

Pion physics at the meson factories

Pi meson probes have contributed much to our ideas about how neutrons and protons are distributed and move relative to each other in nuclei, and along with other probes, to our understanding of basic symmetries in particle physics.

Darragh E. Nagle, Mikkel B. Johnson and David F. Measday

Pions are excellent probes of the structure of the nucleus and are useful in a variety of particle physics experiments of fundamental significance. For the past 15 years, physicists have been producing copious beams of these mesons by directing intense proton beams into targets. Three "meson factories" are now in operation: TRIUMF, in Vancouver, British Columbia; SIN, in Villigen, Switzerland; and LAMPF, in Los Alamos, New Mexico. A fourth is under construction in the Soviet Union, at Troitsk, south of Moscow. This article surveys the scientific achievements that have come out of pion experiments at the meson factories since they came into operation and explains how the availability of pions has caused medium-energy physics to burgeon.

Excitement greeted the realization in the mid-1960s that technological advances in accelerators would make possible a 100-fold increase in the intensity of proton beams of energies between 500 and 1000 MeV. It was the availability of these proton beams that led to the construction of the meson factories. Two reasons for the great interest in pions are that they are believed to play a basic role in the

binding of protons and neutrons in nuclei and that they can be used for a variety of nuclear and particle physics experiments. Intense beams of protons, pions, neutrons, muons and neutrinos have made possible many elegant experiments that elucidate the properties of these particles and their interactions. Even more important, nuclear scattering experiments using beams of these particles as probes are teaching us how the particles propagate and interact inside the nucleus.

The pion is now established as a basic probe, complementing the electron, proton and neutron. The success of facilities using these probes has created a new discipline, intermediate-energy physics, which bridges the gap between classical nuclear physics and the physics of particles and fields. In its style of doing experiments with relatively small teams, intermediate-energy physics resembles classical nuclear physics. Many cherish this style because it allows graduate students to assume more responsibility and initiative in their research projects than is the case in large collaborations.

In this article we have selected the topics of pion physics and basic symmetries to illustrate the research going on at the meson factories. We should emphasize, however, that this work constitutes less than half of the experimental effort at these laboratories. The meson factories are also a source of exciting advances in our understanding of rare decays, the nucleon-nucleon

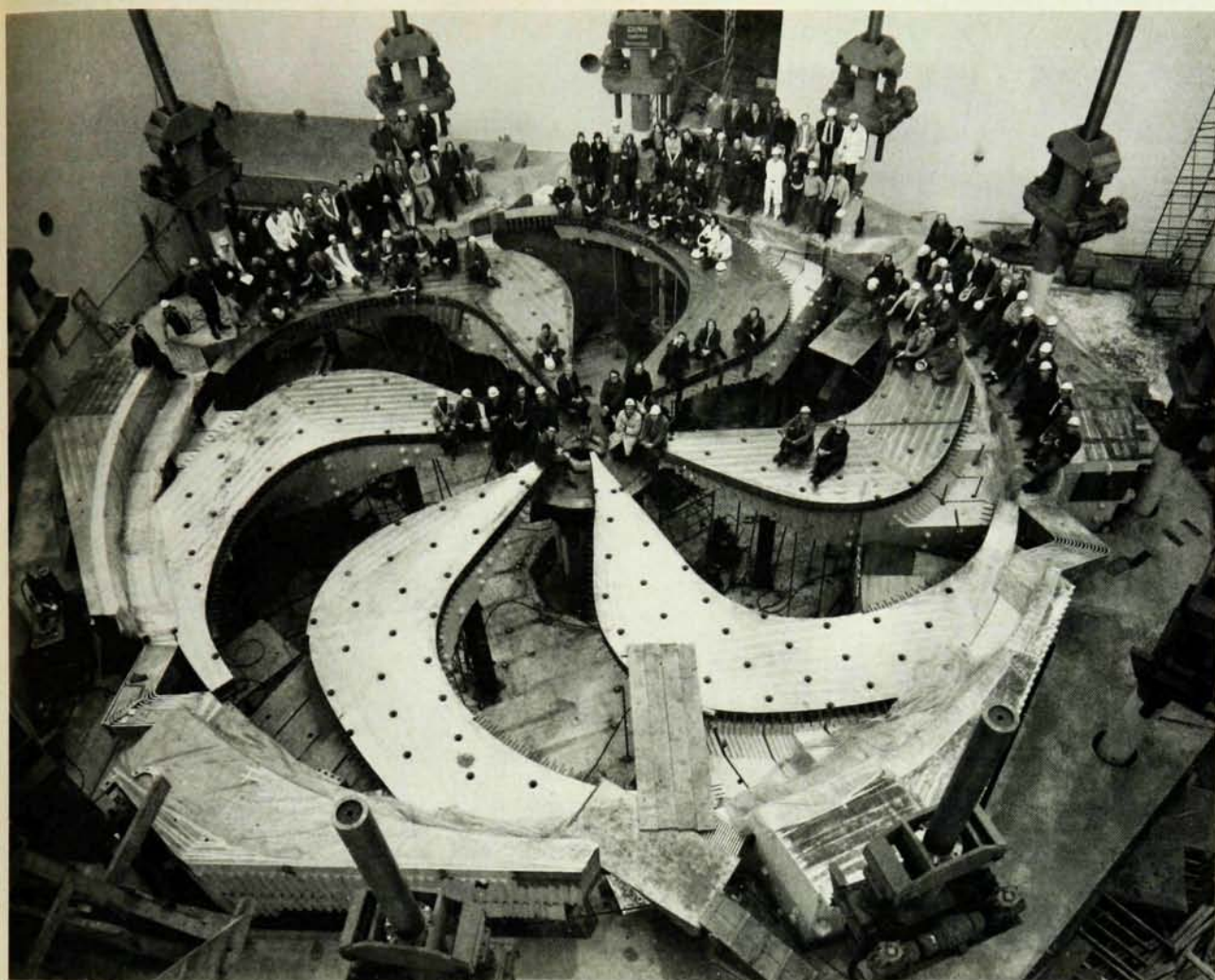
interaction and muon physics. In addition, the muon spin resonance technique for probing matter has blossomed at the meson factories (see *PHYSICS TODAY*, December 1984, page 38), and fields as diverse as medicine, biology and atomic and molecular physics have seen progress at these facilities. All the topics we discuss are related to the two themes mentioned above, which were major motivations for building the research facilities:

- The study of nuclear structure using pions as probes at medium energy
- Tests of the basic symmetry laws governing the interactions of elementary particles.

The accelerators

Intensity is the most important characteristic of the accelerators at the meson factories. The proton beams have currents of at least 100 μA . For comparison, typical beam currents for upgraded synchrocyclotrons in the 1960s were about 1 μA . Because of the high beam intensity from these accelerators, a premium is placed on high extraction efficiency and small internal beam loss. The beam lost internally causes the machine to become radioactive, endangering service personnel. A 1- μA beam loss over some extended region of the accelerator is deemed tolerable, whereas a 10- μA loss produces a serious radiation hazard. One must make careful provisions to handle targets remotely, to shield against nuclear radiation and to use magnetic transport systems to bring secondary

Darragh Nagle is a senior fellow and Mikkel Johnson is a staff member at Los Alamos National Laboratory, in Los Alamos, New Mexico. David Measday is a professor of physics at the University of British Columbia, in Vancouver, one of the institutions that operates TRIUMF, the Tri-University Meson Facility.



Spiral-ridge magnet as it looked during construction of the TRIUMF cyclotron in Vancouver, British Columbia. Protons from this accelerator produce pions upon impact with a target. Figure 1

beams through shielding.

TRIUMF. The isochronous sector-focused cyclotron at TRIUMF (figure 1) accelerates negative hydrogen ions and then strips them of both electrons by passing them through a thin foil at the outer edge of the machine. The resulting protons curve in the opposite direction in the cyclotron magnetic field and come quickly out of the machine.

The cyclotron has two main beam lines, in which one can vary the proton energy and intensity independently. Because of this, investigators have placed a strong emphasis on nucleon-induced reactions, and polarized protons are accelerated about one-third of the time. At present a Lamb-shift source delivers about 600 nA of polarized protons, as table 1 indicates, but an optically pumped source under development should give a factor-of-ten increase in intensity.

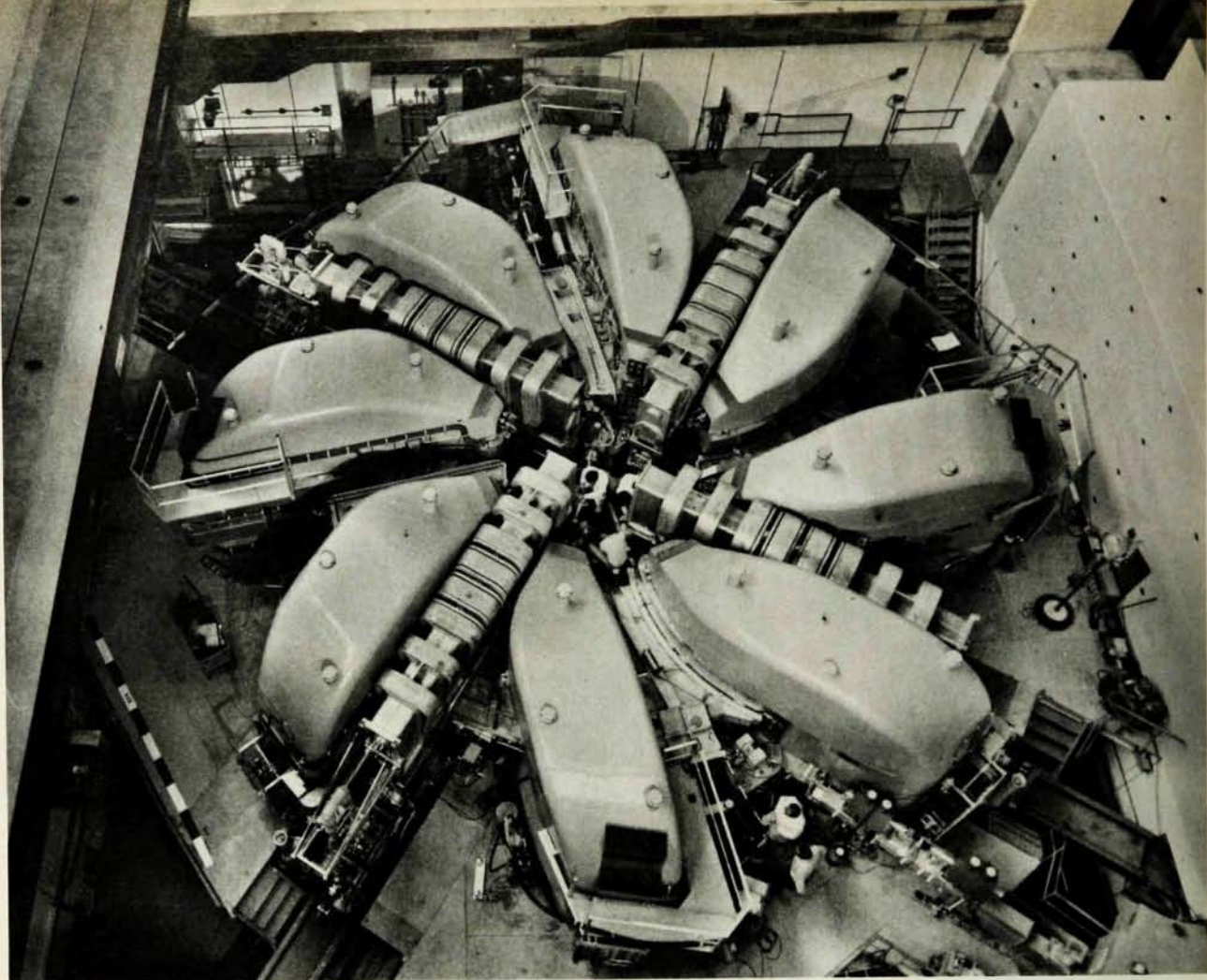
SIN. The accelerator at the meson factory at the Swiss Institute for Nu-

clear Research is a two-stage ring cyclotron. The first stage is a 72-MeV cyclotron with an azimuthally varying field. There are now two such units, which inject protons into an isochronous ring cyclotron, shown in figure 2. The rf cavities in this second-stage accelerator are separated from the narrow-gap sector magnets, unlike in standard cyclotrons, where the rf system has to be squeezed into the magnet gap. This setup reduced construction costs and is economical in power consumption.

The four high- Q cavities operate at 50 MHz and give an energy gain of about 2 MeV per orbit, leading to a clear separation of the orbits at extraction. This separation of orbits is further enhanced by two techniques: adding a third-harmonic cavity (150 MHz), which produces a flat-top voltage waveform that gives an almost monochromatic beam, and injecting the beam eccentrically into the second

cyclotron, producing a coherent radial oscillation that persists up to the electrostatic extraction septum. This system achieves extraction efficiencies on the order of 99.98%.

LAMPF. The linear accelerator for protons is an obvious candidate for meson-factory service because of its high current capability, adjustable energy, good beam quality, 100% extraction efficiency and low internal beam loss. The Alvarez linac design, based on standing electromagnetic waves in tanks containing drift tubes, had served successfully at energies as high as 68 MeV, but was limited in energy by economic and physical constraints. The principal difficulty was the low rf shunt impedance at higher energy, which resulted in poor efficiency in converting rf power to particle energy. This problem led to high capital costs and operating charges for the rf system. To go to higher energy, design groups at Yale and Harwell Laboratory



Sector-focused cyclotron at SIN, Villigen, Switzerland. Figure 2

in England planned to end the Alvarez structure at about 100 MeV and switch to a disk-loaded waveguide system operating at a higher frequency.

Eventually this design concept was realized at the Los Alamos Meson Physics Facility. The LAMPF linac, shown in figure 3, has two stages, with a harmonic transition at 100 MeV from 201.25 MHz to 805 MHz. The higher-energy portion uses the so-called side-coupled $\pi/2$ -mode structure invented at Los Alamos. This structure saves power and reduces the size and cost of the rf system. In addition, the energy propagation is an order of magnitude better than in the older disk structure, resulting in less stringent mechanical tolerances and reduced fabrication costs.

Pion scattering and the nucleus

The pion has become an important tool for investigating nuclei. Of special interest is the interplay among measured cross sections, nuclear structure and nuclear reactions. The availability

of intense pion beams of good purity, well-defined energy and small angular and spatial extent has made detailed studies possible. Thus at least one large spectrometer is now a standard accessory at each pion beam line. The energy and the charge of the incident beam can be changed easily, often without changing the experimental geometry. This makes it possible to take advantage of the intrinsic properties of the pion that make it useful for probing nuclei.

Nucleon-nucleon and pion-nucleon interactions are independent of the charges of the particles except for Coulomb and other small but less well-understood strong-interaction effects. Corresponding to this invariance is the fact that isospin is a good quantum number. The pion is an isospin triplet and the nucleon an isospin doublet. The ground state of a nucleus has a total isospin quantum number T equal to its z projection T_z , or $(N-Z)/2$, where N and Z are the numbers of neutrons and protons. As we shall see,

reactions of pions with the nucleus are a powerful method of probing the isospin character of the ground state and excited states of the nucleus.

Most notable in pion-nucleon reactions is the dominant role played at moderate pion energies (100–300 MeV) by the strong Δ_{33} resonance between pion and nucleon. This resonance is present in partial waves with an orbital angular momentum l of 1, a total angular momentum J of $3/2$ and an isospin T of $3/2$. The other partial waves are much weaker in this energy region. A striking property of scattering through the Δ_{33} resonance is the large ratio of elementary cross sections:

$$\frac{d\sigma(\pi^+p)}{d\sigma(\pi^+n)} = \frac{d\sigma(\pi^-n)}{d\sigma(\pi^-p)} = 9 \quad (1)$$

These cross section ratios allow one to enhance the sensitivity of measurements to the protons in the nucleus, or to the neutrons, by choosing positive or negative pions. Other useful properties of the pion are its relatively small size, its lack of spin and the ease with



Proton linear accelerator at LAMPF, Los Alamos, New Mexico. Figure 3

which it can be detected and distinguished from other products of nuclear reactions.

One of the prominent features of pion-nucleus scattering in the resonance region is the diffractive character of the scattering angle distributions. Relatively simple ideas of geometrical optics have explained much of the physics of pions with kinetic energies near 180 MeV, where the Δ_{33} resonance is most strongly excited. More microscopic treatments have confirmed many aspects of the simple pictures and have led to more detailed quantitative studies. These treatments include the "isobar-doorway model," which focuses on the propagation of the Δ_{33} resonance in the nucleus; the "optical model," which focuses on the propagation of the pion in the nucleus; and the distorted-wave impulse approximation to inelastic scattering.

Neutron distribution in the nucleus

Pion elastic scattering in the resonance region illustrates what we can

learn with pion probes. Figure 4 shows the small-angle portion of the cross sections¹ of pions scattered from Ca^{40} and Ca^{48} . One notices that the angular distribution for $\pi^+-\text{Ca}^{40}$ scattering is nearly the same as that for $\pi^+-\text{Ca}^{48}$ scattering. Because the π^+ scatters more strongly from protons than from neutrons, the results shown on the left side of figure 4 clearly confirm the finding from electron scattering that the density of protons is nearly the same in the two isotopes.

What about the distribution of neutrons? Neutrons are not easily studied with lepton probes, so their density in the nucleus is not well established experimentally. Because the π^- interacts more strongly with neutrons than with protons, the 2° shift in the diffraction pattern on the right side of figure 4 is a measure of the neutron distribution in Ca^{48} relative to Ca^{40} .

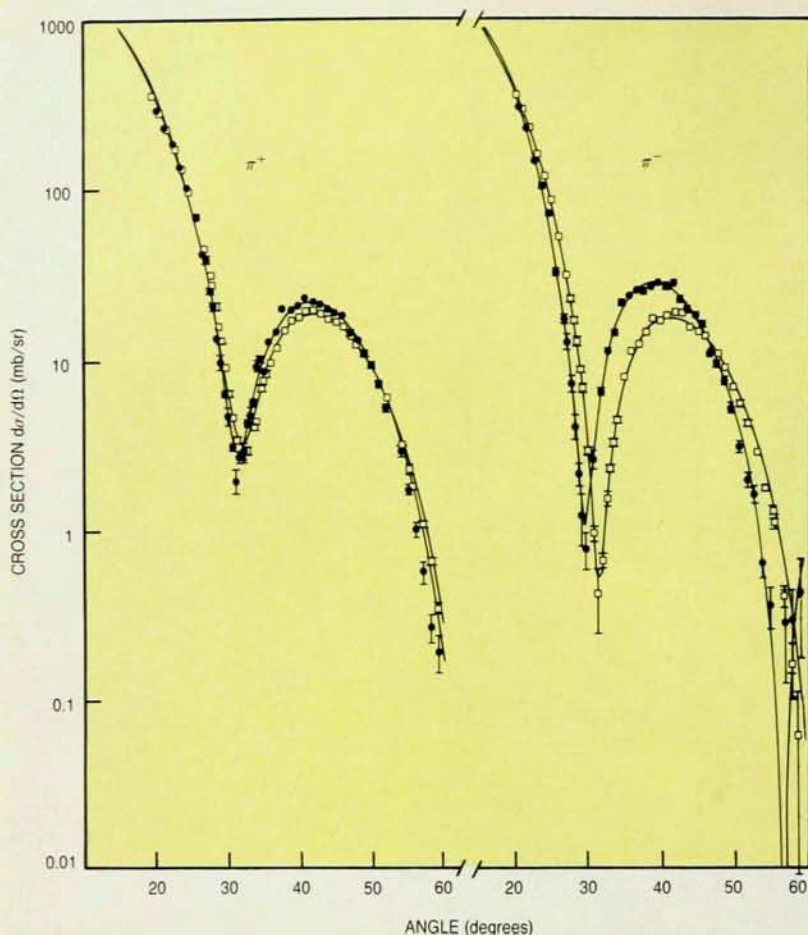
The surface of the nucleus is diffuse and is characterized in the discussion below by a quantity a , which we can think of as a measure of the thickness

of the surface. The classical eikonal theory of optics provides a quantitative link among the density of nucleons at the surface of the nucleus, the forward effective pion-nucleon scattering amplitude $f(0)$ in nuclei, and the scattering angle distribution. Considerations that parallel discussions of diffraction scattering in classical optics lead to the expression

$$d\sigma/d\Omega = (kR)^2 |J_1(qR)/q + aJ_0(qR)[C + \ln(\ln 2) + \frac{1}{2}\ln(1+y^2) - i \tan^{-1}y]|^2$$

The momentum transfer q is $2k \sin(\theta/2)$, C is Euler's constant, J_0 and J_1 are Bessel functions, R is the "black disk radius" and y is the ratio of the real part of the pion-nucleon scattering amplitude to the imaginary part. The J_1 piece is just the familiar classical circular diffraction pattern. That the J_1 Bessel function dominates is clear from figure 4, where the deep diffraction minima imply that the pion energy is very nearly on resonance, so that the ratio y is approximately zero.

We can make a precise determina-



Cross sections for the forward scattering of positive and negative pions from Ca^{40} and from Ca^{48} . Squares represent Ca^{40} data; circles, Ca^{48} . Figure 4

tion of the black disk radius R from the data by applying the condition that the angular distribution have its first minimum near the point where the quantity $J_1(q_0 R)/q_0 R$ is zero. This occurs when $q_0 R$ is 3.83. Table 2 gives the values of the momentum transfer q_0 and the black disk radius R .

The black disk radius R is determined theoretically by the condition that the probability amplitude should be $1/2$ for a pion to pass through the nucleus along a straight line trajectory at a distance R from its center. Because the radial profile of the nuclear

density $\rho_{\text{eff}}(R)$ in the surface for Ca^{48} is similar to that for Ca^{40} and falls exponentially with distance from the center of the nucleus, the amplitude can be evaluated easily,² leading to the condition that $R^{1/2} \rho_{\text{eff}}(R)$ is constant. The constant is determined by quantities such as $f(0)$ and a that are to a good approximation the same in the two isotopes. For π^- scattering the density $\rho_{\text{eff}}(R)$ is related to the neutron and proton densities ρ_n and ρ_p by

$$\rho_{\text{eff}}(R) = \frac{3}{2} \rho_n(R) + \frac{1}{2} \rho_p(R) \quad (2)$$

One finds both theoretically and em-

pirically that the black disk radius is quite large and corresponds to regions where the density has fallen to 10% of its value at the center of the nucleus.

The 3:1 amplitude weighting of neutrons and protons in equation 2 is a property of the pion-nucleon scattering amplitude through the Δ_{33} resonance in free space (see equation 1). Charge-exchange scattering indicates that this ratio is slightly higher in the nucleus. One of the challenges facing theory is to understand the origin of this effect; however, the magnitude of the correction is small enough to be ignored in the present qualitative discussion.

To determine the relative nucleons, as specified by equation 2, at the edges of the black disks in Ca^{48} and Ca^{40} , one may use the numbers in table 2 and the condition that $R^{1/2} \rho_{\text{eff}}(R)$ is constant:

$$\frac{\rho_{\text{eff}}(R^{48})}{\rho_{\text{eff}}(R^{40})} = \left(\frac{R^{40}}{R^{48}} \right)^{1/2} = 0.972 \quad (3)$$

Table 3 gives the resulting experimental value for the density of nucleons in Ca^{48} .

One can obtain theoretical values of the density $\rho_{\text{eff}}(R^{48})$ from a modern Hartree-Fock theory of nuclear ground-state densities, which is known to give a good description of the proton density of nuclei.³ Using the Ca^{40} density from this model in equation 3 leads to the experimental density given in table 3. For purposes of comparison, table 3 gives the result that a "scaled" density would give. This is obtained from equation 2 using the proton density ρ_p determined from LAMPF experiments on μ^- atoms—systems of nuclei with captured muons in atomic orbits—and using the neutron density ρ_n scaled according to

$$\rho_n = (N/Z) \rho_p$$

This equation gives the correct average behavior of the neutron distribution. The Hartree-Fock theoretical density given in table 3 for Ca^{48} is 20% larger than the scaled density because of the "neutron halo." This shift in density comes about in the Hartree-Fock theory because of the extra neutrons in Ca^{48} and because the extra neutrons are in $f_{7/2}$ orbitals, which peak in the surface but not as far out as the radius R .

Looking now at the entry in table 3 from the pion scattering experiment, it is gratifying to see a confirmation of the neutron halo, even if at only half of its theoretical contribution. Perhaps the residual differences seen with pions reflect the need for corrections to the mean-field Hartree-Fock description of nuclear densities and will motivate

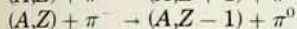
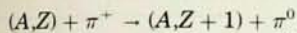
Table 1. Meson factory characteristics

	TRIUMF H ⁻ cyclotron	SIN ring cyclotron	LAMPF linac
Energy (MeV)	175-500	590	212-800
Average current (mA)	0.14	0.15	1
Beam loss in extraction region (%)	3-7	0.02	0
Duty factor (%)	100	100	10.5
Time between micropulses (nsec)	43	20	5
First-stage energy (MeV)	0.3	72	100
Polarized beam intensity (μA)	0.6	1.5	0.040

refinements in the treatment of nuclear dynamics.

Charge-exchange reactions

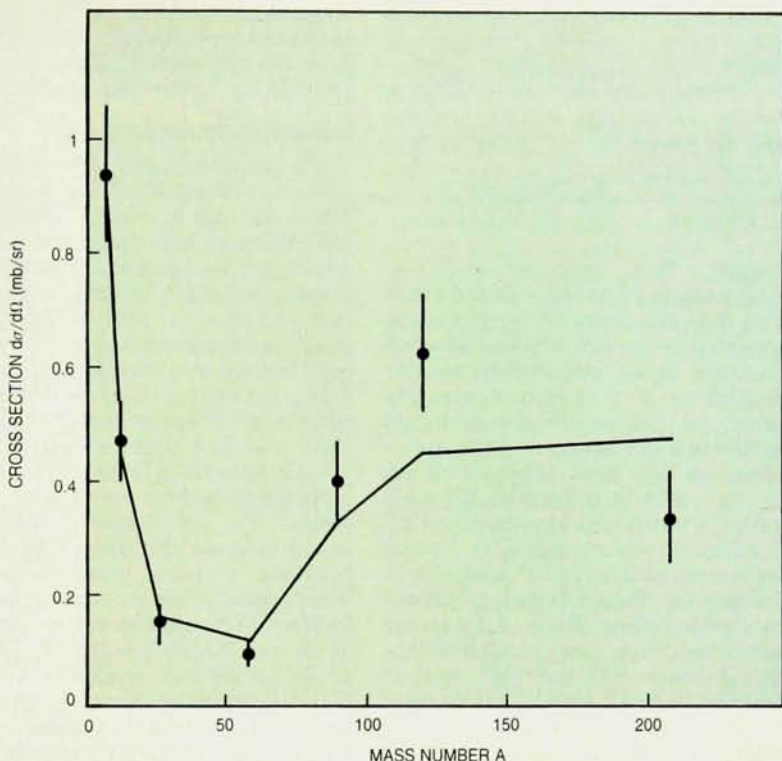
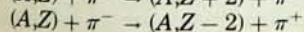
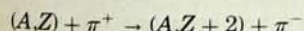
Pion single-charge-exchange reactions have been fruitful in studies of nuclear structure. These reactions have the forms



These reactions were first studied by radiochemical techniques and are now investigated using π^0 spectrometers, which determine the energy and direction of the neutral pion by measuring the energies and directions of the two π^0 decay photons. This method makes possible for the first time the identification of specific excited states in the residual nucleus and the measurement of the angular distribution of the neutral pions.

Single-charge-exchange spectra taken in the forward direction with a 98-MeV π^+ beam and with a variety of nuclei having isospins greater than zero display prominent peaks.⁴ These peaks occur at or near the energies expected for the "isobaric analog state" in the residual nucleus, which was observed earlier through the related (p,n) reaction. The isobaric analog state is a state in which one of the excess neutrons of the target nucleus of isospin T is converted to a proton in the final nucleus with no change in its space and spin quantum numbers: $T_i = T$ and $T_{z,f} = T - 1$. Thus, the pion charge-exchange reaction proceeds strongly to the isobaric analog state in all of these cases. Figure 5 shows how the forward differential cross sections depend on the mass number A . The curve in the figure comes from diffraction theory.⁵ The mass number dependence reflects changes in nuclear structure throughout the periodic table, and the agreement between theory and experiment confirms that the theory is handling this aspect of the problem correctly. The magnitudes of the cross sections are a sensitive check on the π^- -neutron scattering amplitude relative to the π^- -proton scattering amplitude in the nuclear medium. There is an increase in the 9:1 ratio of free pion-nucleon cross sections, and this is attributed to the effect of the nuclear medium on the Δ_{33} resonance.

The pion double-charge-exchange reaction was predicted years ago and has no simple equivalent for nucleon-induced reactions. This double-charge-exchange reaction has the form



Single-charge-exchange cross sections for scattering in the forward direction, as a function of mass number. The curve is a prediction of pion diffraction theory. Figure 5

Because the exchange of two units of charge requires the pion to interact with two nucleons, investigators hoped that the reaction would be sensitive to close spatial correlations of two nucleons, a topic of perennial interest to nuclear physicists. Also, the final nucleus can be quite exotic and not easily studied via other reactions. In the 1950s the Chicago cyclotron was the site of an unsuccessful search for the double-charge-exchange reaction in strontium. Robert L. Burman and his coworkers at LAMPF first observed⁶ double charge exchange in the reaction $O^{18}(\pi^+, \pi^-)Ne^{18}$ to a discrete nuclear state by inserting the O^{18} target at the midpoint of the low-energy pion channel and using the second half of the channel with the magnets reversed in field to form a spectrometer set at 0° .

After a high-resolution spectrometer at LAMPF became available, it was possible to study a variety of nuclei and to determine the energy and angular dependence of the double-charge-exchange cross section. One application of the spectrometer was to measure the mass of C^{18} with a precision of ± 0.15 MeV/ c^2 , using the $C^{12}(\pi^-, \pi^+)Be^{12}$ reaction to calibrate the spectrometer.⁷ Subsequent experiments have identified other exotic nuclei such as H^6 , He^9 and Be^{14} . Similarly, one can study the

four-nucleon system through the reactions $He^4(\pi^\pm, \pi^\mp)$. Experimenters have observed unusual final-state interactions but have found no evidence for bound states such as the postulated tetra-neutron.

Isovector giant resonances

Evidence for collective "giant" resonances in single-charge-exchange reactions is another development of great interest. Because the pion-nucleon scattering amplitude has a strong isospin dependence, pions can excite collective oscillations in which the neutrons and protons move out of phase—the so-called isovector giant resonances. The meson factories are well suited for the study of these excitations of nuclei. Giant resonances can be classified as isoscalar ($\Delta T_z = 0$), isovector ($\Delta T_z = 1$) and so on; as monopole ($\Delta L = 0$), dipole ($\Delta L = 1$) and so on; and as spin-flip ($\Delta S = 1$) or non-spin-flip ($\Delta S = 0$). Giant resonances typically have widths of a few MeV, and properties that vary smoothly with atomic mass A and atomic number Z . They can be excited in a variety of reactions. Collective excitations in which only the quantum number T_z changes are the isobaric analog states.

Giant resonances have large transition densities near the surface of the

Table 2. Results of π^- scattering

Isotope	Ca ⁴⁰	Ca ⁴⁸
First diffraction minimum θ_0	32.0°	30.2°
Momentum transfer q_0 (fm ⁻¹)	0.803	0.759
Black disk radius R (fm)	4.77	5.05

Measurements are for 180-MeV pions.

nucleus. Thus, near 165 MeV, an energy where pions are absorbed mainly in the surface, isovector resonances are enhanced in pion charge-exchange reactions. By determining the angular distribution of a resonance, one can deduce the multipole characterizing its excitation. The isovector giant dipole resonance has been observed as an isospin triplet in the nuclei K⁴⁰, Ca⁴⁰ and Sc⁴⁰, which is to say that the Ca⁴⁰ photonuclear giant dipole resonance has isospin analogs in K⁴⁰ and in Sc⁴⁰. Because the Coulomb energy breaks the charge independence of the strong interaction, there is a Coulomb energy shift between K⁴⁰ and Sc⁴⁰ that is expected to be 12 MeV. This appears clearly in figure 6 as a shift in the location of the giant dipole resonance peak. One can compare directly the reactions (π^+ , π^0) and (π^- , π^0) in a single experimental setup simply by reversing the polarity of the magnets defining the charge of the incoming pion. Such simplicity was not formally possible in comparing (p,n) and (n,p) reactions because the experimental equipment was usually quite different. However, TRIUMF recently completed a spectrometer that can switch from one reaction to the other, so useful comparisons with pion single-charge-exchange will soon be available.

Single-charge-exchange reactions were used to find the isovector monopole resonance.⁸ This is a breathing mode in which the neutron and proton densities oscillate out of phase. It is an important state because it governs the amount of isospin mixing in nuclei brought about by interactions such as the Coulomb force. This state is difficult to observe because it has a relatively high energy and a large width. The advantages of pions over other probes, and the confidence gained through the use of pions in studies of isobaric analog transitions, led experimenters to use pions to search for the isovector monopole resonance. Theory indicated that the isovector monopole resonance could be observed with pions in heavy nuclei. The resonance was first seen in Sn¹²⁰ (π^- , π^0) at a π^- energy of 165 MeV, and then in Ca⁴⁰, Ni⁶⁰, Zn⁹⁰, Ce¹⁴⁰ and Pb²⁰⁸. The experimental signature of this state and its intrinsic properties are in agreement with theory.

Experimenters have searched for the isovector quadrupole resonance in pion single-charge-exchange reactions, but have not observed it. This remains a challenging theoretical puzzle.

Nuclear excitations

The large ratios of the elementary pion-nucleon cross sections in equation 1 indicate that it might be possible to use pion-nucleus inelastic scattering to determine the separate strengths, or amplitudes, of the neutron and proton contributions to nuclear wavefunctions. Such information would provide new tests of the nuclear shell model.

It is interesting to ask in this regard whether a nucleus consisting of a closed shell plus one neutron might sometimes behave like a free neutron in pion inelastic scattering near the Δ_{33} resonance. A π^-/π^+ intensity ratio of 9 would indicate the promotion of the "valence," or extra, neutron from one outer orbital to a higher-energy orbital, leaving the isospin quantum numbers of the core largely unaffected. Carbon-13 is an obvious candidate nucleus. Figure 7 shows the excitation spectra of this nucleus obtained in inelastic scattering of 164-MeV positive and negative pions.⁹ The peak near 9.5 MeV has the desired π^-/π^+ ratio. This is interpreted as a $d_{5/2}$ neutron coupled to a core having an angular momentum J of 2 and positive parity, a 2^+ state. A state at 16 MeV in N¹⁵ shows a ratio $\sigma(\pi^-)/\sigma(\pi^+)$ of $1/9$, suggesting a transition dominated by a change in proton orbital. Most of the excited states yield intermediate values of this ratio, reflecting the fact that the structure is considerably more complex than the single-particle picture indicates.

The simple transitions in C¹³ and N¹⁵ are examples of a class of excitations for which pion scattering has supplied new and unique information. These are the excitations consisting of a nucleon excited by a pion and the hole the nucleon leaves behind, called "stretched" excitations because the angular momenta of the particle and the hole are aligned. In p-shell nuclei these are M4 transitions, for which ΔJ is 4, ΔL is 3 and ΔS is 1. Pion inelastic scattering experiments have identified M4 transitions for the first time in nuclei from B¹¹ to O¹⁶. Experimenters have seen two 6⁻ states in Si²⁸ and seven 8⁻ states in Fe⁵⁴. At the Indiana University Cyclotron Facility similar states appeared in inelastic proton scattering, and a comparison with inelastic pion scattering is proving to be very useful.

Stretched states were the first object of investigation because they were thought to be examples of simple shell-model states. The neutron and proton

Table 3. Nuclear surface densities

Isotope	Ca ⁴⁰	Ca ⁴⁸
Experiment	—	0.109
Hartree-Fock theory	0.113	0.119
Scaled	0.114	0.096

Entries represent the ratio of the density $\rho_{\text{eff}}(R)$ at the black disk radius R to the central density $\rho(0)$, which is 0.16 fm⁻³. The experimental value for Ca⁴⁸ is based on equation 3 and the theoretical value of the density ρ_{eff} for Ca⁴⁰.

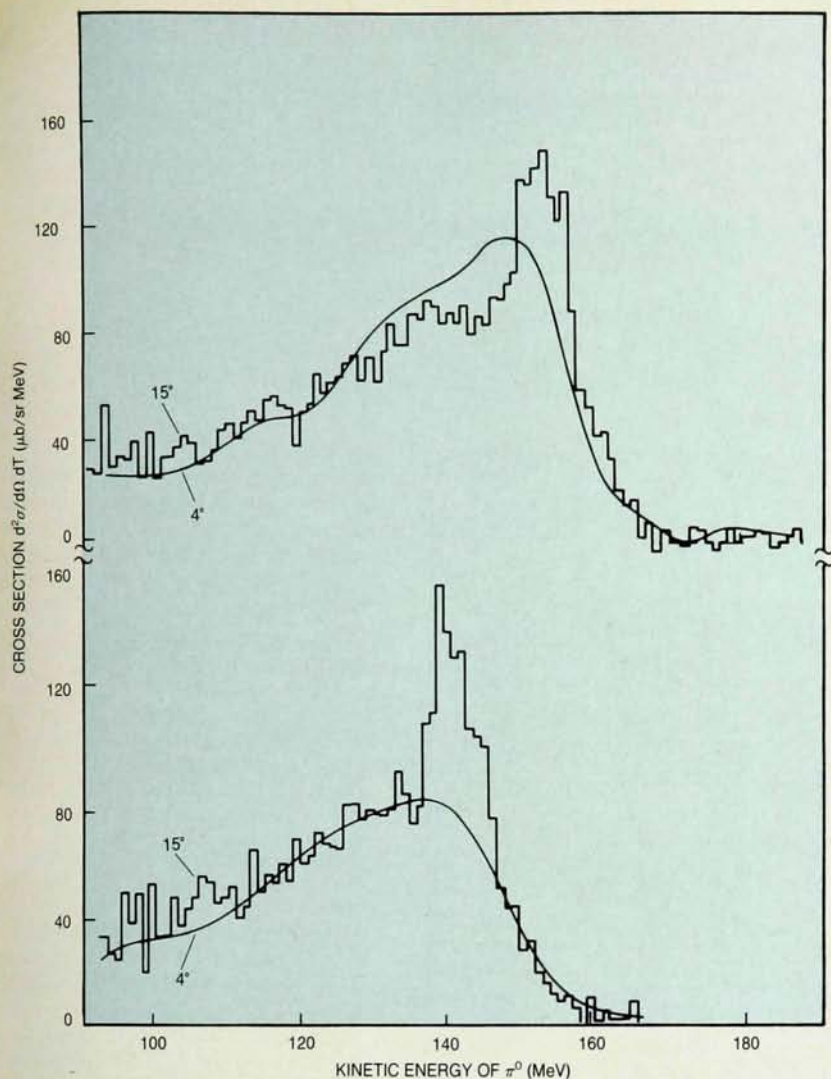
strengths were obtained by combining data from inelastic pion scattering, which selectively excites isoscalar spin-flip states, with data from 180° electron scattering, which selectively excites isovector spin-flip states. The electron scattering data corroborated the pion results and pointed to a unique solution in the data analysis. The experiments¹⁰ showed the observed isoscalar and isovector combination of neutron and proton strengths to be smaller than expected. The extent of this quenching is greater for the isoscalar state. It remains an open question whether the disagreements are due to a more complicated structure of the stretched states or to a modified interaction of pions inside nuclei.

Basic symmetries

Many important experiments at the meson factories have focused on problems associated with the various symmetries observed in nature. A symmetry implies a restriction on what events can occur, and so the most sensitive way of testing such symmetries is to search for processes that are not expected to occur. Perhaps the best known experiments are the multitudinous searches for violations of lepton conservation.

Let us first briefly review some other symmetries. There have been a few recent tests of CPT invariance, but these have uncovered nothing unusual. This symmetry, which is the combined operations of charge conjugation, space inversion and time reversal, requires the properties of a particle and its antiparticle to be the same (or to be opposite in the case of charge and magnetic moment). Experiments at the linear accelerator at Saclay, and by a College of William and Mary group working at TRIUMF, have given precision measurements on the lifetimes of positive and negative muons, finding them to be equal within one part in 10⁴. The μ^+ lifetime τ_μ , found to be 2196.95(6) nsec, is the better known and can be used to calculate the weak coupling constant G_μ , the result being $1.66365(16) \times 10^{-5}$ GeV⁻².

There has been one test of charge conjugation invariance in the electro-



Giant dipole resonance peaks in pion single-charge-exchange reactions with Ca^{40} . Top: (π^-, π^0) reaction. Bottom: (π^+, π^0) reaction. The giant dipole resonance is excited at a π^0 scattering angle of 15° but not at 4° . The shift in the energy of the peak between the π^- and π^+ reactions is mainly a Coulomb effect.

Figure 6

magnetic interaction. A group from Temple University, working at LAMPF, searched for the decay $\pi^0 \rightarrow 3\gamma$, which is not expected to occur. The γ ray has negative C-parity and the π^0 has positive C-parity because the decay $\pi^0 \rightarrow 2\gamma$ is observed, so a decay into an odd number of photons should not occur. The most recent experiment lowered the limit for the branching ratio of the 3γ decay from 1.5×10^{-6} to 3.8×10^{-7} , and there are plans for a measurement with a sensitivity two orders of magnitude better. Even if C-invariance were violated maximally, the branching ratio would be no more than 10^{-6} – 10^{-7} because of phase space limitations and the coupling of the extra photon, so the present series of experiments, difficult as they are, only begin to test this fundamental symmetry.

There have been several tests of time reversal invariance, but no unexpected effects have appeared. One type of test, for example, compares polarization in the initial and final states for neutron-proton scattering or proton-nucleus scattering.

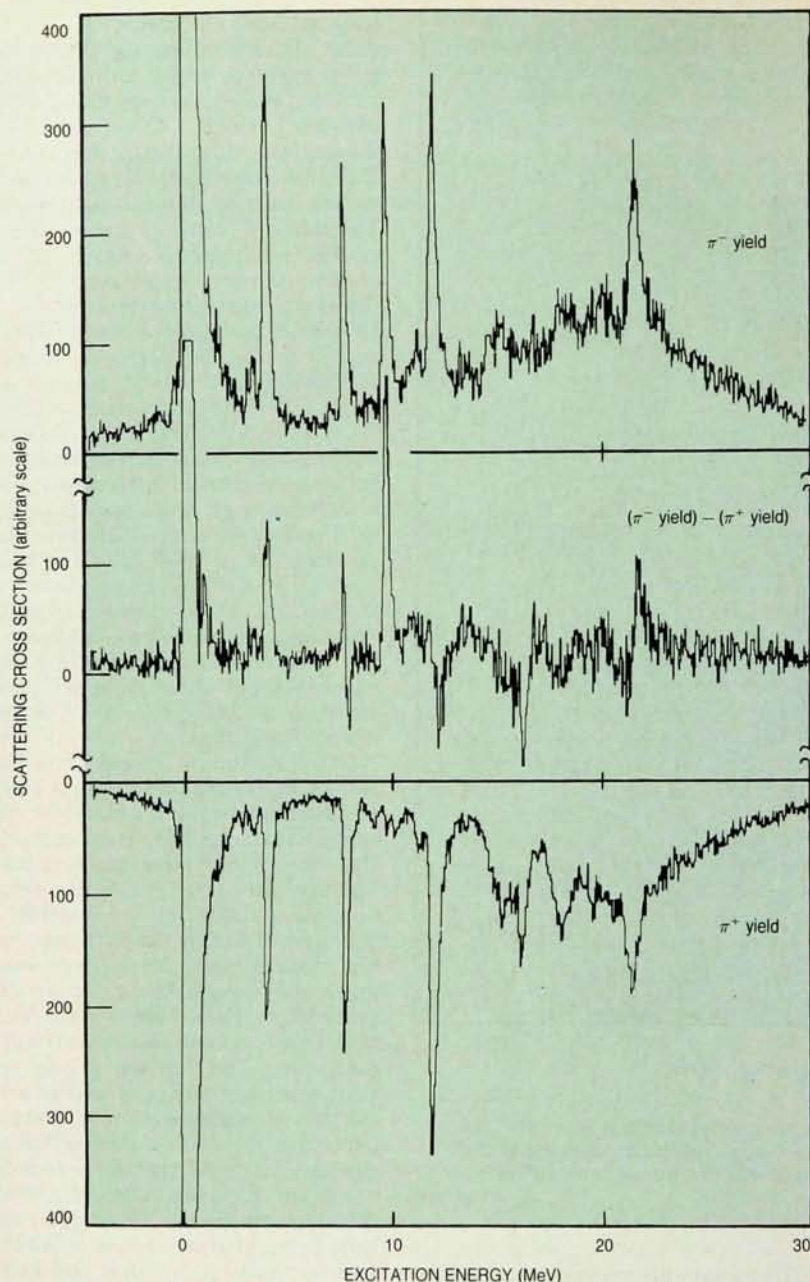
The evidence discussed above showed that there is invariance with respect to charge conjugation and to time reversal. The weak interaction, however, appears to violate parity and charge conjugation maximally, and we will discuss tests of this violation below. No CP violations have been observed in any process other than the well-established effects in K decay, and the present meson factories do not have sufficient energy to produce K beams.

Violations of parity symmetry have shown up in gamma rays from certain

nuclear isomeric states. The violations, which are usually quite small, are thought to be due to interference between the weak and strong forces between nucleons. The complexity of the nuclear wavefunction has made it difficult to quantify the degree of parity violation except for the light nuclei. The study of proton-proton scattering is therefore attractive, and a number of groups have done experiments: A collaboration between Los Alamos and the University of Illinois at Urbana-Champaign has done scattering at 15 MeV, 800 MeV and 6 GeV, and groups at SIN and at Berkeley have done work at about 50 MeV. The electromagnetic and low-energy scattering results are in fair agreement with the theory of the weak couplings that are associated with meson exchanges. However, the pp scattering at 800 MeV, in which parity violation at a level of $(2.4 \pm 1.1) \times 10^{-7}$ appeared as a longitudinal asymmetry, poses a challenge to theorists, and the scattering at 6 GeV, which showed a much larger parity violation of $(26.5 \pm 6.0) \times 10^{-7}$, is even more of a puzzle.

Other symmetry experiments have focused on isospin conservation, a symmetry of the strong interactions. This symmetry is implied by the observation that the pions, ρ mesons and other hadrons fall into multiplets whose members undergo strong interactions that are related by simple rules. Now the electric force clearly does distinguish the various charge states of a particle, so these effects have to be taken into account. Thus isospin symmetry predicts that the strong neutron-neutron interaction is identical to the strong proton-proton interaction. (Note that the neutron and proton are the only particles that have separate names for the different charge states of the same multiplet. We should really refer to the neutral nucleon N^0 and the positive nucleon N^+ , but the names came before the understanding.) For the π^+d and π^-d systems the strong interaction should also be the same.

Experimenters conducted a variety of tests to ascertain the degree to which isospin symmetry holds, and found several apparent violations. Measurements of total cross sections found differences of a percent or two in the πd systems, but these differences can all be understood in terms of known effects, especially the Coulomb force. Another possible violation of isospin symmetry had been identified in comparisons of π^-p elastic scattering with the charge-exchange reaction at energies below 100 MeV. Improved experimental techniques have cleared up these problems. A recent experiment at TRIUMF on the charge-exchange reac-



Inelastic scattering of positive and negative pions from carbon-13. The center plot is the difference between the π^- and π^+ cross sections, shown at the top and bottom. The nonzero difference illustrates that positive and negative pions distinguish between the neutron and proton compositions of nuclear transitions. Figure 7

tion $\pi^- p \rightarrow \pi^0 n$, for example, detected the photons from the π^0 decay with better energy resolution by using one of the large, high-quality sodium iodide crystals that are now available. It was particularly useful to have a good pion beam at low energies of 30–40 MeV. This was possible because pion beams are now typically made with an external proton beam; in the old synchrocyclotrons they were made by internal targets in the magnetic field of the

machine, so low-energy pions spiraled back into the machine and the lowest pion energy available, without use of degraders, was typically 60–70 MeV. Thus an improvement in technique has made possible more consistent experiments and a confirmation of isospin symmetry in the low-energy pion-proton interaction.

We trust that this brief survey of one aspect of the research at the meson factories illustrates the advances in our

understanding of this field at the intersection of nuclear and particle physics. It remains a lively area of research and we can anticipate many further developments.

We acknowledge the expert and indefatigable help of Karen Poelakker in preparing this manuscript.

References

1. K. G. Boyer, W. J. Braithwaite, W. B. Cottingham, S. J. Greene, L. E. Smith, C. F. Moore, C. L. Morris, H. A. Thiesen, G. S. Blanpied, G. R. Burleson, J. F. Davis, J. S. McCarthy, R. C. Minehart, C. A. Goulding, *Phys. Rev. C* **29**, 182 (1984).
2. M. B. Johnson, H. A. Bethe, *Comments Nucl. Part. Phys.* **8**, 75 (1978).
3. J. W. Negele, D. Vautherin, *Phys. Rev. C* **5**, 1472 (1972).
4. H. W. Baer, J. D. Bowman, M. D. Cooper, F. H. Cverna, C. M. Hoffman, M. B. Johnson, N. S. P. King, J. Piffaretti, E. R. Siciliano, J. Alster, A. Doron, S. Gilad, M. Moinester, P. R. Bevington, E. Winkelmann, *Phys. Rev. Lett.* **45**, 982 (1980).
5. M. B. Johnson, *Phys. Rev. C* **22**, 192 (1980).
6. R. L. Burman, M. P. Baker, M. D. Cooper, R. H. Heffner, D. M. Lee, R. P. Redwine, J. E. Spencer, T. Marks, D. J. Malbrough, B. M. Freedom, R. H. Holt, B. Zeidman, *Phys. Rev. C* **17**, 1774 (1978).
7. K. K. Seth, H. Nann, S. Iversen, M. Kalletka, J. Hird, H. A. Thiesen, *Phys. Rev. Lett.* **41**, 1589 (1978).
8. J. D. Bowman, H. W. Baer, R. Bolton, M. D. Cooper, F. H. Cverna, N. S. P. King, M. Leitch, H. S. Matis, A. Errell, J. Alster, A. Doron, M. A. Moinester, E. Blackmore, E. R. Siciliano, *Phys. Rev. Lett.* **50**, 1195 (1983).
9. D. Denhard, S. J. Tripp, M. A. Franey, G. S. Kyle, C. L. Morris, R. L. Boudrie, J. Piffaretti, H. A. Thiesen, *Phys. Rev. Lett.* **43**, 1091 (1979).
10. S. J. Seestrom-Morris, D. Dehnard, C. L. Morris, L. C. Bland, R. Gilman, H. T. Fortune, D. J. Millener, D. P. Saunders, P. A. Seidl, R. R. Kiziah, C. F. Moore, *Phys. Rev. C* **31**, 923 (1985). □