The Pion as a Probe of Conventional Nuclear Physics

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Three meson factories — at SIN in Switzerland, Los Alamos in the USA and Vancouver in Canada — have been in operation for a decade, so that it is reasonable to ask what nuclear physics has been learned from the extensive experiments that have been made on pion-nucleus interactions. The most fascinating research involves the nucleus at high excitation energies, pionic degrees of freedom or the propagation of the delta (pion-nucleon) resonance in nuclei. However, the pion has also yielded information on conventional nuclear physics and it is this more modest aspect which will be stressed here. The pion is a spinless boson of isospin one which can therefore exist in three charge states π^+ , π^0 and π^- ; it is mainly this latter property which makes it competitive with standard low energy probes as illustrated by the following examples.

Masses of Exotic Nuclei

There is no agreed theory to describe pion-nucleus reactions, but much information can be obtained from the kinematics of collision processes. A particularly interesting interaction is one in which the incident pion changes charge by two units: i.e. $\pi^+ \rightarrow \pi^-$ or $\pi^- \rightarrow \pi^+$ as in $^{16}\text{O}(\pi^+, \pi^-)^{16}\text{Ne}$ (ground state). Starting from a target with, in the best case, for (π^+, π^-) reactions, equal numbers of protons and neutrons ($Z = N$) the most exotic nuclei that can be produced ($Z'N'$) via this process have $Z' = N' + 2$ and $N' = N - 2$. Although many such nuclei have been studied through heavy ion reactions, the mass of ^{16}Ne was first measured through the double charge exchange reaction with pions. The situation is even more promising for the (π^-, π^+) mode because one can then start with targets which are neutron rich to produce even richer nuclei. In this way, the masses of ^9He , ^{18}C and ^{26}Ne have been determined¹⁾ at LAMPF (Los Alamos) with a typical uncertainty of 150 keV/c². Such neutron-rich isotopes allow us to study in greater detail the neutron-neutron forces which, in more stable nuclei, are obscured by proton-neutron forces.

Isvector Monopole Resonances

The energy resolution achieved in single charge exchange $(\pi^\pm, \pi^0)$ ex-

periments is typically at least a factor of ten poorer than in the above. This is because the π^0 is neutral and both photons from its decay must be measured accurately. Such reactions are, nevertheless, suitable for the hunting of giant resonances which are several MeV wide. Giant resonances are fundamental to our understanding of nuclear collective motion — they reflect bulk properties of the nucleus rather than the idiosyncrasies of a particular nucleon. Monopole or breathing resonances involve the periodic compression and expansion of the neutron and proton densities in the nucleus, but the isovector type, where the neutrons and protons oscillate out of phase, have proved very difficult to identify in the past. The probe used to excite them must be capable of transferring isospin and preferably should be strongly interacting and have spin zero in order to suppress the small angle production of the giant dipole resonances which are well known from photo-absorption. The background can be further diminished if charge exchange is also required and this suggests that the states be looked at via the (π^-, π^0) reaction. [The alternative (K^-, K^0) reaction could give a better energy resolution but such studies must await the building of a kaon factory!]

On the basis of a simple hydrodynamical model, the resonance energy is estimated to be of the order of 170 MeV/A^{1/3} although this value is modified a little in more microscopic calculations. It was therefore gratifying when recent experiments²⁾ at LAMPF with the π^0 spectrometer clearly identified such states, starting from the targets ^{120}Sn and ^{90}Zr , close to the predicted positions. These findings depend little upon the pion-nucleus scattering theory. In the 100 - 200 MeV range of energies the middle of the nucleus is black to pions due to the production of the delta resonance (see p. 2) and the multipolarity of the state can be seen by inspection of the angular distribution using the Blair strong absorption model. More detailed calculations do however reproduce the magnitude of the observed cross-sections.

It is expected that these and similar measurements will help resolve uncertainties associated with isospin mixing

The SIN Universal Spectrometer Installation (SUSI) mounted on a pion beam-line of the SIN isochronous synchrocyclotron which accelerates protons up to an energy of 590 MeV. The pion intensity at the experimental target is 10^6 - 10^7 pion/s and the overall resolution of the spectrometer is about 1.5×10^{-3} $\delta p/p$.

and provide constraints to the isovector components of the effective nucleon-nucleon interaction in the nucleus.

Nuclear Radii

One of the major features of the pion as a probe is the strong dependency of its interactions on energy: in contrast to the delta region, where the nucleus looks like a black disk, at low energies the mean free path of the pion is quite long. The pion-nucleus interaction has also an important isospin dependence which suggests that a comparison of the elastic scattering of π^+ and π^- by a nucleus should give information on the relative proton and neutron densities in its interior. Scattering theory is not yet sufficiently advanced to yield precise absolute nuclear parameters from such data, but having adjusted the strength of the effective interaction on an isoscalar nucleus which has equal numbers of neutrons and protons, for example ^{12}C , it is possible to derive the relative density differences of ^{13}C experimentally. This approach has been used extensively with other nuclei at TRIUMF in Vancouver over the energy range 30 - 50 MeV. By extracting the various functional forms for the optical potential from the current gamut of theoretical models, realistic error bars which include some uncertainty from the scattering theory can be constructed.

Relatively simple experiments³⁾ seem to give the differences between the

r.m.s. radii of the neutrons in the (^{13}C , ^{12}C) and (^{18}O , ^{16}O) pairs as 0.04 ± 0.03 fm and 0.21 ± 0.03 fm respectively. The numbers are close to theoretical estimates and further confidence in the technique comes from a comparison of the charge radii of ^{12}C and ^{11}B which agrees with that deduced with electromagnetic probes.

More advanced low energy pion spectrometers are being commissioned at all three meson factories and so we can expect more refined experiments in this domain soon.

Charge Symmetry of Nuclear Forces

In the analyses of the experiments described so far, it has been assumed that the interactions conserve isospin, but the pion is an ideal probe to test for isospin violation in nuclear forces. Since the deuteron is symmetric with regard to the interchange of its constituent proton and neutron, from the charge symmetry of nuclear forces it would be expected that, apart from Coulomb effects, its scattering of the charge conjugates π^+ and π^- would be identical.

When seeking to verify whether this is found in practice, experimental charge-dependent biases can best be reduced by performing total cross-section measurements. Results of such measurements at SIN⁴) covering the energy range 70 - 350 MeV where the production of Δ resonances dominates the interaction, indicated that there are indeed π^+ , π^- differences amounting to a few per cent. Unlike the case of the proton-proton versus neutron-neutron scattering lengths which is the classic test of charge symmetry, Coulomb effects are, in the pion interaction, relatively small. Consequently, there is less uncertainty introduced when correcting for them. The strongly energy-dependent signal that remains, could best be understood as a mass splitting in the multiplet of the pion-nucleon delta resonances with the Δ^{++} being lighter than the Δ^- by about 4 MeV/ c^2 and with a corresponding width change. Very similar results have since been obtained from elastic scattering⁵) though the Coulomb corrections are there somewhat larger. This clear charge symmetry violation is in accord with the naive quark model estimate of three times the neutron-proton mass difference, and with more modern particle physics estimates.

A large part of the nucleon-nucleon force arises from virtual pion-nucleon scattering where a pion is shaken off from one nucleon, scatters from the second and is reabsorbed by the first. However it seems that little of the

charge symmetry violation in pion-nucleon scattering propagates through the nucleon-nucleon system just because the difference in the delta masses compensates that of the nucleons.

Isospin Mixing of Nuclear Levels

Charge symmetry violation in pion scattering by nuclei more complex than the deuteron can also occur through isospin impurities in the nuclear states. In the absence of any symmetry breaking, the excitation of any level of a self-conjugate nucleus such as ^{16}O should be

the same in π^+ and π^- scattering. This nucleus possesses three spin-4 negative parity levels in the 18 - 20 MeV range, two with isospin zero and one with isospin one. In an experiment carried out with 164 MeV pions at LAMPF, it was found that the lower isoscalar level was excited 60% more strongly by π^+ and the upper similarly by π^- , whereas the isovector level was equally populated in π^+ and π^- scattering. The authors could explain these ratios quantitatively by a $\pm 12\%$ contamination of the isoscalar levels by the isovector, and the

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parameters of their three level model have since been checked in proton scattering and most dramatically electron scattering⁷⁾ experiments. In the latter, the lower state is enhanced by a factor of five by the mixing, whereas the upper state is suppressed by a factor of ten and has so far not even been seen. The technique for measuring isospin mixing has also been tested on other nuclei such as ²⁸Si with similar success.

The nuclear information gleaned from the examples outlined here depends relatively little upon the ambiguities of reaction theory since distortion effects should be very similar for the different charge states of the pion. There is a little more model dependence in other phenomena such as the extraction of information on the convection current from inelastic transitions induced by the strong energy dependence of the effective interaction. There is a wealth of other information associated with more exotic reactions such as pion absorption, but this may be dominated by more exotic nuclear physics and we are still at the stage of exploring the reaction mechanism. Pions are expensive but they have many features which make them rather special nuclear probes.

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Members are invited to make proposals for topics to be placed on the Agenda in time for publication in the May issue of *Europhysics News*.

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3. Report of the Treasurer
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