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MESON DEGREES OF FREEDOM IN NUCLEAR REACTIONS.

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Abstract

A short review of recent topics where mesonic degrees of freedom play an important role is made. First a brief exposition of the present status of the microscopical description of pion nucleus interaction is made and its connection with photonuclear reactions is exploited. Second, a new example where the interaction of particles with the nuclear meson cloud is important is shown for the case of K^+ nucleus scattering. The channel of Λ decay induced by two nucleons is connected to the absorption of virtual pions and finally the process of coherent pion production and its implications for pion nuclear physics are addressed.

1 Low energy pion physics.

In a recent work [1] a microscopical many body description of the pion nucleus optical potential was provided by evaluating explicitly the first and second order terms in the density expansion for the p-wave part. This work, complemented with the analogous one for the s-wave part done in ref. [2], has led to a rather satisfactory description (although improvements could be made) of the widths and shifts of pionic atoms and the data of pion nucleus scattering at low energies. One of the appealing features of the many body field theoretical methods used in [1] is that it allows one to evaluate simultaneously elastic, quasielastic or absorption cross sections. The essence of the method is contained in the following equation

$$-\frac{1}{q} Im\Pi(q,\rho) \equiv Probability\, of\, reaction/length \qquad (1)$$

where $\Pi(q,\rho)$ is the pion selfenergy at density $\rho \equiv \rho(\vec{r})$ and q is the pion momentum. The field theoretical methods, by means of Cutkosky rules, allow the separation of the different sources of $Im\Pi$ and its association to the different reaction channels [3]. This is depicted in fig. 1 for some selected diagrams of the many body expansion. $Im\Pi$ is obtained when the intermediate states cut by the horizontal line are placed on shell in the integrations. The source of $Im\Pi$ from fig. 1a is associated to the $ph1\pi$ excitation (quasielastic scattering) while the one from fig. 1b is associated to pion absorption. By means of this information one can then obtain the quasielastic and absorption cross sections,

as well as the elastic cross section, which is obtained by a numerical solution of the Klein Gordon equation with the full pion selfenergy, $\Pi(q,\rho(r))$.

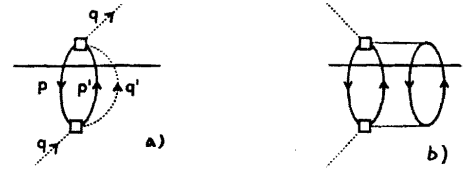

fig. 1

In ref. [1] one can see the results for the differential elastic, quasielastic and absorption cross sections for different nuclei. The agreement with the experimental data is rather good for elastic and absorption cross sections, but there are no data to contrast the quasielastic cross sections at low energy. Given the spectacular differences for this latter cross section for π^+ or π^- scattering, these experimental measurements would be rather valuable to test the consistency of the theory.

1a) The "s-wave missing repulsion".

Although the agreement of the results of [1] with the data of pionic atoms is rather satisfactory globally, one can see by adding extra phenomenological pieces to the model and carrying out a fit to the data that some extra repulsion in the s-wave part of the pion selfenergy is welcome. There are many papers devoted to this problem and different ideas have been suggested. A discussion of the different approaches would fill up the whole time of the talk and is not my purpose here. However, I would like to mention that the problem is still open and ideas are welcome. Here I briefly mention one approach followed in [4] which involves the scattering of pions with the pion cloud in the nucleus, and which is not contained in the approach of [1]. The mechanisms considered in [4] are depicted in fig. 2

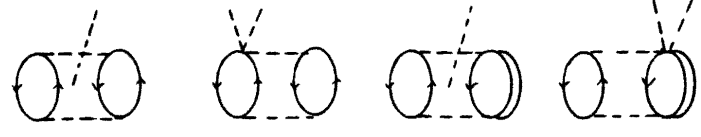

fig.2

The mechanism involves the scattering of pions with the virtual pion cloud together with their chiral partner terms [5] depicted in fig. 3

fig.3

The terms in fig. 2 lead to an extra repulsion, which according to a re-

analysis of the problem done in ref. [6] is still small compared to the 'missing repulsion'. The idea is however interesting, and as I shall mention later, it has also been used in the problem of K^+ nucleus scattering.

1b) Deeply bound pionic atoms.

This topic was revived by the Tokyo group [7] and has seen a spectacular bloom in recent years. The fact that all existing pionic atom potentials, without exception, provide a width smaller than the separation between the levels for these deeply bound states [8] (1s, 2p in Pb region, 1s in Ca region) has stimulated people to find reactions in which they could show up. The list is long [9] and many of the reactions lead to small signals compared to the background. I shall mention only two of them which are presently running. One of them is the $(d,^3He)$ reaction [10] under consideration at SATURNE, which is reported in this Conference [11], and the (π^-,γ) reaction [12] which is presently running at TRIUMF [13] and also scheduled to run in summer 1994 at Los Alamos [14].

The (π^-,γ) reaction is the most efficient, at least from a theoretical point of view, since it has all the properties which are welcome to provide large cross sections: coherent, small momentum mismatch, no distortion of the incoming and outgoing waves and small background. The preliminary experimental results indicate a strength for the 1s, 2p states of ^{208}Pb compatible with the predictions of [12], recently reconfirmed theoretically in [15], but more statistics and better resolution are needed to separate these states. The measurement of the widths is very valuable since different potentials providing similar good fits to the existing data, differ appreciably in the predictions of the widths of these depply bound pionic states [8].

2 Photonuclear reactions.

A similar approach to the one of ref. [1] has been carried out for photonuclear reactions [16, 17] and once again one can separate the different reaction channels, (γ,π) and γ absorption as shown in figs. 4a and 4b respectively

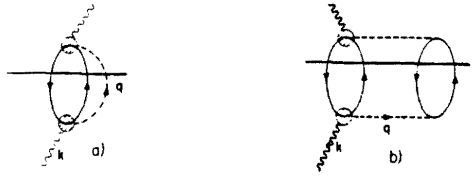

fig. 4

The approach is very rewarding and one obtains (γ,π) cross sections and total photoabsorption cross sections which are in very good agreement with present experiments [18, 19].

One point is, however, worth making. When making an experiment and

looking for photon absorption one is counting for two sources of γ absorption: direct and indirect. The first one occurs when the photon is directly absorbed by a nucleon pair like in fig. 4a (a trio sometimes). The pions exchanged or other mesons are off shell and the process qualifies as one step process. The indirect absorption is a two step process in which there is first the creation of a real pion in a $\gamma N \to \pi N$ collision followed by the propagation of this real pion and its absorption by a pair of nucleons (a trio sometimes). This is depicted in fig. 5.

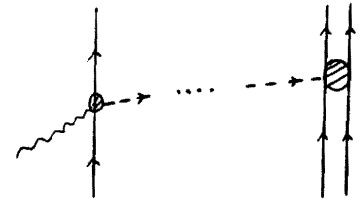

fig. 5

This process requires at least three nucleons in opposition to direct photon absorption which requires a minimum of two. The weight of the two forms of absorption varies with the nucleus and in heavy nuclei the indirect absorption dominates. This is seen in fig. 6 for ^{12}C and ^{208}Pb.

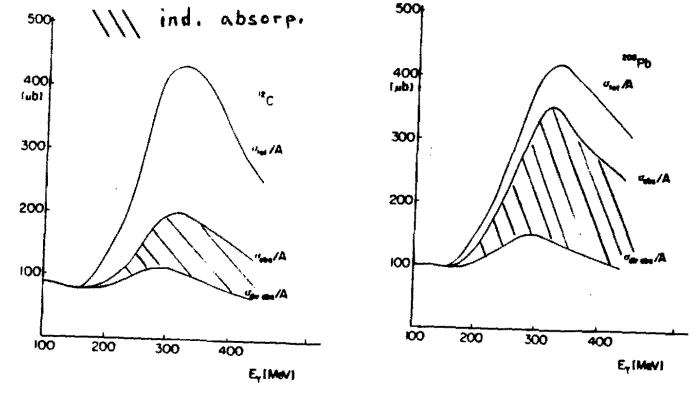

fig. 6

The experimental separation of these two channels is a real challenge. This separation would give us information both on γ direct absorption and on pion absorption. This latter one would be a novel information because the pions are created all throughout the nuclear volume and absorbed at high nuclear densities, unlike the absorption of pions in reactions with pion beams which occurs at the nuclear surface.

3 Pion cloud contribution to K^+ scattering.

The K^+N amplitude is relatively small and one expects that the lowest order K^+ selfenergy in the nucleus) should already provide accurate results for the elastic and total cross sections. However, as shown in [20] and in other more recent works, the experimental cross section is higher than the theoretical one with the IA selfenergy. Some suggestions which amount to having the nucleons fatter in the nuclear medium were given in refs. [21, 22]. More recently a new approach was followed in ref. [23], suggesting the K^+ scattering with the virtual pion cloud in the nucleus might be responsible for it. The idea of [23] is simple, the author assumes that

$$\sigma_{K^+A} \simeq A\sigma_{K^+N} + N_\pi \sigma_{K^+\pi} \qquad (2)$$

where N_π is the pion excess number in the nucleus. The idea is followed and considerably improved in [24] where the extra K^+ selfenergy is constructed by folding the $K^+\pi$ amplitude (complex) with the pion excess momentum distribution in the nucleus. The contribution obtained from this source goes in the right direction but is not sufficient to account for the discrepancies, although there are uncertainties associated to the off shell extrapolation of the amplitude. The work of [24] has been further improved in [25], where one shows that the folding with the pion excess number comes as a consequence of making a static approximation in the K^+N amplitude ($q_\pi^0 = 0$ in [24]). If the approximation is released one cannot establish a connection of the pion cloud contribution with the pion excess number because this latter one comes from an integral over q^0 from $-\infty$ to ∞ of the imaginary part of the pion propagator, while in the physical process, due to energy and momentum conservation, there are large constraints on the range of the variable q^0. On the other hand it was found in [25] that there are other contributions to $Im\Pi_K$, additional to these considered in [24], and which are bigger than those of [25]. To clarify this we show in fig. 7a the diagrams which appear in the evaluation of Π_K

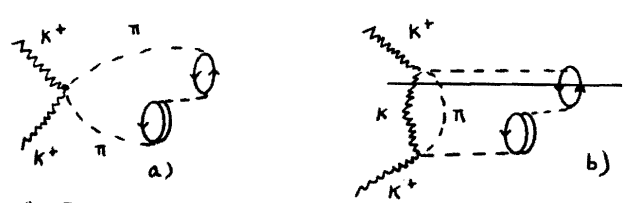

fig. 7.

where the dot symbolizes the $K^+\pi$ amplitude. The imaginary part of Π_K in [24] is associated to $Imf_{K^+\pi}$ and diagramatically this contribution is shown in fig. 7b where the horizontal line cuts the states which are placed on shell in the integration over intermediate states from where the contribution to $Im\Pi_K$ comes.Note that $Imf_{K^+\pi}$ from unitarity is related to $(f_{K^+\pi})^2$, or as shown in fig. 7b to the cut of the K^+ and π lines. The novelty in [25] is to show

that there are two pions in fig. 7, one which is renormalized (with ph and Δh excitations) and the other one which is a free pion. Obviously one could have the two pions simultaneously renormalized as shown in fig. 8.

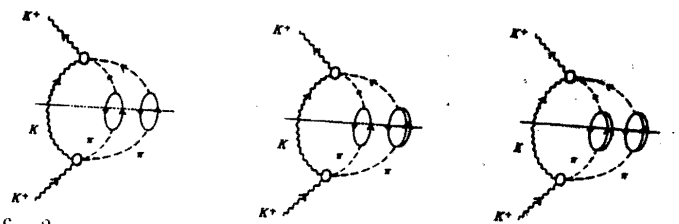

fig. 8

These diagrams are included and evaluated in [25] and turn out to be more important than those in fig. 7b. There are still uncertainties in $Re\Pi_K$ in [25] tied again to the off shell extrapolation of $f_{K^+\pi}$. By taking $Re\Pi_K = 0$, which is compatible with acceptable off shell extrapolations of $f_{K^+\pi}$, one obtains the results of fig. 9. There is an appreciable improvenement of the agreement with the data and the energy dependence of the corrections follows the experimental trend. The remaining discrepacies might be less significant in the view that correlation effects and uncertainties in the K^+N phase shifts lead already to corrections of this order of magnitude and in the direction of improving the agreement with the data [21].

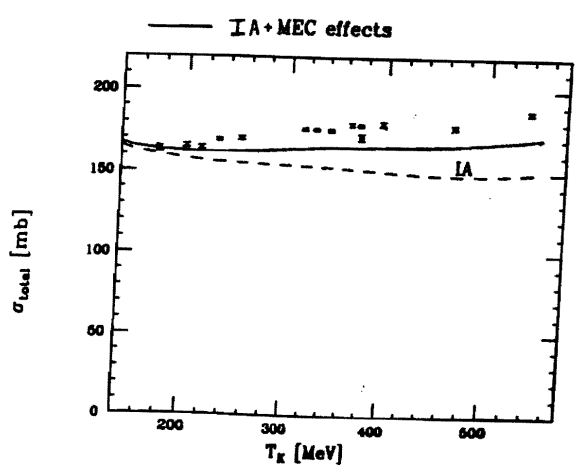

fig. 9

4 Two nucleon induced Λ decay.

The free Λ decays into πN. In a nuclear medium for a Λ with $p_\Lambda \simeq 0$ the nucleon momentum in the $\Lambda \to \pi N$ decay is $p_N \simeq 100 MeV/c$, which is smaller than the Fermi momentum, $K_F = 270 MeV/c$, for normal nuclear matter. Hence the Λ pionic decay is forbidden in nuclear matter. In finite nuclei it is allowed because of the nuclear surface, where K_F can be smaller than 100 MeV/c. In heavy nuclei, however, the mesonic decay is very small, although the consideration of the pion renormalization in the medium makes Pauli blocking less effective and enhances considerably the mesonic decay width [26, 27]. The most important Λ decay channel in the nucleus is the non mesonic one. In figs. 10a,b we show diagramatically the mesonic and non mesonic decay channels.

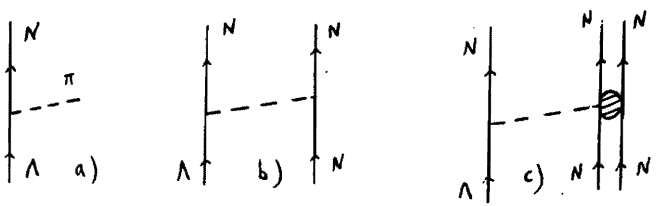

fig. 10

Recently, there was an interesting study [28] which suggests that an appreciable fraction of the Λ decay width comes from a two nucleon induced channel (fig. 10c) in addition to the one nucleon induced one (fig. 10b). The work has been reanalyzed and some approximations of [28] have been improved in [29]. The new channel provides a width which is about 30% of the free Λ width. Its consideration is essential to extract the proper ratio of p to n Λ induced decay from the experimental measurements of neutrons and protons in the final state [30]. This new channel has a direct link to the pion nuclear interaction: as we said, the mesonic decay is forbidden in nuclear matter because of Pauli blocking. However, a pion in the medium acquires a width due to its coupling to the absorption channel. As a consequence, part of the distribution of the pion strength falls now in the Pauli allowed region and the decay is possible, however, in the form of two particle emission corresponding to the absorption of a pion with energy somewhat below the pion mass. The phenomenon can be branded as the 'cheating of Pauli blocking' by the pion finite width in the nuclear medium. The study of this channel will teach us about pion absorption of virtual pions not far from its mass shell, a complement to the absorption of real pions, which should help us understand better the absorption mechnisms. The phenomenon bears much ressemblance to the process of virtual pion absorption in $(p,p'), (p,n), (^3He,t)$ etc. collisions in nuclei, from where interesting information could also be drawn [31].

5 Coherent pion production.

The discovery of this channel came as a byproduct of the study of the shift of the Δ peak in nuclei in the (p,n) and $(^3He,t)$ reactions at Dubna and SATURNE [32, 33]. The process is

$$p + A_{gs} \to n + A_{gs} + \pi^+ \tag{3}$$

which bears ressemblance to the radiation of photons in (e, e') collisions in nuclei. This latter process, Bremsstrahlung, proceeds through the interation of the electron with the nucleus which acts as an external static source: it provides momentum but not energy. This is depicted diagramatically in figs. 11a,b.

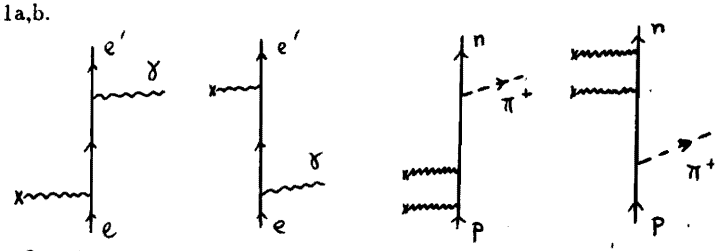

fig. 11

The equivalent picture for radiation of pions would be given by figs. 11c,d where the p or n interact strongly with the nucleus. However one can prove that this is not possible, at least for forward scattering in the (p,n) or $(^3He,t)$ reactions, due to the finite mass of the pion [34]. Hence, what makes the process possible is the interaction of the pion with the nucleus as depicted in fig. 12.

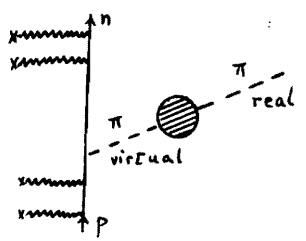

fig. 12

The process qualifies then as virtual pion production followed by elastic scattering of this virtual pion till it becomes real. The study of this channel should provide complementary information on the pion nuclear interaction to the one provided by reactions with real pions. The subject has been studied theoretically in [34, 35, 36] and some experimental results are already available for the $(^3He,t)$ reaction [37] and estimates done for the (p,n) reaction [38]. We show in fig. 13 some results for coherent π^+ production with the (p,n) reaction on

^{12}C and ^{208}Pb

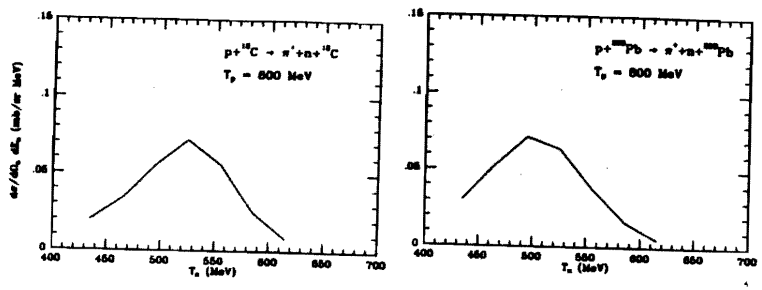

fig. 13

The cross section is rather peaked in the pion angular distribution around the direction of the (p,n) momentum transfer, particularly in heavy nuclei. The reaction provides then a source of rather monochromatic and unidirectional pions. The possibility of using a tagging technique in the (p,n) reaction to produce monochromatic pions, similar to the one used to produce monochromatic photons, should be explored. One should also not neglect the fact that one can produce coherent π^0 's. The elastic scattering of the virtual π^0 till it becomes real is the closest situation to a hypothetical elastic collision of real π^0 with nuclei. However, the information that one obtains from this is good enough to test theories of π^0 nucleus interaction, hence offering new challenges to the microscopical description of the π nuclear interaction.

6 Summary.

We dealt with several topics involving real, virtual and quasireal pions, showing that the mesonic degrees of freedom evidence themselves in curious ways in the different processes at intermediate energies, providing a glue to a unified microscopic description of these processes.

We showed that the field theoretical many body approach to these processes is an appropriate and very rewarding tool which can provide such a unified scheme.

On the other hand we also showed a few new examples of physical processes which require experimental and theoretical attention and which can provide missing pieces of the big puzzle of nuclear reaction mechanisms.

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