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Pion Absorption Results from the Meson Factories

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Pion absorption studies at the meson factories have covered the full range of nuclear masses from A = 2 to 208, at incident pion energies from 0 to around 500 MeV and the experimental investigations have now largely drawn to a close. The most interesting data are on the helium isotopes, but recent data on heavier nuclei put the helium data into an interesting perspective as well as being of interest themselves. The outstanding unknown is the origin of multi-nucleon absorption, and this is of particular relevance to this conference since if this is understood it should provide new information on the hadron interaction, in particular, on the few body force. Previous speakers have referred to the role of virtual Δs in the three-body force, while the data in this talk are dominated by real Δs. The data discussed here are limited to π^+ at energies around the Δ. They are largely from the LADS detector at PSI, which was the only modern detector with helium data, but also because it was the qualitatively superior detector.

Pion absorption is a special reaction in that it requires the participation of two nucleons, involving large energy and momentum transfers. It is also special for its apparent relationship to real pion exchange and thus hadron interaction dynamics. And since it forms around half the reaction cross section it is also important in all nuclear interactions above the pion threshold. The required participation of at least two nucleons leads to the quasi-free absorption on a pair of nucleons (2NA) being the "elementary" process in nuclei heavier than the deuteron. This process is predominantly on I=0 pairs, and leads to two fast protons emitted back-to-back, with the remaining nucleons as spectators. The proton angular distributions are very similar in shape to those for absorption on the deuteron for all nuclei and pion energies and these dynamics are broadly understood. By contrast, absorption with the emission of three or more nucleons (≥3NA), which is found to be substantial, even in ^{3}He, is hard to explain as 2NA plus rescattering, and is not understood [1,2].

The elementary 2NA, absorption on the deuteron, peaks around 130 MeV [1], some 50 MeV below the maximum of the total π-D cross section: the origin of this shift is not entirely clear, but a consequence is that at higher pion energies the absorption cross section is relatively weak. On heavier nuclei, the total absorption cross section roughly scales with the deuteron cross section (see Fig. 1), except that above ~200 MeV the cross section declines more slowly, with the "excess" noticeable already in ^{4}He, and growing with A. This may be a reflection of the pion's

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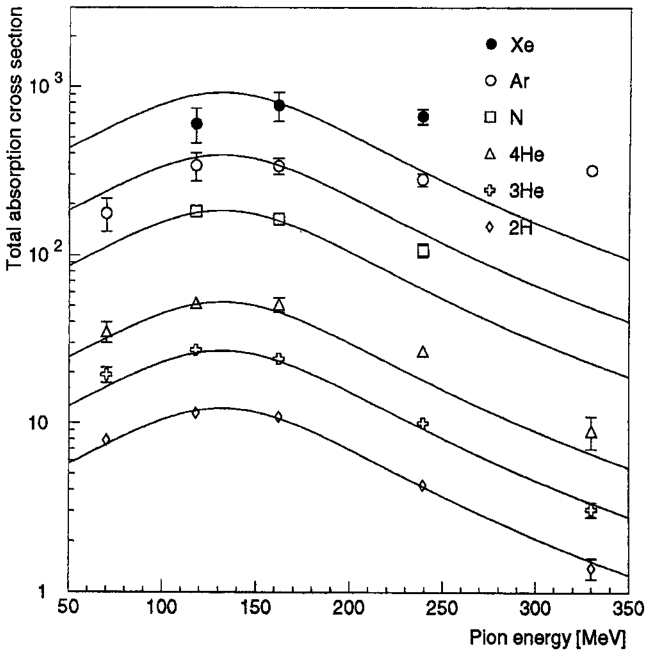

Figure 1. π^+ - total absorption cross sections (mb). The curves show the shape of the cross section for the deuteron. From [4].

ability to be absorbed after losing energy by nucleon knock-out in a cascade-like process. The total absorption cross section has a fast rise from D to ^{4}He, but between ^{4}He and Pb it lies on a line $\propto A^x$, with x around 0.75; the data from LADS [3,4] and the BGO Ball at Lampf [5] are typically some 25% lower than earlier results.

The cross section increase from D to ^{4}He (factor 4.5, or 2.5 for the 2NA component), is similar to the ratio of the number of I=0 pairs (3), while allowing some increase due to increased nuclear density. But strong sensitivity to the square of the density, which increases by 16, seems excluded. Thus the A-dependence indicates a „fast" rise in the absorption probability between D and ^{4}He, after which the steady A-dependence suggests that it has already reached some saturated nuclear value.

2NA in nuclei has long been observed as the kinematic correlation between two protons, typically measured with 2-arm detectors. However, both 1-arm experiments measuring integral multiplicities [6] and such 2-arm experiments [7,8] suggested that 2NA alone could not account for the total absorption cross section on medium and heavy nuclei, and soon a substantial 3NA yield was observed directly in ^{3}He [9,10]. Attempts to explain the situation in heavier nuclei in terms of absorption followed by rescattering processes led to a re-evaluation of nucleon propagation in nuclei, but the conclusion was that these could not make up the difference between the observed 2NA yield and the total absorption cross section [11].

Discussions of the absorption dynamics often refer to rescattering processes, namely 2NA plus N-N rescattering or final state interactions (FSI) and π-N scattering (initial state interaction or ISI) followed by 2NA, as distinct processes. The reason is to have some guideline for the discussions and also because such processes are typically modelled in attempts to understand the data. But the potentially interesting new dynamics would be some coherent 3N process, and these two-step processes are not strictly distinguishable. Indeed, the pion interaction „before" absorption may even be considered to be a part of the dynamics to be understood.

The 1- and 2-arm experiments, while identifying the problem of too high a multi-nucleon yield to be easily understood, did not provide insight into the processes and did not allow unambiguous interpretation beyond the basic conclusion. To get further, it became apparent that large acceptance detectors with good kinematic definition were needed. The BGO Ball at Lampf has provided a large amount of data over a large range of pion energies, from lithium to lead. This detector was very compact, with 94% of 4π solid angle. However, it suffered from poor angular definition and while neutral particles could be detected there was no n/γ separation. Thus, in a recent paper [12], the inclusive yields for proton multiplicities ≥ 2 were determined, and the contribution to the absorption cross section from final states with fewer than 2 protons taken from a model [13]. This was tuned to match the observed 2p/3p ratio by varying the residual nucleus excitation energy, and the contributions from <2p final states then estimated to be up to 20-60% of the absorption cross section (C-Pb) at 90 MeV. The CHAOS detector at Triumf has excellent kinematic definition covering nearly 360°, with magnetic analysis of the charged particles, but lacks neutral particle detection and is limited to ±7° in azimuthal angle [14]. The result is that final state nucleon multiplicities are dependent on the models used to cover the missing acceptance. The LADS detector at PSI had 98% of 4π solid angle, a detection threshold around 20 MeV, ~10 MeV(/c) energy (momentum) resolution and p,d,$\pi_{\pm}$ and n, π_0 identification.

Before discussing the results from LADS, the method of analysing the data (broadly the same for all experiments measuring multi-nucleon final states) needs to be outlined: simple physics models are used to generate distributions of final state nucleons by Monte Carlo, and these are then passed through a model of the detector including all efficiencies and acceptances. Then the resulting distributions from the various physics models are fitted simultaneously to the data for some sets of kinematic variables, with the model distributions' normalisations as free parameters. The normalised full integral of a distribution of each physics model then gives the partial cross section attributed to that process. In this paper the particles within the brackets are those deemed to have participated in the absorption, even though they may not have been detected and their energies extend down to 0 MeV: eg the (ppp)n channel from ^{4}He indicates that the neutron (only) was a spectator. For correcting for the acceptance of the detector this procedure is reliable, and for LADS the overall correction was only a factor of 2-3 for the main channels. Less good are the physics models: the main ones used for final states with 2 or 3 fast nucleons were of 2NA, (ISI+2NA), (2NA+FSI) and 3N phase space. In particular it should be noted that the 2-step models used incoherent products of two cross sections.

The large solid angle of LADS permitted the observed 3NA yield from ^{3}He [9,10] to be confirmed in more detail [15], and determined to be around 30% of the total absorption cross section at energies around the Δ. Also, an enhancement was observed in the plot of proton angle vs momentum, near the trajectory for quasi-free π-N knockout, and this was attributed to the above-mentioned ISI prior to 2NA, and quantified to be about 30% of the 3NA yield. In fact this enhancement has also been seen in all nuclei investigated by LADS (^{3}He, ^{4}He, N, Ar, Xe), constituting some 20-30% of the 3p final state in each case [16]. (The fraction of the total yield going into the 3p final state however falls rapidly with increasing A.) The enhancement attributed to ISI is clear, but the simple models do not fit it well, which may indicate that its origin is such a process, but modified by interference with other amplitudes.

The LADS data on ^{4}He permitted full kinematic reconstruction of almost all events and thus reliable decomposition of the partial cross sections. With all nuclei heavier than ^{3}He, deuterons are observed in the final state, with a yield of order 10% of a corresponding pure nucleonic state. These deuterons have distributions consistent with pick-up processes [17] and so when considering multiplicities are here classified as single nucleons. Then a simple decomposition of the absorption cross section on ^{4}He at 162 MeV gives 55% 2NA, 41% 3NA and 3% for 4NA.

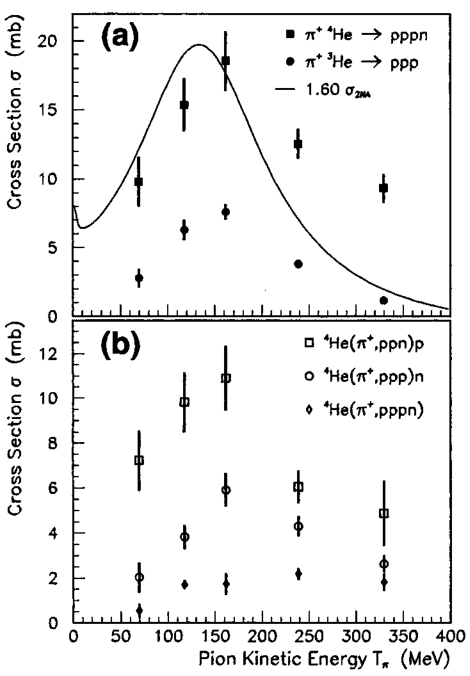

Figure 2. (a) Absorption cross sections for ^{3}He and ^{4}He compared to the deuteron cross section (line). (b) Partial cross sections for ^{4}He. From [18].

The 3p distributions from ^{4}He are remarkably similar to those from ^{3}He [18], and with a similar energy dependence. The 2p1n distributions (2 fast protons and one fast neutron) from ^{4}He are also very similar, but the yield here is around a factor of 2 stronger, as shown in Fig 2. The 3NA cross section on ^{4}He falls more slowly above 160 MeV than that on ^{3}He, consistent with the possibility of pionic cascade (ISI) processes as discussed for the total cross section. This figure also demonstrates that 4NA never becomes a very strong channel, even at 330 MeV.

The fits to the 3NA channels from He did not require a strong contribution from the 2NA+FSI process, or rather disfavoured any, in contrast to ISI+2NA. This may not be surprising, since the cross section for NN is smaller than for πN. However, the favouring of the (ppn) over the (ppp) final state for ^{4}He suggests FSI processes since the pn cross section is typically double that for pp.

The main points to stress for absorption on the two helium isotopes, are that the 3NA distributions are very similar in shape; that there is an ISI-like signature (in both (ppp) and (ppn)), and the pion energy dependence of the cross sections also suggests this process may be significant; that the shape of the distributions do not indicate a strong FSI yield, but that the ppn/ppp ratio does. In addition there is no evidence for a strong preference for absorption on 4 nucleons, nor a high sensitivity to the nuclear density, both of which have long been topics of speculation. Perhaps more remarkably, these observations apply to absorption on heavier nuclei, N, Ar and Xe [19], except that the model fits now also suggest FSI processes.

For the heavier nuclei, beyond examining the 3p final state in some detail, the LADS analysis concentrated [19] on multiplicities, partly because there are so many channels open, but also because the final state generally has at least one neutron and is thus not completely defined kinematically. Nevertheless final states with detected pions were identified and vetoed and the remaining π^0 events quantified and subtracted. Low energy particles were attributed to nuclear de-excitation and ignored. This analysis was different to an earlier one [3] aimed at extracting reliable total absorption cross sections, and those results provided a useful check.

The analysis considered up to 26 data channels, of nucleon multiplicity up to 6. The same number of simulated distributions were then generated, typically just phase space distributions, and fitted simultaneously to the data. Comparison of the resultant distributions with the data led to some adjustment to the simulated distributions, such as varying the range of missing energy (up to 150 MeV) or adding some ISI, and the procedure iterated.

A very important point here is that as with all detectors with finite efficiencies and thresholds, the various final state channels mix: eg a real 3p final state may be detected as 2p or 3p, while a detected 3p event may be due to 3p, 3p1n, 3p2n or even higher multiplicity real final states. Because the mixing flows in and out of channels it is not a priori possible to say whether a detected yield is greater than or smaller than the true yield. The strength of the LADS detector here is its almost complete kinematic coverage with high efficiency: the consequence is that it is not possible to move strength in or out of a channel to improve agreement with that channel alone, since the strength moved must have come from or gone to another observed channel which must also be reproduced. This has to be qualified in that for neutron multiplicities >1 there was an increasing ambiguity about the relative strengths of the different neutron multiplicities, because the efficiency per neutron was only some 30%, but this is not a major weakness.

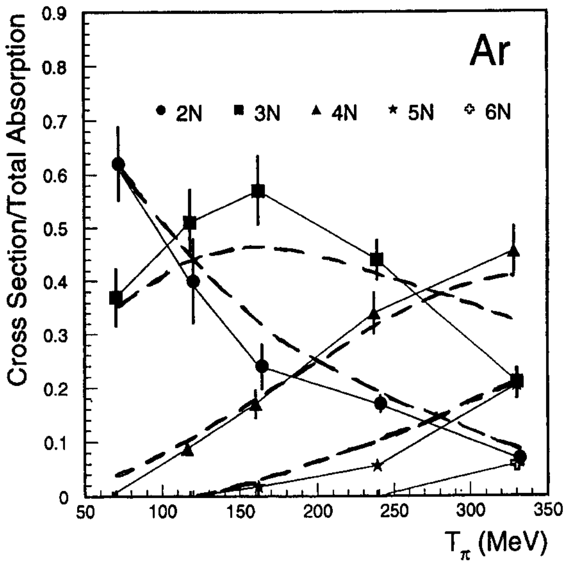

Figure 3. Final state multiplicities after absorption on Ar as a function of pion energy. The full lines join the data; the dashed lines represent a phase space calculation of V. Markushin. From [19].

Fig 3 shows the final state nucleon multiplicities for Ar as a fraction of the absorption cross section, as a function of pion energy, with the deuteron considered as a single nucleon. The strength moves to higher multiplicity with energy, and this statistical sort of behaviour is confirmed by the results of phase space calculations by V. Markushin, which are also shown. Fig 4 shows the A-dependence of the multiplicities at 239 MeV, which shows increasing multiplicity with A, but nevertheless has the 3N channel at a near constant ~40% of the total from ^{3}He to Xe.

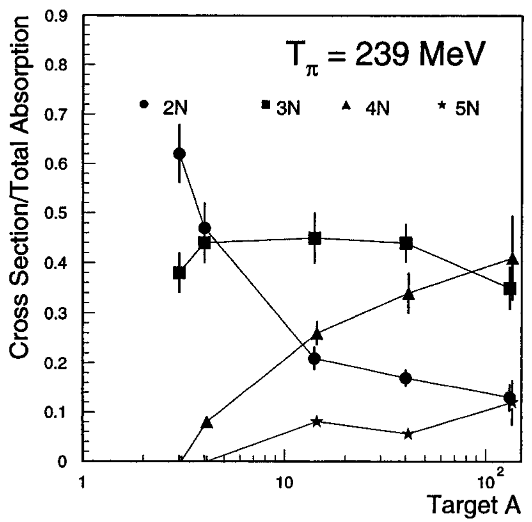

Figure 4. Final state multiplicities at 239 MeV as a function of target mass. From [19].

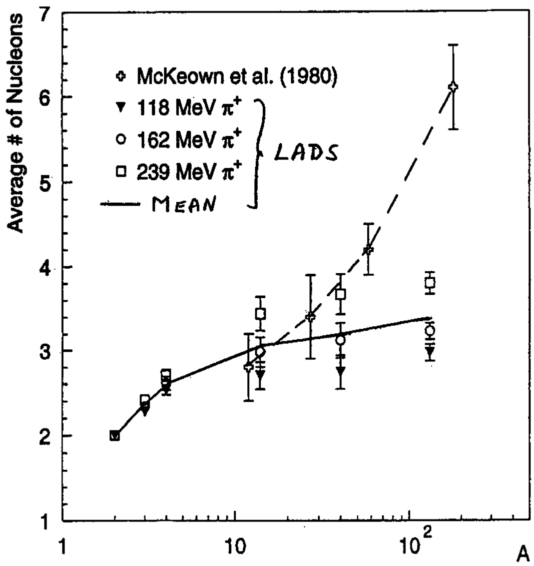

Figure 5. Average final state multiplicities as a function of target mass, compared to those of reference [6], which are the mean of three similar energies. From [4].

Finally, Fig 5 shows the average multiplicities as a function of A, from the LADS data, which suggest that the earlier McKeown data exaggerate the increase in multiplicity with A. The LADS data indicate a rather modest growth with A from ^{4}He to Xe. Then the heavy nucleus data show that: the 3N distributions are A-independent from ^{3}He onwards; the multiplicities develop statistically with pion energy; while the A-dependence of the total cross sections (shown at the beginning of this talk) and of the average multiplicities suggest that the full absorption dynamics has been developed by ^{4}He, if not already in ^{3}He. Evident but not shown here is the preference for neutrons over protons in the final state which was already seen in ^{4}He. Thus the physics appears to be essentially in the absorption on ^{3}He, with possibly a significant extra isospin degree of freedom in ^{4}He, and going to heavier nuclei only smears things out kinematically, with a slow increase in the overall multiplicity.

Before concluding, a brief remark on photon absorption, where 3NA has also been investigated. Recent examples are on ^{3}He [20] where comparison to calculation by Laget indicates that pion production followed by 2NA is important while nucleon rescattering is not; and in absorption on ^{12}C [21], where calculations from the same model [13] used to assist the BGO Ball analysis, suggest that nucleon rescattering is important; however comparison with the weak (pp) final state suggests that the model could seriously overestimate this. However, for count rate reasons the photon data do not give exclusive distributions with good statistics which are needed if their interpretation is not to be ambiguous.

To summarise, there now exists a large body of data giving a comprehensive overview, including reliable total and partial cross sections with complete multiplicities. ≥3NA is important for nuclei heavier than the deuteron, but its origin remains unexplained. There are indications of ISI (kinematic signature) and FSI (n/p ratio) cascade processes, but the trends of the multiplicities indicate a rather statistical increase with incident energy, and no strong trend from ^{4}He to Xe. One could then conclude that there is just 2NA plus cascade-like processes with the kinematics smeared out; then our understanding of nucleon propagation in the nucleus might be re-examined in the light of these data. But one is still left with the question of why the multi-nucleon absorption is so strong already in ^{3}He.

For further understanding a good theoretical calculation for ^{3}He is essential, and also a good understanding for ^{4}He. A good theoretical calculation should almost certainly provide input to the 3-nucleon force, and it should be emphasised that in the Δ-region the 3NA is a large cross section. The few body conference appears to be the right address to say this and I urge theoreticians to take up the challenge.

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