Pion Absorption in Nuclei

Ron Ransome
Rutgers, The State Univ of New Jersey

December 8, 2013

Outline

- General Comments
- Overview of cross sections
- Absorption on Light Nuclei (A ≤13)
- Absorption on Heavy Nuclei (A ≥ 12)
- Conclusions

Pion absorption is an intrinsic 2-body process – absorption on a single nucleon is forbidden due to momentum and energy conservation.

Because of this, early on it was felt studies of pion absorption could give insight into two body correlations.

However, as I'll show, this proved to be more difficult than anticipated.

Pion Nucleus Cross Sections

- Total
  - "Easy" – attenuation of initial beam
- Elastic (nucleus in ground state)
  - "Easy" – differential cross section integrated
- Inelastic (nucleus in excited state or broken up)
  - "Moderately hard" - double differential cross section, need to measure to zero energy
- Charge Exchange (π^+,π^0), (π^+,π^-)
  - Single charge exchange - "Hard" - need to detect neutral pion
  - Double charge exchange – "Easy" but very small
- Absorption (no pion in final state)
  - "Really Hard" – need to confirm no pion in final state, or subtract all other cross sections from all others.

See review article Lee & Redwine, Ann. Rev. Nucl. Sci, 52, 23 (2002)

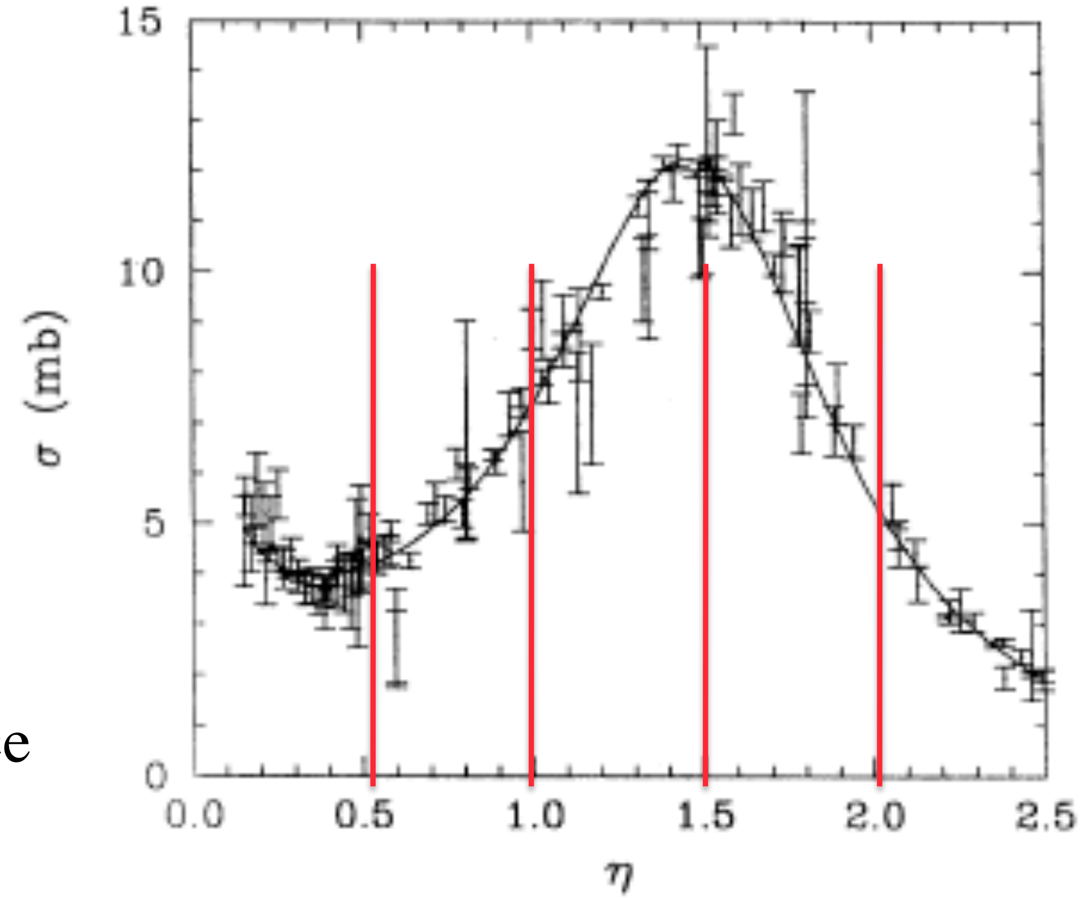
Absorption on the deuteron is the simplest case.

Studies of $d\pi^+ \rightarrow pp$ show a strong relationship to the Δ resonance.

Cross section increases rapidly as pion energy increases to about 160 MeV, then drops rapidly afterward.

$\pi^+ d \rightarrow pp$

Absorption on deuteron shows clear Δ dominance of reaction.



T_π (Mev) 20 80 160 270 390

B.G. Ritchie, PRC 44, 533 (1991)

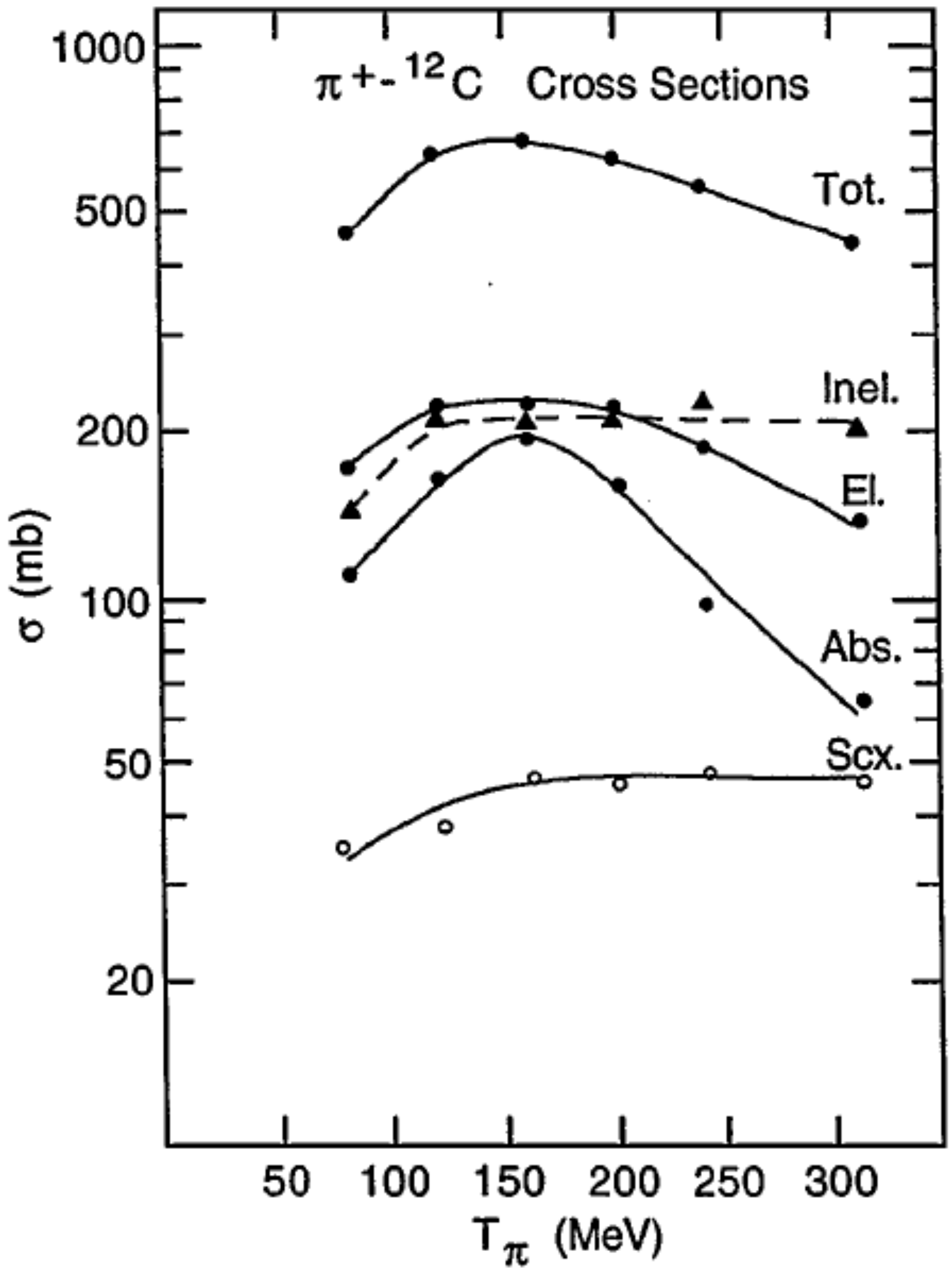
Later experiments on ^{3}He with π^+ and π^- showed that isospin 0 (i.e. deuteron-like) pairs was much (~20 times) more likely than on isospin 1 pairs, at energies near the Δ and below.

S. Mukhopadhyay PRC 43, 957 (1991), and refs. therein.

This leads to the expectation that most absorption in nuclei comes through "quasi-deuteron" absorption (i.e. on np pairs)

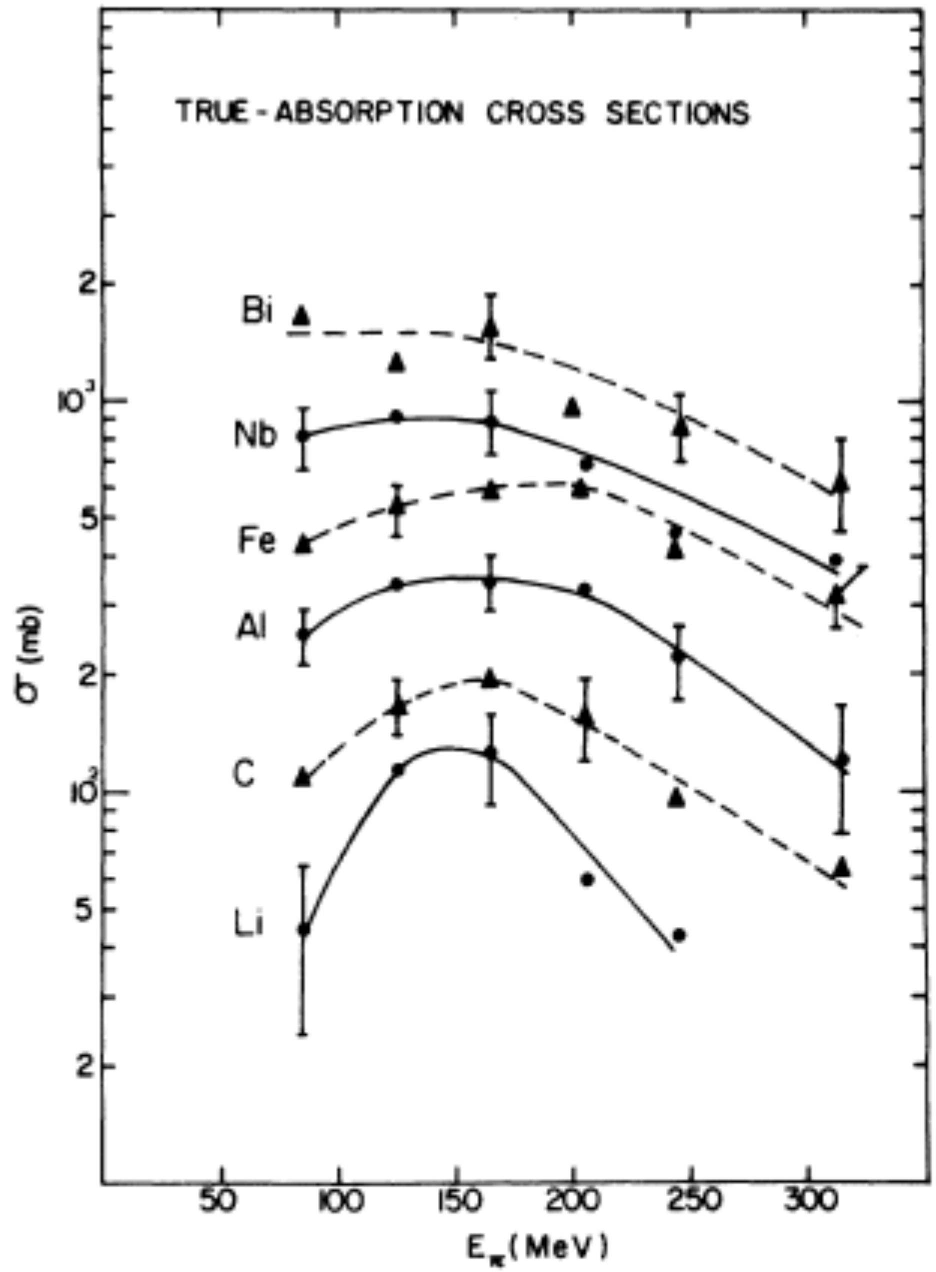
Ashery et al. (PRC 23, 2173 (1981)) published a fairly comprehensive set of cross sections on nuclei in 1981. Although both systematic and statistical errors on absorption cross sections are large (~10-20%), they show the general trends of energy and A dependence of absorption.

They showed the same general energy dependence as absorption on the deuteron, although the energy dependence was weaker with increasing A.



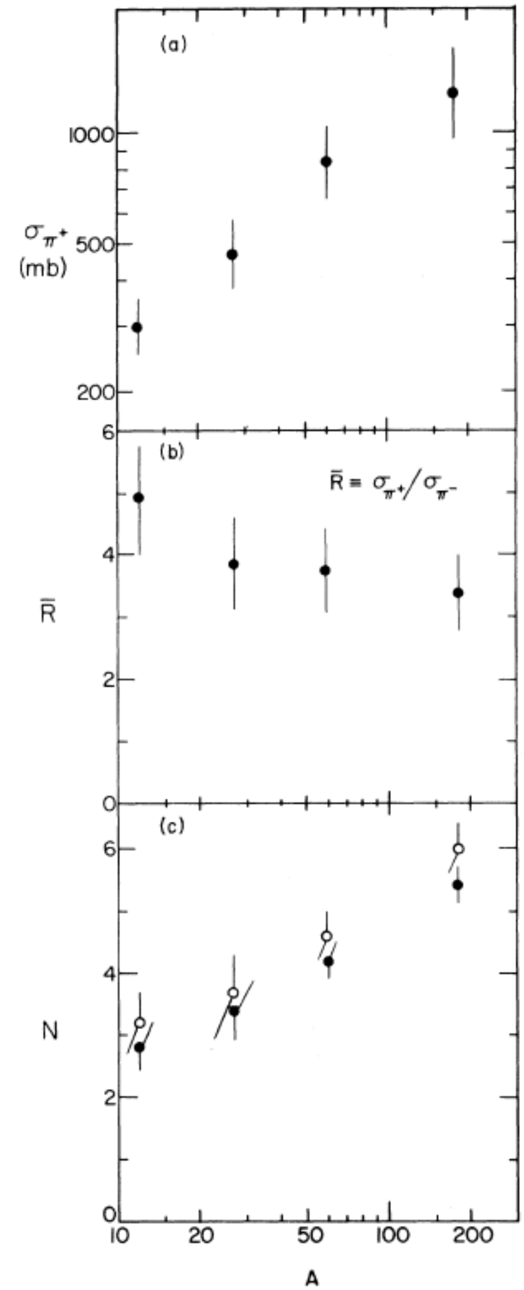
Ashery, PRC 23, 2173 (1981)

Note these are 100-1000 mb



Ashery, PRC 23, 2173 (1981)

In the early 1980's, McKeown et al. showed that pion absorption occurred on more than 2 nucleons, with the number increasing with A.



McKeown et al., PRL 44, 1083 (1980)
McKeown et al., PRC 24, 211 (1981)

The McKeown results led to the development of two large solid angle detectors: The BGO Ball (LAMPF) and LADS (SIN, now PSI).

The BGO ball had 30 BGO detectors covering ~90% of 4π. Experiments studied solid targets (CD_2, C, ^{6}Li, ^{7}Li, ^{9}Be, ^{10}B, ^{11}B, ^{12}C, ^{13}C, Al, Ni, Sn, Pb, U).

LADS was a wire chamber/plastic scintillator experiment covering ~98% of 4π. Experiments studied gas targets (^{3}He, ^{4}He, N, Ar, Xe).

LADS on 3He

TABLE I. Total cross sections for π^+ absorption on ^2H and ^3He. Also listed are the values of Ritchie's parametrization of absorption on ^2H [21], and the division into 2NA and 3NA components for the absorption on ^3He. Both systematic and statistical uncertainties are represented; the systematic uncertainties dominate.

	^2H		^3He		
T_{π^+} (MeV)	LADS (mb)	Ref. 21 (mb)	2NA (mb)	3NA (mb)	Total (mb)
118	11.5 ± 0.4	11.9	21.3 ± 1.0	6.0 ± 0.6	27.3 ± 0.8
162	10.9 ± 0.3	10.6	17.4 ± 0.8	7.2 ± 0.7	24.7 ± 0.7
239	4.3 ± 0.2	4.2	7.0 ± 0.6	3.0 ± 0.5	10.0 ± 0.4

Clear evidence for multi-nucleon absorption in 3He, amounting to ~1/4 of total absorption cross section.

Alteholz, PRL 73, 1336 (1994)

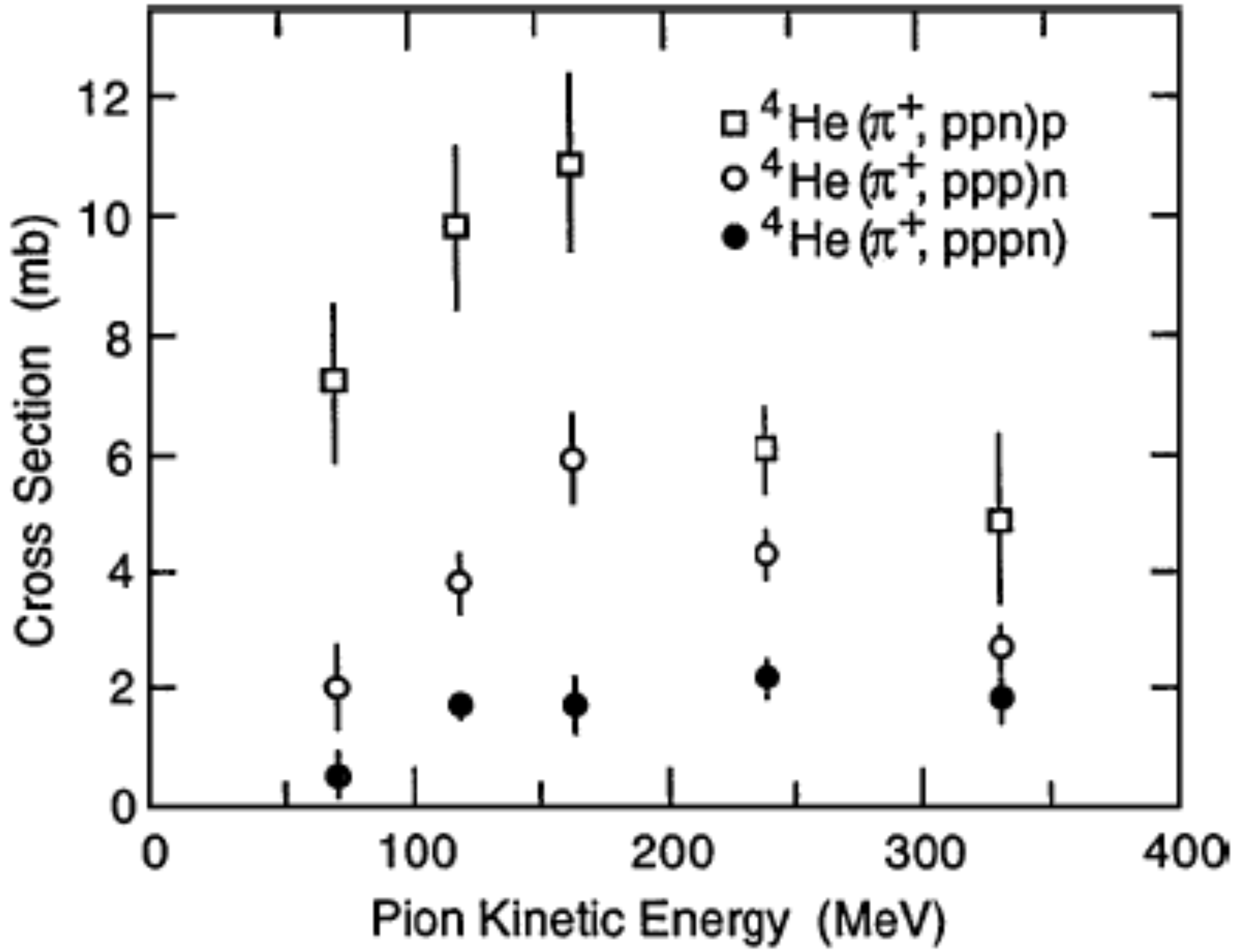
LADS on 4He

TABLE II. Decomposition of the total absorption cross section, according to the reaction participants. The results for $(ppp)n$, $(ppn)p$, and $(pppn)$ are taken from Ref. [39]. All cross sections are in mb.

Physics channel	70 MeV	118 MeV	162 MeV	239 MeV
$(pp)d/pn$	19.9±3.2	28.4±2.6	24.1±2.5	10.9±1.0
$(ppp)n$	2.0±0.7	3.8±0.5	5.9±0.7	4.3±0.4
$(ppn)p$	7.2±1.3	9.8±1.3	10.9±1.4	6.0±0.7
$(pppn)$	0.6±0.3	1.7±0.2	1.7±0.5	2.2±0.2
$(pd)p$	2.5±0.4	2.5±0.2	2.1±0.2	0.8±0.1
(ppd)	2.2±0.3	4.1±0.3	4.2±0.4	1.5±0.1
$(pn)pp$	0.6±0.3	1.8±0.9	1.6±0.8	0.9±0.4
Total	35±5	52±4	51±5	27±2

Confirmed large fraction of multi-nucleon absorption.
Distributions followed phase space.

Mateos PRC, 58, 942 (1998)



Cross Section (mb)
Pion Kinetic Energy (MeV)
0
2
4
6
8
10
12
0
100
200
300
400
□ ^{4}He (π^+, ppn)p
○ ^{4}He (π^+, ppp)n
● ^{4}He (π^+, pppn)

LADS on Argon

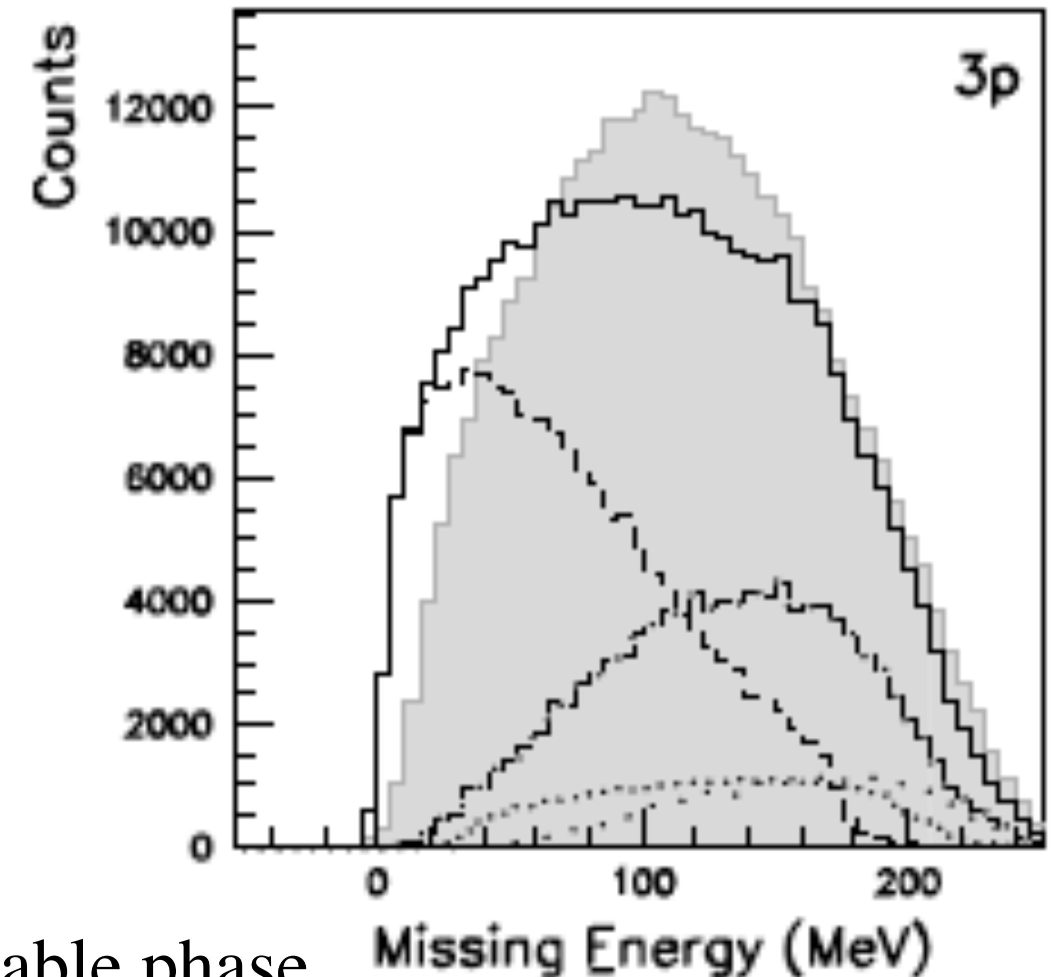
Data at 239 MeV

	Raw Data	30 MeV Threshold	Extrapolated to 0 MeV
5p	0.013 ± 0.001	0.04 ± 0.01	0.64 ± 0.13
4p	1.11 ± 0.10	2.0 ± 0.2	5.1 ± 1.0
3p	19.9 ± 1.2	26.8 ± 2.5	28.4 ± 4.0
3pn	2.0 ± 0.2	11.9 ± 1.3	33.2 ± 7.5
2p	69.8 ± 4.2	72.9 ± 5.8	43.6 ± 5.2
2p1n	11.9 ± 0.9	62.9 ± 6.6	$75. \pm 10.$
2p2n	0.67 ± 0.05	5.6 ± 1.0	$21. \pm 8.$
2pd	9.2 ± 1.0	10.3 ± 1.2	7.9 ± 1.4
pd	14.6 ± 2.3	9.8 ± 1.7	4.2 ± 1.0
pdn	3.0 ± 0.4	13.8 ± 2.4	10.6 ± 2.5

229 mb

Note that 2p is only 20% of cross section.
Alson note ~10% have deuteron in final state.

Ar(π^+,3p)
T_π=239 MeV



Distributions fill available phase space.

Kotlinski, EPJ 9, 537 (2000)

BGO ball on lighter nuclei

BGO ball experiment required 2 or more detected protons and no detected pion.

Threshold for proton detection was ~20 MeV

Unable to distinguish between neutron and photons.

Mainly looked at identified particle distributions.

Found angular and energy distributions filled phase space.

Energy	Nucleus	2p	2p QD	3p	2pn	Deuteron
140	^{6}Li	31	20	2.1	1.4	5.6
	^{7}Li	32	19	1.8	1.4	6.5
	^{9}Be	32	18	1.8	1.3	6.2
	^{10}B	35	17	2.8	1.6	10
	^{11}B	49	24	3.3	2.0	11
	^{12}C	47	22	3.8	1.9	9.6
	^{13}C	47	21	3.5	2.0	12

Clear effects of nuclear structure, with 6Li and 7Li being nearly the same, as are 11B, 12C, 13C.

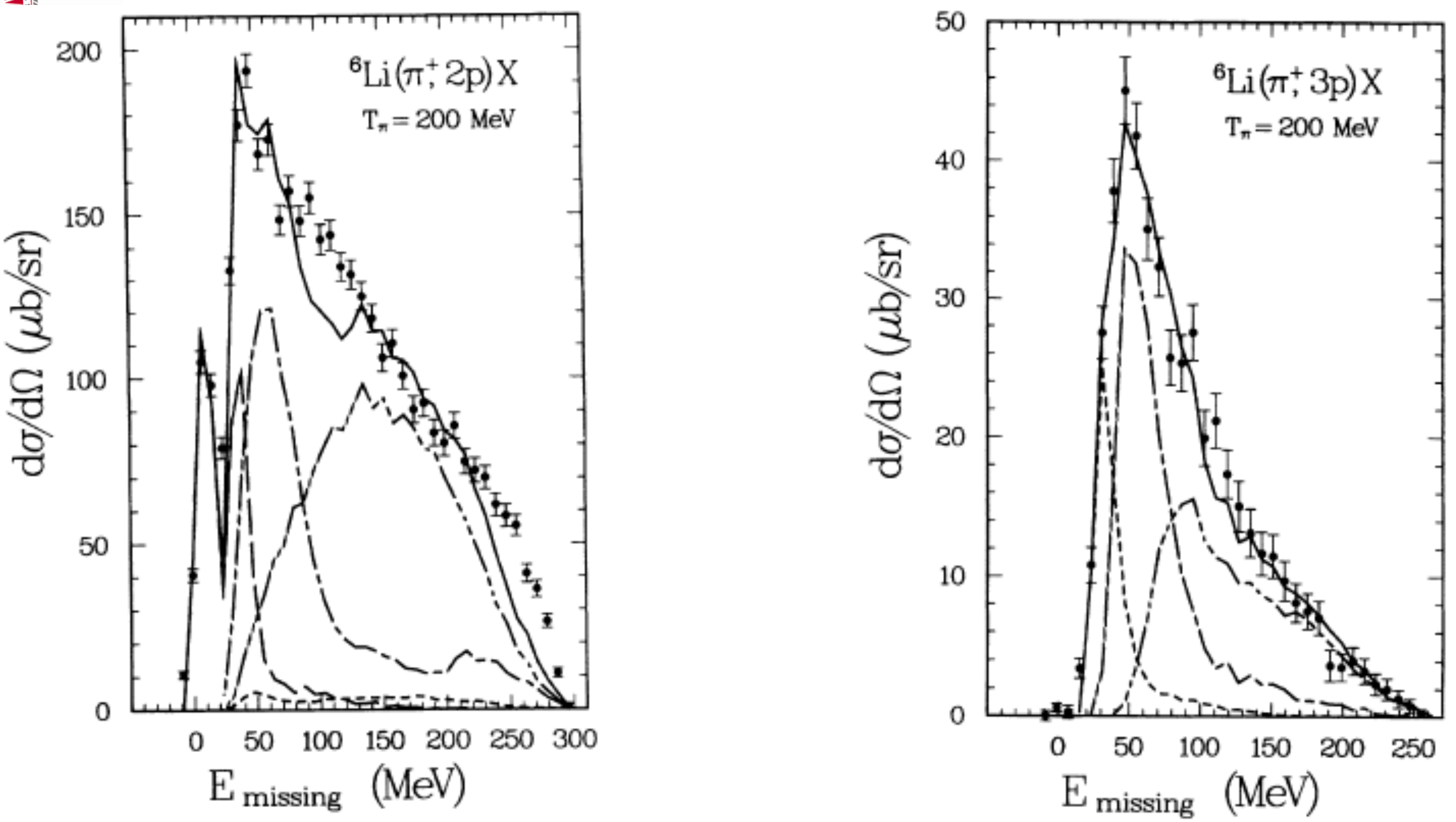
Results were not consistent with shell model calculations of number of "quasi-deuteron" pairs in the nuclei.

Substantial deuteron emission from all nuclei.

Ransome, PRC 46, 273 (1992)

Comparison with an earlier measurement, Yokota PRC 40, 270 (1989) on 6Li, 7Li, 12C were completely inconsistent, with the BGO ball getting 3-4 times larger cross sections.

Yokota had two small, coplanar detectors, and assumed QDA with some final state interactions described by cascade code to extrapolate to full absorption cross sections. The lack of multinucleon absorption caused underestimate of cross section.



The 3p cross section is small (as later confirmed by LADS)

BGO ball heavier nuclei

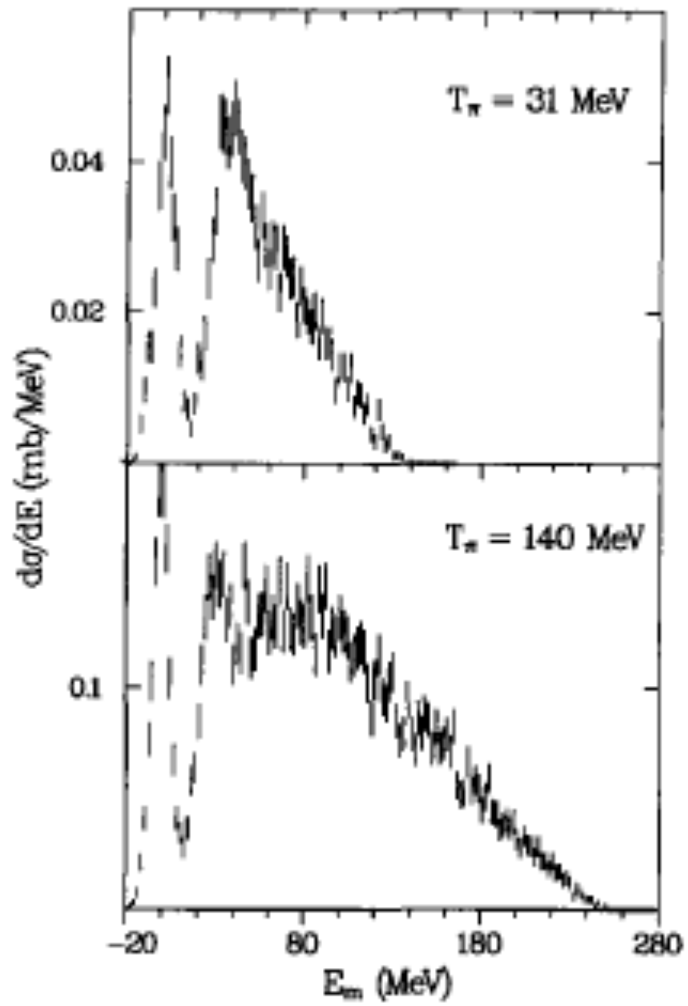
The extensive set of measurements with the BGO ball were done on a heavier set of nuclei, including a CD2 target for calibration and normalization checks.

Ransome, PRC 45, R509 (1992) 50-200 MeV

Jones, PRC 48, 2800 (1993) 250-500 MeV

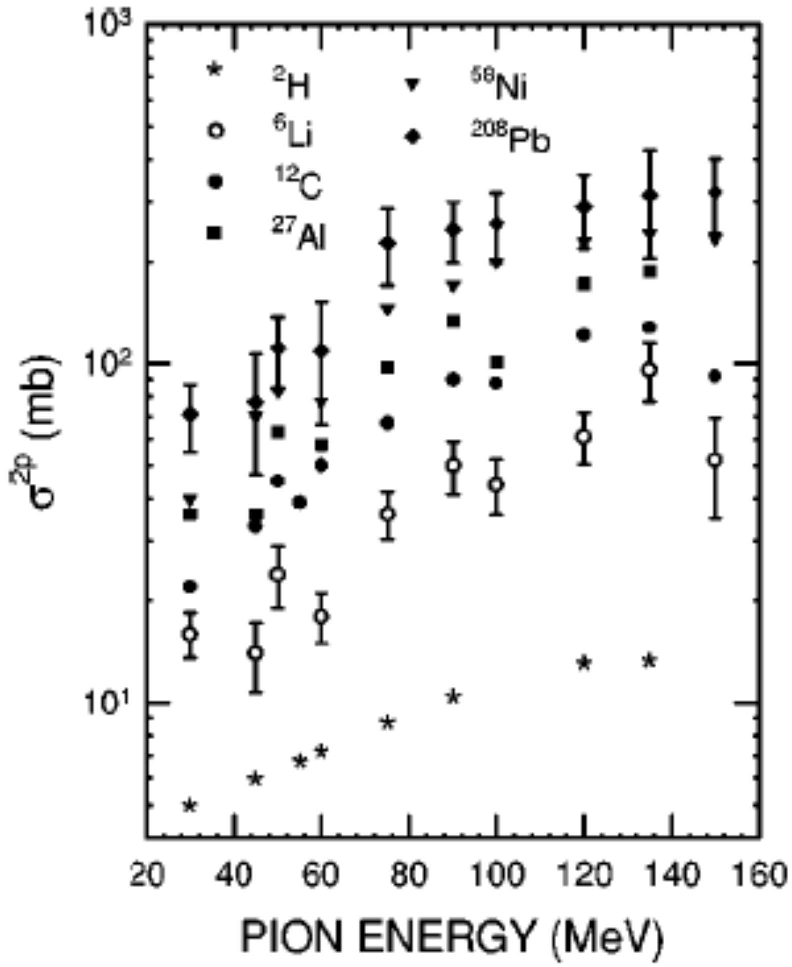
Gianelli PRC 61, 054615 (2000)

BGO ball measurements on a CD2 target demonstrate the energy resolution, and broad distribution in C even at low energies.



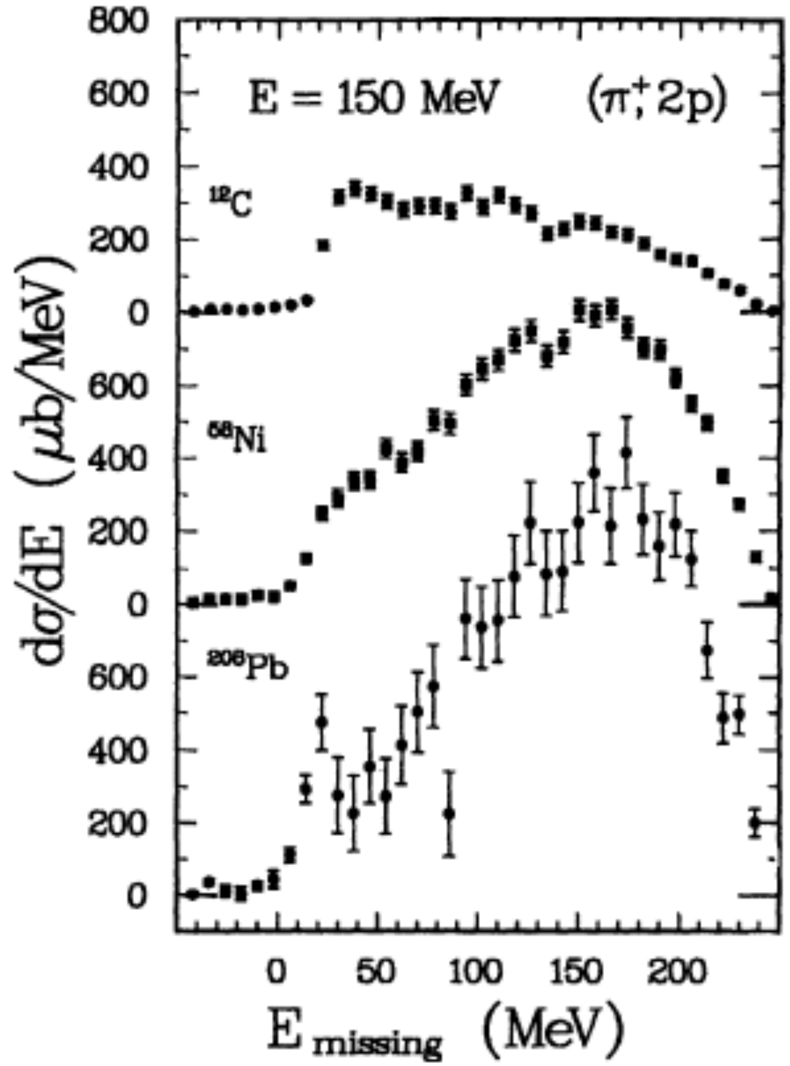
Jones, PLB 278, 419 (1992)

There is a gradual, smooth increase with both A and energy at low energies.



Gianelli PRC 61, 054615 (2000)

The low missing energy part of the spectrum increases with energy.

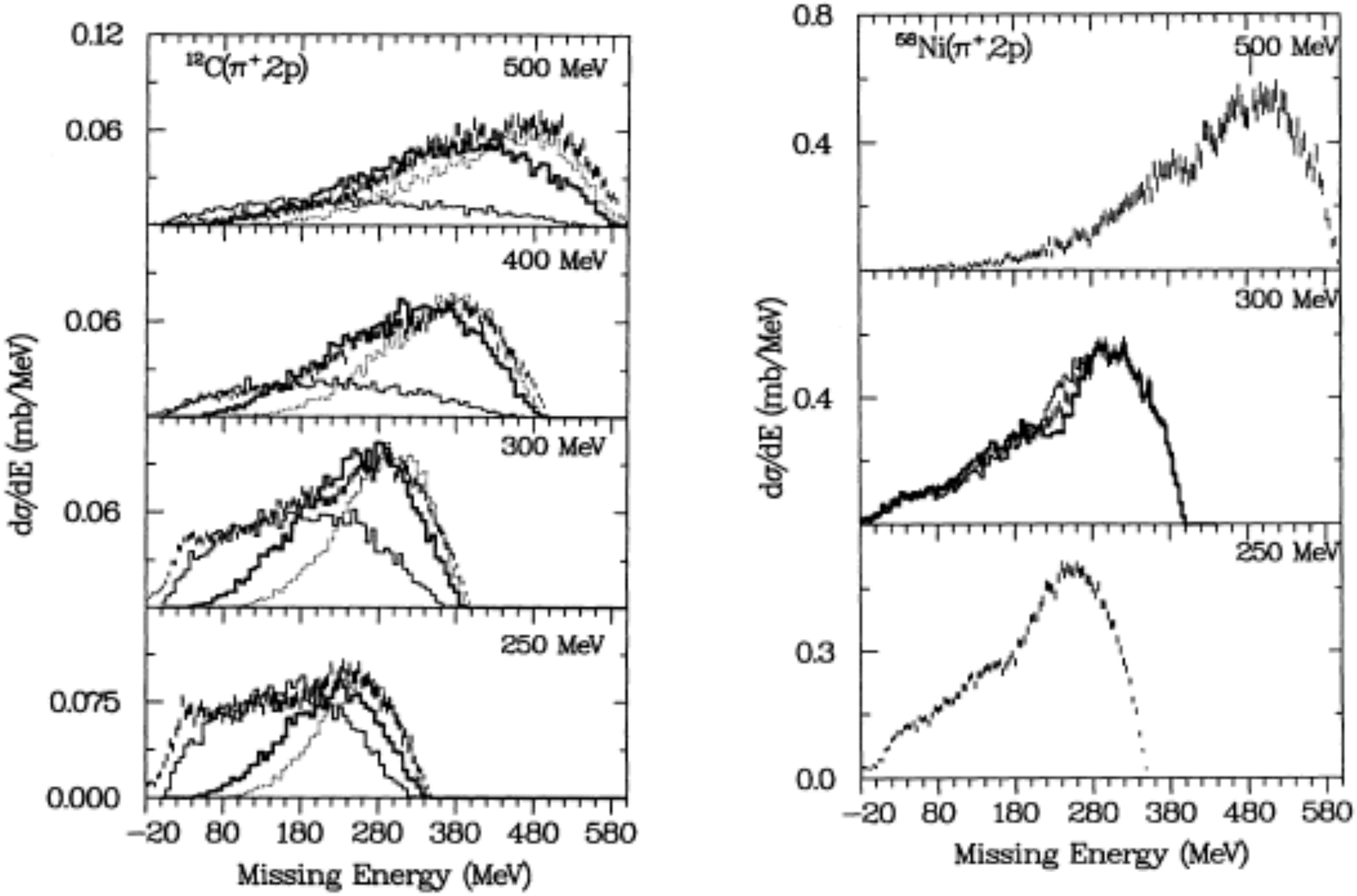


Ransome, PRC 45, R509 (1992) 50-200 MeV

Energy (MeV)	Nucleus	2p inclusive	2p 50	3p inclusive	Deuteron
150	^{6}Li	36	14	2.6	5.2
	^{12}C	52/110	18	5.4/14	11
	^{58}Ni	124/300	19	11/33	23
	^{118}Sn	124/320	13	10/31	36
	^{208}Pb	159/400	19	7.7/24	45

Heavier nuclei show similar properties to light, with substantial deuteron emission, and 2pn or 2p2n being a substantial part of the cross section.

Ransome, PRC 45, R509 (1992) 50-200 MeV



Increasing missing energy at higher energies, with "pure" 2p absorption quite small.

Jones, PRC 48, 2800 (1993)

Absorption was measured for missing energy < 100 MeV, and >100 MeV

QDA becomes increasing small, following the absorption cross section on deuterium

Total absorption remains fairly constant

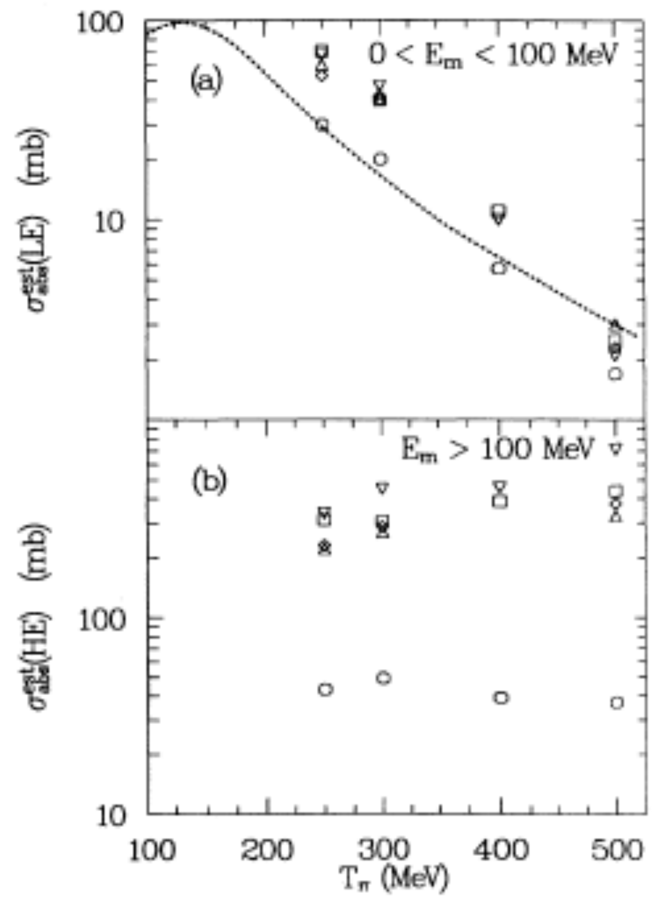
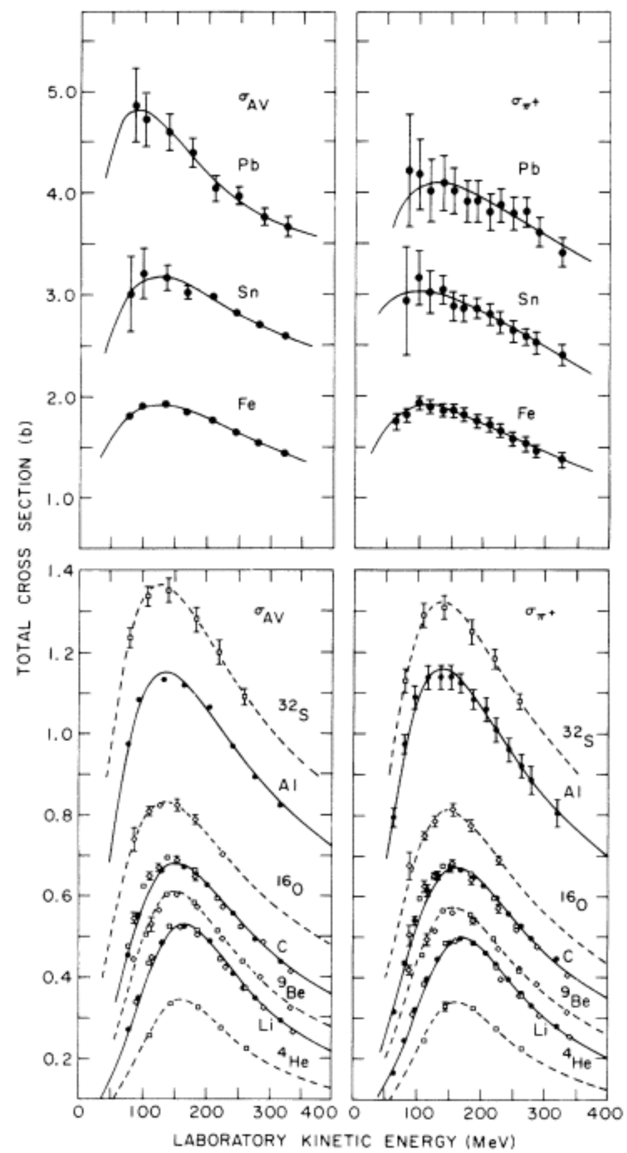


FIG. 10. The estimated two-proton inclusive cross sections (a) $\sigma^{\rm est}_{\rm abs}$(LE) and (b) $\sigma^{\rm est}_{\rm abs}$(HE) for targets of ^{12}C (○), ^{58}Ni (△), ^{90}Zr (◇), ^{118}Sn (□), ^{208}Pb (▽). The dashed line is from a parametrization of the $\pi d \to pp$ total absorption cross by Ritchie [25] normalized to the $\sigma^{\rm est}_{\rm abs}$(LE) data.

RUTGERS

The total cross section show a similar behavior, indicating that absorption remains at ~15% of the total cross section up to 500 MeV



Carroll PRC 14, 635 (1976)

Theory

There is not currently a satisfactory theory describing absorption. The Valencia group has done extensive modeling of the pion-nucleus reaction and has qualitative overall agreement, although not in detail. The true mechanism of multi-nucleon absorption remains an open question.

See Vicente-Vacus NPA 568, 855 (1994)

Summary

- Pion absorption is a large part of the pion-nucleus cross section from ~50 MeV to 500 MeV, slightly decreasing with energy. There are no higher energy measurements that I am aware of.
- Near and above the Δ, 3 nucleon or greater absorption dominates
- From the experimental point of view, pure two nucleon final states are a small fraction of the final state for nuclei heavier than carbon.
- Positive pion absorption leads to multiple neutron emission. Negative pion absorption should lead to primarily neutron emission. Deuterons are present ~10% of the time.
- Nuclear structure effects absorption in light nuclei in a significant, but as yet not explained fashion.