Pion Physics in the Meson Factory Era

R. P. Redwine

Bates Linear Accelerator Center
Laboratory for Nuclear Science
Department of Physics
Massachusetts Institute of Technology
Meson Factories

- Los Alamos Meson Physics Facility (LAMPF)
  - 800 MeV Proton Linac
  - Los Alamos, New Mexico

- Swiss Institute for Nuclear Research (SIN), now Paul Scherrer Institute (PSI)
  - 600 MeV Proton Coupled Cyclotrons
  - Villigen, Switzerland

- Tri-Universities Meson Facility (TRIUMF)
  - 560 MeV Proton Cyclotron
  - Vancouver, Canada
Meson Factories

- The primary goal of the meson factories was to produce copious quantities of pions to use in nuclear structure and reaction studies.
- Beams of protons, muons, and neutrinos were also available.
- Fundamental symmetry tests played a large role at the meson factories (and still do to an extent).
- I will concentrate on pion-nucleus reactions.
Meson Factories


- SIN and TRIUMF followed very soon after.
- From Boston, it is equally difficult to get to Los Alamos, Vancouver, and Villigen
Pions

- The pion is a spin-0 boson with isospin 1.

- It has three charge states (+, 0, -).

- Pi–nucleon interactions involve single-charge-exchange as well as elastic scattering.

- As a boson, the pion can be absorbed, although absorption on a single nucleon in the nucleus is very unlikely.
Throughout most of the energy region of interest, the Delta (1232) pi-nucleon resonance plays a dominant role.

- The Delta is a spin 3/2, isospin 3/2 resonance with a width of about 120 MeV.
- The pi+ is sensitive primarily to protons, the pi- to neutrons.
- The pion-nucleus interaction is very strong – most of the action is on the nuclear surface.
Pion nucleus cross sections

- The Delta resonance appears strongest in the absorption channel.
- This is still not well understood.
Mass dependence of cross sections

\[ \pi^+ \165 \text{MeV} \]

\[ \sigma \text{ (mb)} \]

A

10^1

10^2

10^3

10^1

10^2

10^3
Comparison of proton spectra following pion and photon absorption

- 220 MeV incident pions (points)
- 343 MeV incident photons (histogram) (X 55)
  - a) 45 deg
  - b) 65 deg
  - c) 120 deg
Theoretical Approaches

- Many calculations using multiple scattering to describe pion-nucleus interactions.

- The Delta-hole model explicitly took into account the fact that the pion in this energy region was likely to excite a Delta resonance, leaving a hole in the nucleon states.
Elastic Scattering

- The data are highly diffractive in nature.

- Optical potential calculations show strong sensitivity to the radius of the nucleus.
The agreement of the Delta-hole model with data is improved if a “Spreading Potential”, taking into account pion absorption and the spin-orbit interaction of the Delta, is included.
Delta – hole model calculations – with and without the spreading potential

pi elastic scattering from 16O at 240 MeV
Inclusive pi scattering on $^{16}O$

Solid curve includes medium effects on Delta propagation
Inelastic scattering to discrete states

DWIA calculations
Pi – Carbon inelastic scattering

- Delta – hole model calculations.
- The solid curves include medium effects on the Delta propagator.
Pion single-charge-exchange

- Angular distributions integrated over the outgoing pion energy
- The lines represent the angular distribution for pi-nucleon SCX
Pion SCX to discrete states

- LAMPF pi0 spectrometer data
- This is an isobaric analogue transition.
Pion Double Charge Exchange

- This was the first observation of pion DCX to a discrete state.
- It also is the largest single pi DCX cross section to a discrete state ever measured!
- The hope for pi DCX was that it would show great sensitivity to two-nucleon correlations.
Pion Double Charge Exchange

\[ \frac{d\sigma}{d\Omega} (\mu b/st) \]

\[ \theta_{c.m.} (\text{deg.}) \]

\[ ^{18}\text{O}(\pi^+, \pi^-)^{18}\text{Ne (g.s.)} \]

\[ T_\pi = 164 \text{ MeV} \]
Inclusive data are well described by a model which includes successive SCX reactions in competition with other important reactions.
Pion DCX on 4He

- Data at 25 deg
- a) 270 MeV π+
- b) 240 MeV π+

- The curves represent a sequential model of DCX.
Pion Absorption in Nuclei

- This was a major area of investigation.

- Pion absorption involves dumping a large amount of energy in the nucleus.

- Pion absorption was expected to be sensitive to two-nucleon correlations.

- The prototype reaction is $\pi^+ + d \rightarrow pp$.

- The data turned out to be very interesting.
Pion Absorption

- (pi+,pp) reactions on Ni at 165 MeV
- There is a clear indication for two-nucleon absorption, but there is evidence for a lot of cross section involving more than two nucleons.
Pion absorption on $^3$He

![Graph showing pion absorption on $^3$He](image)
Pion absorption at 160 MeV
Pion Absorption in 4He

The figure shows a graph with the following data points:
- $^4\text{He}(\pi^+, \text{ppn})p$
- $^4\text{He}(\pi^+, \text{ppp})n$
- $^4\text{He}(\pi^+, \text{pppn})$

The x-axis represents the pion kinetic energy in MeV, ranging from 0 to 400. The y-axis represents the cross section in mb (millibarns), ranging from 0 to 12.
What do we know about pion absorption in nuclei?

- It is a major reaction channel.
- It resonates more than the other channels.
- Two-nucleon absorption is important, but so is multi-nucleon.
- There is some evidence for coherent absorption involving more than two nucleons that may be new physics, but it is not definitive.
- The breakup into separate channels in 4He is hard to understand and may be an important clue.
Summary

- The meson factory era was a rich and exciting one, and I have only been able to touch on some important aspects.
- The special properties of pions do give one access to some important states and reactions which are not available with other probes.
- The difficulty in describing precisely the interactions of pions in nuclei ultimately limited the utility of pions as a probe of nuclear structure.
- Understanding the important reactions of pions with nuclei remains an important challenge.
Large Acceptance Detector System (PSI)
Delta – Hole model fits to elastic scattering and total cross sections