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HOW IS A PION ABSORBED IN LIGHT NUCLEI ?

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Contents

1. Introduction

Pions have always played a special role among the mesons. Theory has not succeeded in describing, as originally proposed, the whole nucleon-nucleon interaction in terms of the exchange of pions. But in the modern potential models available today (Bonn , Paris) the long-range part is described by 1π-exchange and the medium-range part by 2π- and 3π-exchange. Only for the short range part one has to resort to a parametrization via the exchange of other mesons or in alternative approaches to quark/gluon degrees of freedom.

Similarly, pions have a special function in chiral bag models [RHO83] , where the nucleons are described by a quark core surrounded by a pion cloud which determines the size of hadrons as e.g. measured in electron scattering. Even in a pure quark/gluon environment the small mass of the pion indicates its role as a "would-be" Goldstone boson of the chiral SU(2)xSU(2) symmetry ([BRO69], [GOL83]).

In view of the importance of absorption and emission of virtual pions it is appealing to study the absorption of real pions too. Their importance is not limited to a special energy region (remember e.g. the creation of pions as the dominant part of hadronization in high energy reactions). This review, however, is confined to the energy region of the Δ_{33}-resonance, which couples strongly to pions, and concentrates on the discussion of the different reaction mechanisms. Recent extensive reviews of pion absorption can be found in [ASH86], [GIB87].

An important aspect of nuclear absorption is the number of nucleons involved. We know from a multitude of interactions of composite systems the tendency that the reactions occur on a subset of the available elements. Well known example are the inelastic scattering of electrons and pions on a nucleus which is dominated by quasielastic electron-nucleon and pion-nucleon scattering. Absorption on a single nucleon is, as we will see below, strongly suppressed, similar to the case of double charge exchange.

If we think of pion absorption in terms of a series expansion in the number of nucleons involved we may have therefore access to higher terms of this expansion. That one can expect non-negligible contributions from many-body absorption is demonstrated by the fact that in a geometrical interpretation the area corresponding to the πN cross section is larger than the projected area of the ^{4}He nucleus [SCH80].

The topics discussed in connection with absorption mechanisms are still qualitative (only the elementary case of πd->pp has reached a quantitative description). The problems addressed are:

- How many nucleons are involved in the absorption ?
- How does the reaction depend on the isospin of the absorbing system ?
- What is the fraction of many-step processes ?
- What is the importance of Δ-intermediate states ?

2. Total Absorption Cross Sections

The total absorption cross section can be decomposed in the following way:

$$\sigma_{tot} = \sigma_{el} + \sigma_{inel} + \sigma_{cex} + \sigma_{abs}$$

with:

σ_{el} = elastic scattering
σ_{inel} = inelastic scattering
σ_{cex} = charge exchange
σ_{abs} = absorption

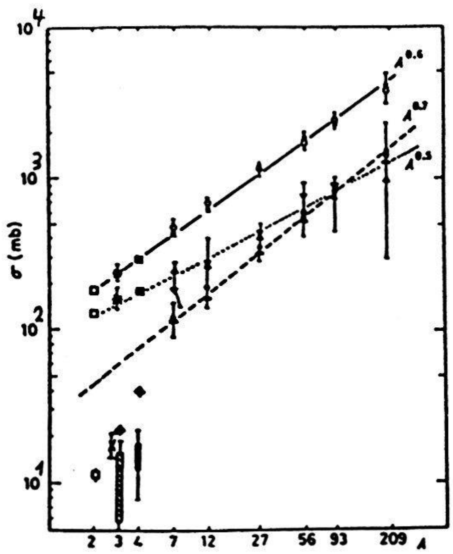


Fig. 1: π-Nucleus cross sections as function of A. Full line: total cross section, dashed: absorption , dotted: inelastic and charge exchange. A>6: [ASD81], A=2: [SER70], A=4: [BAL81], [KAE80], A=3: [ANG85], [BAC87], [KAE80].

Here absorption is defined as a reaction leading to a final state with no pion. For a number of nuclei the various contributions have been determined. Fig. 1 shows the results of the experiments of [ANG85], [ASD81], [BAC87], [BAL81], [SER70], where the straight lines are drawn to guide the eye.

All cross sections have a behavior approximately proportional to $A^{0.5}$-$A^{0.7}$. Inelastic scattering with $\sigma \sim A^{0.5}$ is more peripheral while for absorption and elastic scattering the nucleus has the appearance of a black disk.

For medium to heavy nuclei the total cross section shows about equal parts of elastic scattering, inelastic scattering and absorption. For lighter nuclei, however (A<20) the contribution from absorption is smaller but still very important. It is hard, however, to draw conclusions from these integral data on the influence of selection rules or reaction mechanisms.

3. Reaction mechanisms

Different reaction mechanisms are expected to reveal themselves by the different number of nucleons involved. For lack of sufficient experimental information one has often studied in the past just the number of nucleons in the final state above some experimental threshold. This is a simplifying approach well suited for initial investigations. But because of the strength of the πN and NN interaction the absorption proper is expected to be always preceded by an initial state interaction (ISI) and followed by a final state interaction (FSI). In addition the absorbing nucleons have a Fermi-momentum distribution. Therefore the progress of our understanding of pion absorption is strongly coupled to the new generation of 2-fold coincidence measurements at the meson factories giving access to differential distributions which can be compared to microscopic calculations.

3.1 Absorption on One Nucleon

Because of momentum conservation a pion cannot be absorbed on a single free nucleon. For a nucleon bound in a nucleus this is possible in principle. Here the nucleon can have enough Fermi-momentum before absorption to counterbalance the momentum transfer from the absorption. The required momentum transfer to the nucleon, however, is about 500 MeV/c, which is twice the typical Fermi momentum of a nucleon within a nucleus.Therefore, such a reaction is quite improbable (~ 1 % [BAS79]). In addition, while the kinematical definition for a 2-body final state is clear, the interpretation is less clear. Sakamoto et al. [SAK85] investigated e.g. the reaction $\pi^- \, ^4He \rightarrow n \, t$ and found in their calculation that, even for this process which has a kinematical signature quite different from 2N absorption half of the reaction strength had to be attributed to 2N absorption followed by FSI. Single nucleon absorption will therefore be neglected in the following.

3.2 Absorption on Two Nucleons

The next simplest possibility is the absorption on a pair of nucleons. In this case both nucleons share the energy of the pion and leave with opposing momenta ("quasi-deuteron absorption (QDA)" fig. 2a)

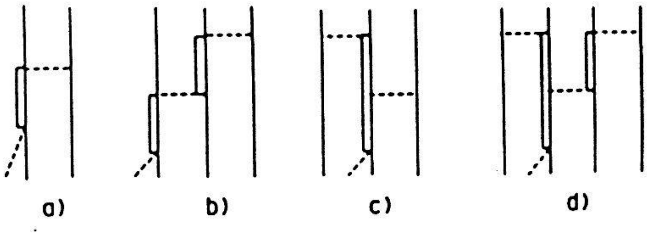


Fig. 2: Dominant graphs in a isobar description of pion absorption. Fig. 2a) : 2-nucleon absorption, figs. 2b) and 2c) : sequential respect. non-sequential 3-nucleon absorption, fig. 2d) : four-nucleon absorption, double-Δ mechanism.

This Ruderman mechanism has been the prevailing model of absorption for a long time and is e.g. the origin of the ρ^2 term in the absorptive part of the Ericson-Ericson optical potential [ERI66].

3.2.1 The Deuteron System

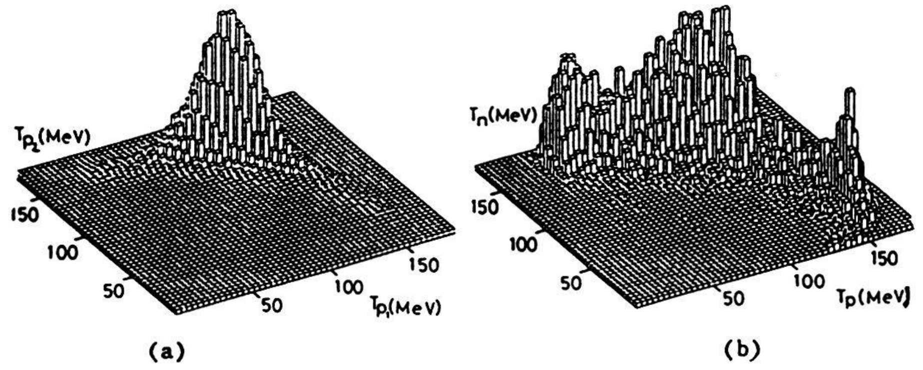
The best studied system for 2N absorption is the deuteron. A multitude of experimental and theoretical investigations has been performed. For a review of the situation see e.g. [BLA87] [LOC85]. In general it can be stated that there is good agreement, up to ~10% for all variables

(differential cross sections and polarization variables). In the Δ-region in a Legendre expansion of the differential cross section higher coefficients can be neglected and the cross section is dominated by a_0 and a_2 with $a_0 \approx a_2$. This is due to the fact that the reaction is dominated by one partial wave, $^1D_2$, which corresponds to a $^5S_2$ intermediate ΔN state. It is, however, not possible to extrapolate simply from the deuteron to heavier nuclei. Because the nucleons are loosely bound and confined to be in a isoscalar state the deuteron is a very special nucleus.

3.2.2 A > 2

The next most elementary system is ^{3}He. Isovector nucleon pairs are now also available and the nuclear density is much higher. Here a substantial increase in our knowledge has been recently achieved. The first exclusive measurements have been performed at SIN with π^- at rest [GOT82]. They uncovered the unexpected effect that absorption on a isoscalar nucleon pair dominates by a factor 7.5 over the absorption on a isovector one. This effect was and is surprising. A factor of this order of magnitude could be expected if, prior to absorption, the pion has been in an atomic p-orbit and Δ-dominance is assumed, whereas for s-absorption one expects only a factor 2 . Therefore a 3-fold coincidence measurement with the detection of the X-ray to the 1s state has been performed [BAC87]. This revealed that this factor is as high for s-absorption.

Calculations which extended the deuteron concept to ^{3}He ([HAC78], [SHI80] , [SCH81]) showed a strong sensitivity to the off-shell behavior of the absorbing nucleons and had small predicting power. Therefore this reaction has to be regarded as still not understood.



(a) (b)

Fig. 3: Dalitz plots of events from π absorption at T_p = 120 MeV. Detector setups for the two detected particles were θ_1= 117°, θ_2= 40° , (a) for π^+, (b) for π^- .

In the region of the Δ-resonance several experiments have been performed [ASH81], [ASH84], [ANI86] , [BAC87]. Fig. 3 shows a typical example of the data of Backenstoss et al.[BAC87] in a Dalitz plot representation. Fig. 3a for the (π^+,pp) reaction shows the dominant peak of isoscalar absorption whereas fig. 3b with the (π^-,pn) data contains the isovector absorption. We also see in fig. 3b significant contributions from FSI. The different ratio of FSI to QDA is qualitatively understood from the different scattering lengths of pp to pn and nn and the fact that because of kinematical reasons FSI is coupled more strongly to the 3-nucleon absorption amplitude (see below) which is relatively stronger in the isovector case.

The absorption cross section for the quasifree mechanism $^3He(\pi,NN)N$ may be factorized as follows:

$$d^5\sigma \sim G(\theta) \cdot F(p_S) \cdot \Phi \cdot d\Omega_1 d\Omega_2 dp_S$$

where $G(\theta)$ describes the absorption on the two-nucleon subsystem leading to particle emission at an angle θ relative to the pion momentum. $F(p_S)$ is the momentum distribution of the spectator nucleon and Φ is the phase space factor, which can be calculated by Monte Carlo techniques.

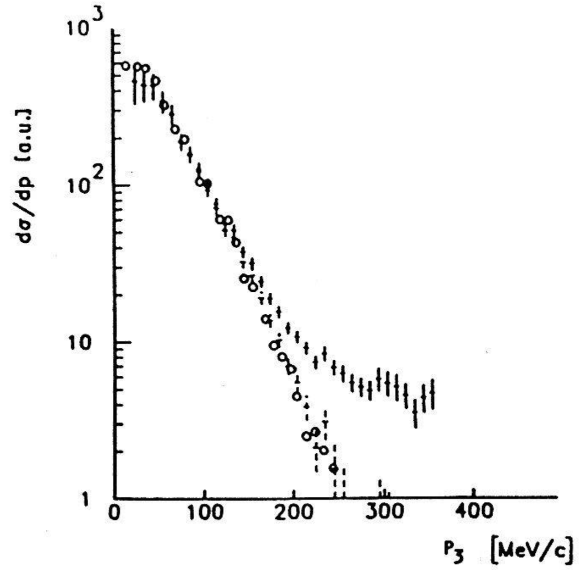


Fig. 4: [BAC87] Momentum distribution of the third (reconstructed) particle. Full points are obtained by dividing the experimental distribution by phase space. For the dashed points the experimentally determined three nucleon absorption contribution has been subtracted. The circles show the momentum distribution of a nucleon in ^3He as measured with (e,e') [JAN82].

Using this factorization the distribution $F(p_S)$ has been obtained by [BAC87] up to a constant multiplicative factor by dividing the measured recoil distribution by Φ. The result is shown in fig. 4 together with that from the $^3He(e,e'p)$ reaction[JAN82]. A quasifree interaction requires $F(p_S)$ to be the same as the proton momentum distribution measured in (e,e'p) experiments. The agreement in fig. 4 is impressive and provides a direct proof that the process is quasifree in the sense that the third nucleon behaves as a spectator.

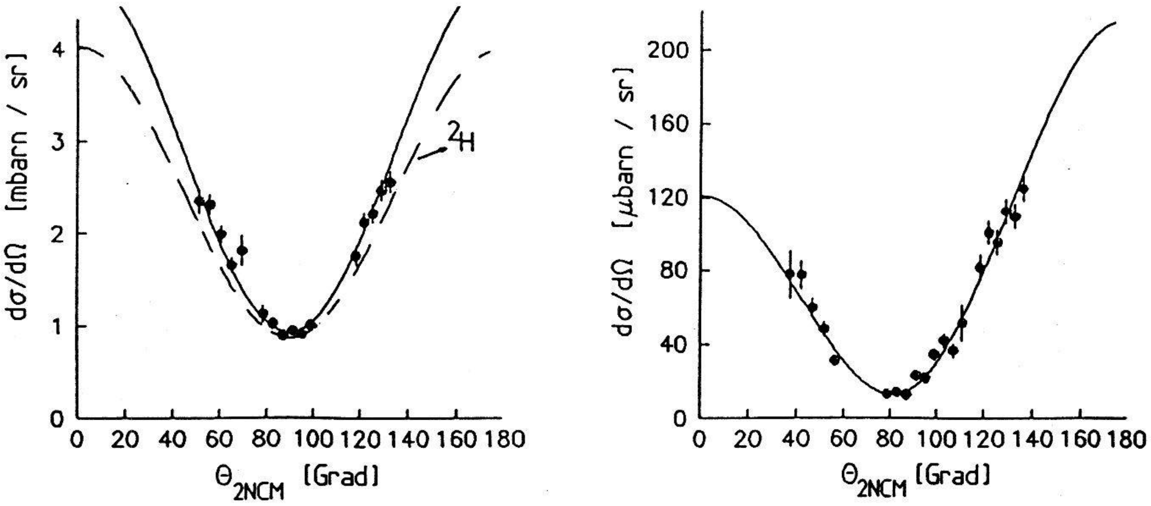


Fig. 5: Differential cross sections from [BAC87] at $T\pi$=120 MeV for quasifree absorption π^+,pp (left) and π^-,pn (right) in the 2N center of mass system. Full lines are Legendre fits to the data . For comparison the dashed line shows a Legendre fit to πd->pp .

In fig. 5 the differential cross sections of [BAC87] for QDA of π^+ (left) and π^- are displayed. As indicated by the dashed line the π^+ cross section is very similar to the $\pi d \to pp$ case. The π^- data (right) show an asymmetry which can be traced to the interference between Δ and non-Δ intermediate states. Fig. 6 shows the ratio of isoscalar to isovector absorption as function of the pion energy together with theoretical calculations. The experimental ratios are determined from the a_0 coefficients of the Legendre fits. The data peak at the Δ-resonance with a value of ~ 20 . This has to be compared to a value 13/2 which follows directly from Clebsch-Gordan coefficients and the assumption of Δ-dominance. The form of the distribution indicates that the isoscalar cross section is more strongly influenced by the Δ than the isovector one. This is explained as follows: The measured isoscalar cross section is very similar to the absorption on the deuteron (see fig. 5a) and also has a strength increase which is near to a factor 1.5 which one expects from counting of isoscalar nucleon pairs. This cross section is dominated by the pp partial wave $^1D_2$ ($^5S_2$ in intermediate ΔN) which determines the $\pi d \to pp$ reaction. This amplitude is, however, Pauli-forbidden in isovector absorption. Therefore ΔN intermediate states with L>0 or even NN′ intermediate states, both of which normally are not so important, contribute significantly. The influence of the $^1D_2$ partial wave on the isospin ration has also been found in phase shift analyses of NN scattering [JON83] but the effect is smaller.

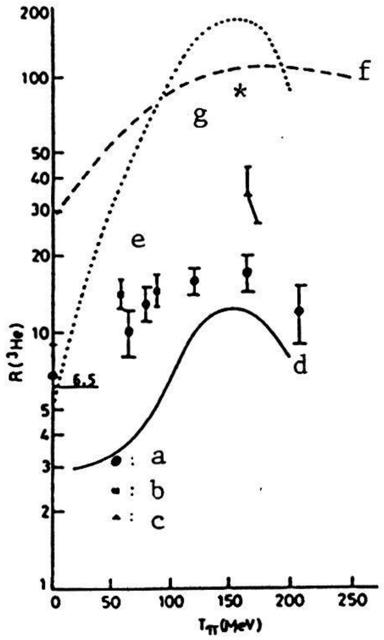


Fig. 6: Ratio of isoscalar to isovector absorption on ^{3}He obtained from the ratio of Legendre coefficients: $R = a_0(\pi^+)/a_0(\pi^-)$. Data are from a: [BAC87], [GOT82], b: [ANI86], c: [ASH84], Calculations are d: [MAX86], e: [TOK82], f: [SIL84], g: [LEE82].

An interesting observation is that the cross sections on deuteron and ^{3}He differ by just the number of isoscalar nucleon pairs. It has been repeatedly argued in the past that because of the high momentum transfer the absorption should be very sensitive to short-range NN correlations. This cannot be confirmed experimentally because the appreciable different density in deuteron and ^{3}He should produce observable effects.

The dominance of $^1D_2$ explains also the somewhat confusing theoretical situation. The first experimental ratios in the Δ-resonance region [ASH81] were found to be around 100-200 . Those values could be accommodated theoretically by taking only L>0 ΔN partial waves [LEE82]. It was pointed out, however, by [SIL84] that also the nucleon pole term has to be taken into account. This raises then the isovector cross section and lowers therefore the isospin ratio, although the calculation of [SIL84] because of other shortcomings gave also an isospin ratio which was too high. Subsequent measurements [ANI86], [ASH84], [BAC84], [BAC87], [MOI84] agreed on values below 20 and a recent theoretical calculation [MAX86] which takes into account both ΔN and N'N intermediate states is near the experimental data.

Quasifree absorption has been measured for many nuclei in the resonance region (see e.g. [ALT86], [RIE86]). All data show clear peaks in the angular distributions corresponding to the πd->pp kinematics. For A>6 these peaks have been mostly fitted by a sum of 'narrow' and 'broad' Gaussians where only the narrow Gaussian has been attributed to QDA. The conclusion was then that even in such light nuclei as ^{12}C the QDA component was only ~10% of the absorption strength. This interpretation was strongly questioned [RIT84] by pointing out that the angular correlations were much more complicated than assumed e.g. in the case of non-zero angular momentum of the absorbing pair. This was recently experimentally confirmed by an experiment [SCH87] on ^{16}O which was able to resolve different angular momentum states. Therefore the question of the relative importance of the QDA mechanism should be reexamined.

3.3 Absorption on More than Two Nucleons

There have always been discussions about the fraction of reaction mechanisms other than the QDA mechanism. An important experiment in this respect has been that of McKeown et al. [MCK80]. Inclusive proton spectra after π^+ and π^- absorption have been analysed by rapidity plots. In the Lorentz frame with the correct number of absorbing nucleons (hot spot) the intensity of the outgoing protons should be isotropic (or at least forward/backward symmetric).The analysis of [MCK80] for a number of nuclei resulted in an effective number of participating nucleons ranging from 3-5 increasing with A. This analysis has been questioned as it is not trivial to disentangle in this way genuine absorption from secondary reactions. But it seems impossible to explain all the data of [MCK80] by QDA alone.
Before discussing non-QDA absorption in more detail we make some general comments on the absorption reaction. The particles before and after absorption cannot be described by plane waves. As both the incoming pion and the emerging nucleons are strongly interacting particles, a realistic absorption is expected to happen in 3 steps:
1) ISI, initial state interaction, the incoming pion interacts before the genuine absorption process with the nucleons by scattering or charge exchange.
2) the genuine absorption
3) FSI, final state interaction, the emerging nucleons interact with other nucleons. In the case of FSI one should distinguish two types:
3a) 'hard' FSI. This would be the interaction of an on-shell nucleon after absorption with another nucleon with the kinematics of nucleon-nucleon scattering. A look at kinematics tables shows that in this case the final nucleons have always an angle $\Theta_{NN} \sim 90^o$.
3b) 'soft' FSI. This is a well known phenomenon in reactions where the kinematics allows 2 nucleons (or in general 2 hadrons) to have a small relative momentum. In the rest system of these 2 nucleons this can be regarded as low energy NN scattering. For T_{rel} ->0 the amplitude can be evaluated in the 'effective range approximation' with scattering length and effective range being known parameters. One obtains an enhancement (Jost enhancement) in the differential cross section for this kinematics.

Therefore 'soft' FSI is not to be regarded as a new reaction mechanism. A mechanism beyond QDA would be indicated by either initial state interaction (ISI) or 'hard' FSI. Another possibility would be a totally new mechanism which could not be subdivided into these 3 steps.

3.3.1 A > 3

A possible 2-step process with QDA preceded by ISI:
1) πN -> πN ---> 2) πNN -> NN
has been investigated by Altman et al. [ALT86]. They deduced that in this case the energy of the pion in step 2) should be reduced which in the angular correlation would give rise to an asymmetry as predicted by a cascade calculation. By comparison with the measured data no sign of a 2-step process was observed. [BUR86] find for ^{58}Ni(π,pp) a contribution from scattering before absorption to be significantly less than 30%. A similarly negative result has been reported by [TAC85] from a 3-fold coincidence measurement on ^{12}C.

[YOK87], however, have measured ^{6}Li(π,pp) and report evidence for both ISI and 'hard' FSI. At the present time, however, this must be regarded as a first indication only and background investigations and counting statistics should be improved before the question of experimental identification of multiple-step processes can be settled.

3.3.2 The ^{3}He System

Less contradictory is the situation of non-QDA absorption in the A=3 system. As it was possible here to perform exclusive measurements [BAC85], [ANI86], there was access to fully differential information. Because both QDA and 'soft' FSI show up in collinear kinematics (near the perimeter of the allowed region in a Dalitz plot representation) other mechanisms should be searched for in non-collinear kinematics. This is shown in fig. 7. θ_1 , the angle of one detected nucleon is fixed while θ_2 the angle of the second detected particle is varied in the kinematically accessible range. Around 40° there is the clear peak from QDA but if one goes to higher angles the cross section does not vanish. Outside the QDA region it shows a behavior compatible with pure phase space dependence and quite different from QDA.

The cross section derived for π^+ and π^- is the same within the error bars and amounts to ~ 1/4 of the total absorption strength (see fig. 8). The TRIUMF data [ANI86] below 100 MeV/c are higher but the discrepancy may partly be explained as in the analysis of [BAC85] where a more restrictive background subtraction via a kinematical constraint could be applied.

The energy dependence of this 3-nucleon absorption suggests a Δ-doorway approach. [OSE86] performed calculations within the Δ-hole model by including the graphs of fig. 2b and 2c. The dashed line in fig. 8 shows their results for ^{12}C without medium corrections. As can be seen the authors are able to reproduce the general trend in the total absorption strengths. It is unclear, however, if there is also agreement on the level of differential distributions, as the authors show only integrated cross sections. Laget [LAG86] has investigated in a calculation a graph which is very similar (incoming π replaced by a gamma) to fig. 2b) . He found because of the triangular singularity the strongest contribution when the virtual pion exchanged between nucleons 1 and 2 is nearly on mass shell. This, however, corresponds to scattering and absorption as a 2-step process, for which the experimental evidence is controversial.

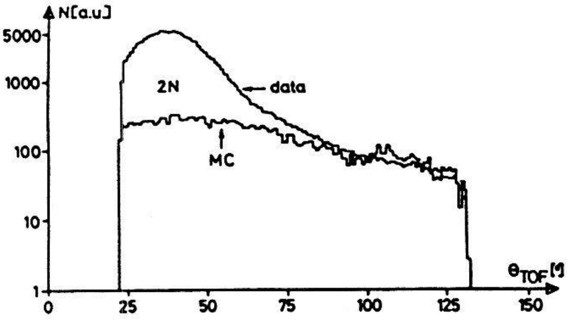


Fig. 7: Angular correlation from [BAC87] for $^3He(\pi,pp)$ at T_π=120MeV as function of θ_{TOF}. θ_1 kept at 120°. The curve labelled MC is a Monte Carlo simulation of the 3-nucleon phase space.

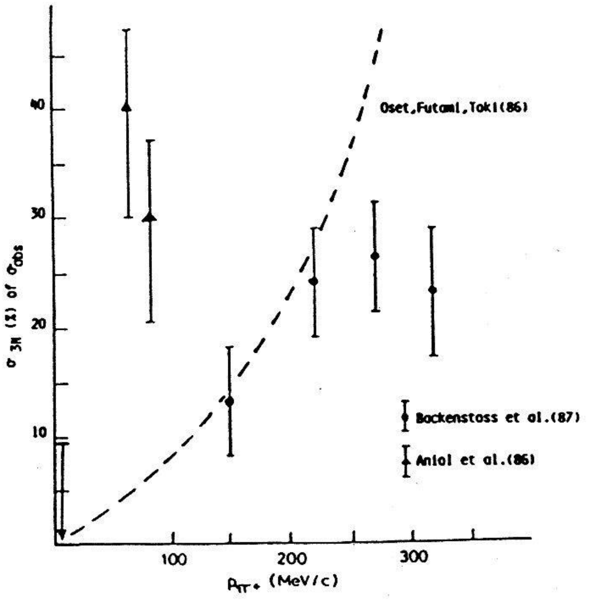


Fig. 8: Contribution of 3-nucleon absorption to the total absorption as function of pion momentum. The dashed line indicates the calculation of [OSE86].

It will be therefore very interesting to see comparisons of differential information in a calculation explicitly for absorption on ^{3}He.

4. Conclusion

For a long time absorption has been the less known among the π-nucleus reaction modes and only for the deuteron were good data and calculations available. But now, after a decade of experimental and theoretical activity, there is more information available also for heavier nuclei, especially ^{3}He. We know and understand qualitatively that isoscalar absorption is much stronger than isovector. This justifies 'a-posteriori' the notation of QDA. QDA is a strong mechanism but other processes contribute significantly. In ^{3}He there is clear evidence for a non-QDA mechanism which contributes 1/4 to σ_{abs}. By comparing the QDA component with integral absorption cross sections one finds that for A>3 at least half of the strength has to go via other mechanisms which are not clearly identified yet. Non-QDA contributions could come again as in ^{3}He from phase space type mechanisms or e.g. a 3-nucleon mechanism with the rest of the nucleus as spectator. In this context also the double-Δ mechanism proposed by [BRO82] (see fig. 2d)) should be investigated. As all these new reaction modes are characterized by multinucleon final states their investigation by few-arm spectrometers is hard, both because of counting rates and the influence of the acceptance on the measured distributions. Progress in our understanding of pion absorption will therefore be connected with the advent of new 4π-detectors now being discussed.

Acknowledgements

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