105)
		1	1/2	1/2	(-219,-275)				
^{7}Li	3/2	1	3/2	1	(-190,-276)				(-336±60,-228±95)
		1	1/2	1	(-215,-293)				
^{12}C	0	2	5/2	5/2	(-9,-38)	(-10,-34)	(-10,-39)	(-9,-38)	(-4±10,-21±9)
		2	3/2	3/2	(-9,-38)	(-10,-34)	(-6,-36)	(-9,-38)	
^{16}O	0	2	5/2	5/2	(-145,-335)	(-153,-304)	(-158,-341)	(-145,-335)	(-135±8,-235±13)
		2	3/2	3/2	(-145,-335)	(-153,-304)	(-125,-326)	(-145,-335)	
^{17}O	5/2	2	5/2	1	(-173,-342)			(-162,-351)	(-165±8,-280±15)
		2	3/2	1	(-145,-355)			(-180,-320)	
^{18}O	0	2	5/2	5/2	(-181,-375)	(-191,-339)		(-181,-375)	(-206±8,-320±15)
			3/2	3/2	(-181,-375)	(-191,-339)		(-181,-375)	

TABLE 1 : Energy level shifts for the nuclei in column 1. The quantum numbers in columns 2-5 are angular momenta of the nuclear ground state (J), the orbital (l) and total (j) angular momentum of the antiproton single particle state and the angular momentum of the total system (F). Model 1 and model 2 refer to two versions of the DR potential [31]. Central, spin-orbit and tensor refer to the two-body interaction. The energy units are always eV. Where no entries are given, the contribution has not been calculated.

There is a systematic overestimate of the widths. The reason is probably that the DR potential [31], being energy independent and adjusted to the pre-LEAR cross-sections at $E \gtrsim 100$ MeV, overestimates the absorption at rest. In any microscopic calculation [36], the summation over intermediate states

$$N\bar{N} \rightarrow \text{mesons} \rightarrow N\bar{N}$$

which occurs in computing the imaginary potential, gives phase-space factors which vary rapidly near the $N\bar{N}$ threshold, especially in channels involving vector mesons.

As seen in the above table, the isospin and spin dependence is nicely tested in antiprotonic atoms. The $\bar{p}$-n interaction is deduced from the comparison between ^{6}Li and ^{7}Li or ^{16}O, ^{17}O and ^{18}O isotopes. The spin-orbit amplitude≠ influences the fine structure, while the tensor one plays a role in ^{17}O. The analyzing power on ^{12}C has also been measured [38] and interpreted [39,40] : the result is unfortunately (but not surprinsingly) small, so that ^{12}C cannot be used as an analyzer of antiprotons.

7. Medium and relativistic corrections have also been considered, and generally found to be smaller than in the proton case. The former have been included by von Geramb [39] and T. Suzuki [40] who used the so-called G-matrix instead of the simple T-matrix to derive the optical potential. The relativistic corrections have been discussed for instance by B.C. Clark et al. [41] and J. Mahalanabis [42].

Inelastic antiproton scattering

The above optical potential calculations provide us with the wave-functions of the $\bar{p}$-A or $\bar{p}$-A* systems. Here A* denotes an excitation of the nuclear ground-state. It is now rather easy, at least in the DWBA approximation, to work out the amplitude for the inelastic process $\bar{p}\text{-A} \rightarrow \bar{p}\text{-A}^*$. Such reactions have the

≠ Since some spin-dependent forces are strong [37], they cannot be treated to first order. So, there is no one-to-one correspondence between the various terms in the potential and in the amplitude. For instance, the spin-orbit amplitude is due, to a large extent, to the tensor potential.

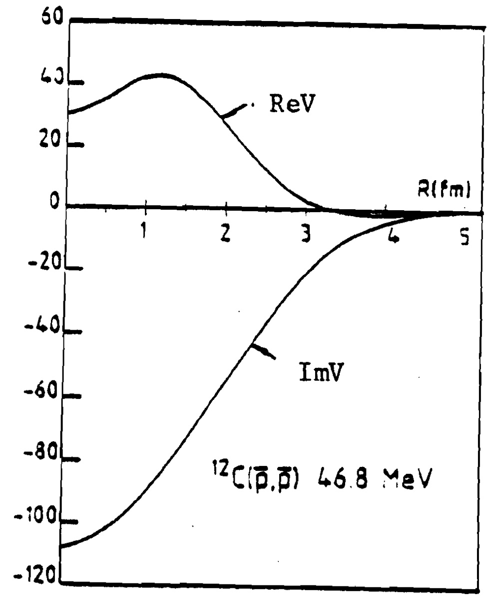

Fig. 4a - The $\bar{p}$-^{12}C optical potential calculated by von Geramb et al. (S. Janouin, Thesis, Orsay)

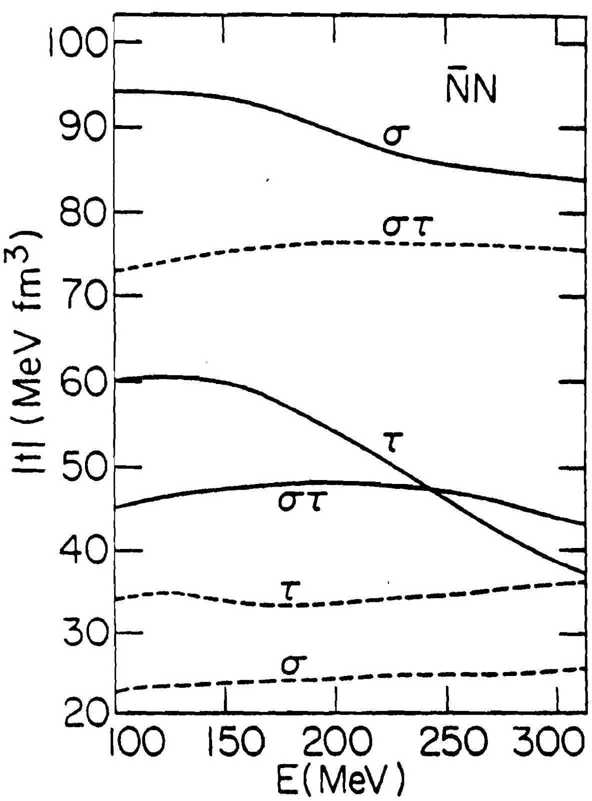

Fig. 4b - The magnitude of various spin-isospin components of the central $N\bar{N}$ t-matrix as a function of kinetic energy for zero momentum transfer. The solid curves correspond to the Paris model, the dashes ones to Dover-Richard (from Ref. [43])

remarkable property to filter particular spin-isospin components of the $\bar{p}$-N interaction. This was emphasized several times by Dover and collaborators [43] and confirmed in other calculations [16].

An illustration is given in Figure 4b, where are shown the various central amplitudes ($1, \sigma, \tau$ and $\sigma\tau$, following the standard and obvious notations). First, there is a dramatic model dependence. Secondly, the antiproton excitation properties differ from these corresponding to the nucleon. An explicit calculation of the $\bar{p}\ ^{12}C \rightarrow \bar{p}\ ^{12}C^*$ (12.7 MeV) has been performed by M.C. Lemaire et al. [16]. As seen in Figure 4b, there is almost a difference of one order of magnitude between the predictions of the two models that they have used. As acknowledged in Ref. 16, the PS 184 experiment has, however, reached here the limit of its energy resolution. A systematic study of the inelastic reaction would require new detectors.

Charge-exchange

This is a natural continuation of inelastic scattering. Since the isospin of the target or recoil nucleus is not always very pure, the $(\bar{p},\bar{n})$ reaction helps in selecting unambiguously isovector exchange forces.

The data of ref. [17] concerns the inclusive charge-exchange reaction $\bar{p}\ ^{12}C \rightarrow \bar{n}X$ at 590 MeV/C. The angular distribution is similar to that of the elementary process $p\bar{p} \rightarrow n\bar{n}$.

Exclusive charge-exchange measurements would be much desirable. As pointed out by Yavin [21], this is well suited to study the excitation of isovector giant resonances. Also, a dramatic spin-dependence might be anticipated, as for the elementary process [37].

Flavour exchange

One can imagine to study $(\bar{p},\bar{\Lambda})$, $(\bar{p},\bar{\Lambda}c)$, etc. as a generalization of the above charge-exchange reaction. The kinematical conditions for the deposition of flavour in a nucleus are not optimal at first (as for (π,K) reactions) but, for some hypernuclear levels, the dynamics favours the antibaryonic entrance channel over the mesonic one. It is not necessary to recall that there is a very rich physics associated with hyper nuclei [44] which are described either in terms of the ΛN interaction or in terms of the behaviour of the strange quark in the nuclear medium.

$\bar{p}$-annihilation on nuclei; microscopic aspects

There is an intense activity on the study of N$\bar{N}$ annihilation, described some years ago in terms of baryon exchanges and presently in terms of quarks. Some models have been elaborated, where the quarks either preferentially rearrange themselves (Fig. 5a) or are annihilated and recreated as in Fig. (5b).

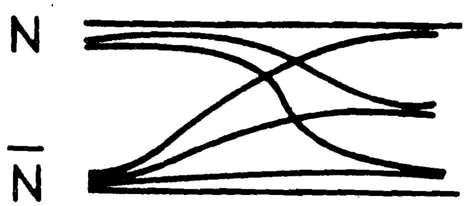

Fig. 5a - Quark rearrangement

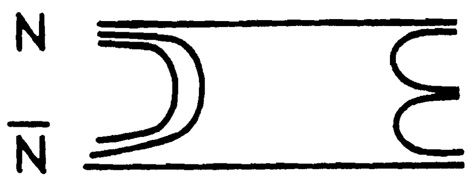

Fig. 5b - A planar diagram

Even in the most conventional approach, one expects some multibody interactions like ($\bar{p}$ NN), which have been mentioned and studied in several papers [6]. The diagram of Figure 6a is similar to the familiar 3-nucleons forces in Nuclear Physics. In Figure 6b, a virtual K^- is reabsorbed, leading to Λ production at rest.

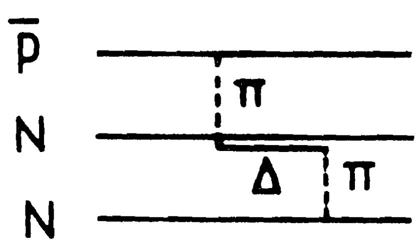

Fig. 6a

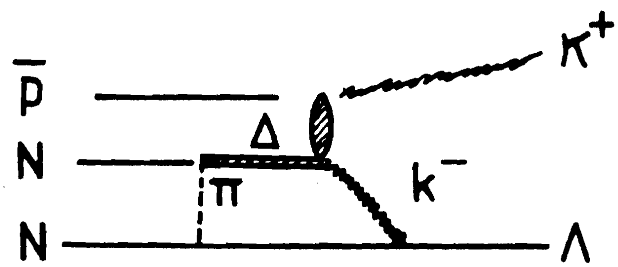

Fig. 6b

Figure 6 : Some multibody effects in the $\bar{p}$-A interaction

In a quark picture, such effects occur naturally as soon as the quarks of different nucleon overlap and have to be antisymmetrized : for instance the diagram 7a) where the second nucleon is spectator implies the existence of the diagram 7b) where both nucleons participate.

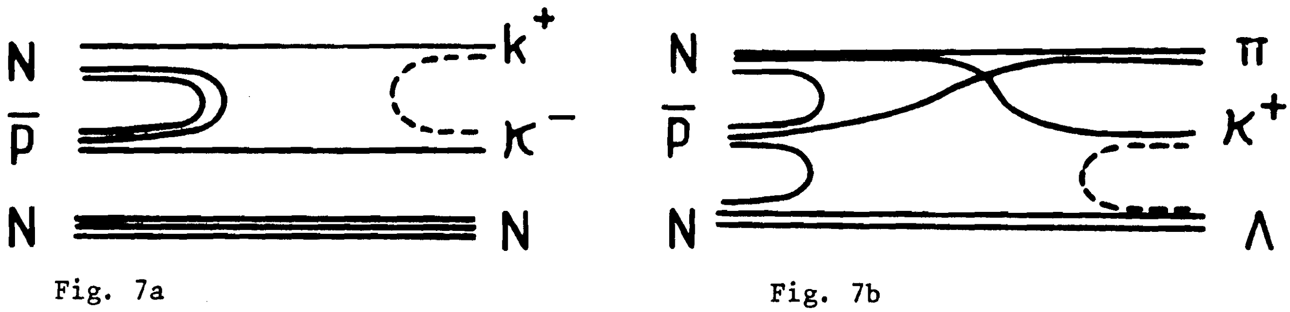

Figure 7 : Two quark diagrams for $\bar{p}$ NN annihilation

$\bar{p}$ annihilation on nuclei ; macroscopic aspects

In most cases, the annihilation of an antiproton produces a bunch of 4 or 5 pions. At rest, the antiproton does not penetrate much in the interior of the nucleus, and half of the pions, on the average, are ejected directly outside. When the $\bar{p}$ energy increases, however, this situation is modified. First, the total $\bar{p}$ cross-section slightly decreases, and the $\bar{p}$ has better chances to penetrate inside the nucleus.

Secondly, the Lorentz boost focuses the pions of annihilation toward the interior of the nucleus. What may occur in the most favourable cases is described in the contribution by W.R. Gibbs [8]. The temperature (of this concept holds here) at which the wounded nucleus blows up is measured by the mass and momentum distribution of the emitted fragments. A study has been already done at LEAR [14,23-25]. Further systematic investigations are planned [26].

Conclusion

The use of cooled antiproton beams has provided spectacular progress in the knowledge of the $\bar{p}$-A interaction. The prospects opened up in the near future by antineutron beams or, in the longer term, by antideuterons are also very attractive. Of course, it would be neither interesting nor useful to measure the interaction of antinucleons on any nucleus at all energies, but selected experiments with specific initial and final states are highly desirable since they give unique information on the $N\bar{N}$ amplitude. Also, even if we are far from a fashionable quark-gluon plasma, it is a very exciting idea to study how a nucleus reacts to the shock produced by the annihilation of an antinucleon. The knowledge of $\bar{p}$-A and $\bar{A}$-A' cross-section is crucial, if antimatter plays any role in the Universe. At the microscopic scale, the annihilation corresponds to a transition from the baryonic to the mesonic state of matter. The quark model describes it essentially as a rearrangement from a (qqq) or ($\bar{q}\bar{q}\bar{q}$) structure to stable or unstable ($q\bar{q}$) meson states. Whether this is the correct description should be tested in the antinucleon-nucleus annihilation.

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