play only a minor role. This finding makes reaction modes (1)–(3) unlikely.

The nucleon exchange as presented in Ref. 5 would result in a different bump energy than observed here. Further experimental and theoretical investigations are needed. The problem could be investigated by looking for p and t coincidences. These will only occur for the two reaction modes: breakup followed by n pickup by the deuteron and n pickup to α^* followed by $\alpha^* \rightarrow t+p$. However, both processes are expected to be separated on the basis of the reation kinematics. In addition, measurement of d-d coincidences from breakup followed by n pickup by the proton would give definitive statement on the two-step reaction mechanism (breakup followed by pickup).

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Observation of Isobaric Analog States in Pion Single-Charge-Exchange Reactions

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Isobaric-analog-state transitions have been observed throughout the periodic table in the (π^+,π^0) reaction. The forward-angle differential cross sections at $T_\pi = 98$ MeV on targets of CH_2, ^7Li, ^{13}C, ^{27}Al, ^{58}Ni, ^{90}Zr, ^{120}Sn, and ^{208}Pb are reported. The A dependence follows $(N-Z)A^{-4/3}$, which is qualitatively understood in terms of a strong-absorption model. Optical-potential calculations which demonstrate the sensitivity to neutron density distributions and to the isospin dependence of higher-order dynamical effects are discussed.

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We report the first direct measurements of isobaric-analog-state (IAS) cross sections for (π^+, π^0) transitions on nuclei throughout the periodic table. These transitions have been measured previously in light nuclei by radiochemical techniques[1] and it has been a matter of controversy[1] whether the (π^+, π^0) reaction would selectively populate the IAS.

It is generally believed that the strong interaction respects isospin invariance with only small violations. Indeed, the discovery[2] of a narrow isobaric-state resonance in heavy nuclei was striking confirmation of isospin invariance in nuclei. The pion-nucleus optical potential, therefore, has a particularly simple representation in terms of the pionic isospin operator $\vec{t}_\pi$ and the nuclear isospin operator $\vec{T}$,

$$U = U_0 + U_1 \vec{t}_\pi \cdot \vec{T} + U_2 (\vec{t}_\pi \cdot \vec{T})^2,$$

where U_0, U_1, and U_2 are complicated functions which depend on nuclear density distributions and meson-nuclear dynamics. The term associated with U_1 is analogous to the Lane term[3] in the nucleon-nucleus optical potential. The term associated with U_2 arises from the isospin 1 of the pion and, therefore, is not present in the nucleon-nucleus optical potential. The transition under study here is driven by U_1, and the fact that we observe the IAS clearly makes possible a direct, systematic study of U_1. In lowest order, U_1 depends linearly on the difference $(\rho_n - \rho_p)$ in neutron and proton densities. Since the pion has a short mean free path in nuclear matter, the IAS cross sections are expected[4] to be sensitive to the excess neutron density in the nuclear surface. Calculations presented below demonstrate this sensitivity.

The experiment was performed with the newly developed π^0 spectrometer[5] mounted in the low-energy-pion (LEP) channel at the Clinton P. Anderson Meson Physics Facility. The spectrometer was set with its axis at 0° and the individual photon detector axes set at ±34.5° relative to the beam centerline. The target-to-first-converter distance was 1.623 m and the fiducial area for the conversion point in the first converter was 0.350 m × 0.588 m. Each photon detector used two converters, with each one consisting of 0.68 radiation length of lead glass. The γ-to-charged-particle conversion probability per converter is 0.34 ± 0.02 for 120-MeV photons.

The $\pi^- p \rightarrow \pi^0 n$ reaction was used to check the spectrometer energy scale and effective solid angle. A spectrum obtained with a CH_2 target is shown in Fig. 1. The arrow shows the expected peak position, and it is seen to be in good agreement (±0.8 MeV) with the observed peak. The π^0 kinetic energy is computed directly from the measured quantities as $T_{\pi^0} = M_0\{\sqrt{2}\,[(1-\cos\eta)(1-x^2)]^{-1/2} - 1\}$ where M_0 is the π^0 mass, η is the opening angle between the γ rays, and x is the energy-sharing parameter $(E_1 - E_2)(E_1 + E_2)^{-1}$ obtained from the photon energies E_1 and E_2.

The spectrometer solid angle was determined by a Monte Carlo calculation which incorporated the beam and target geometry and energy spreads, the photon-detector geometry, and the photon position and energy resolutions. For the detector geometry given above, the solid angle for detecting a 100-MeV π^0 with the condition $x \leq 0.2$ imposed, and with both photons converting in the first converter, is 0.187 ± 0.025 msr. The corresponding value extracted from CH_2 runs is 0.19 ± 0.04 msr. For the latter, we assumed the value

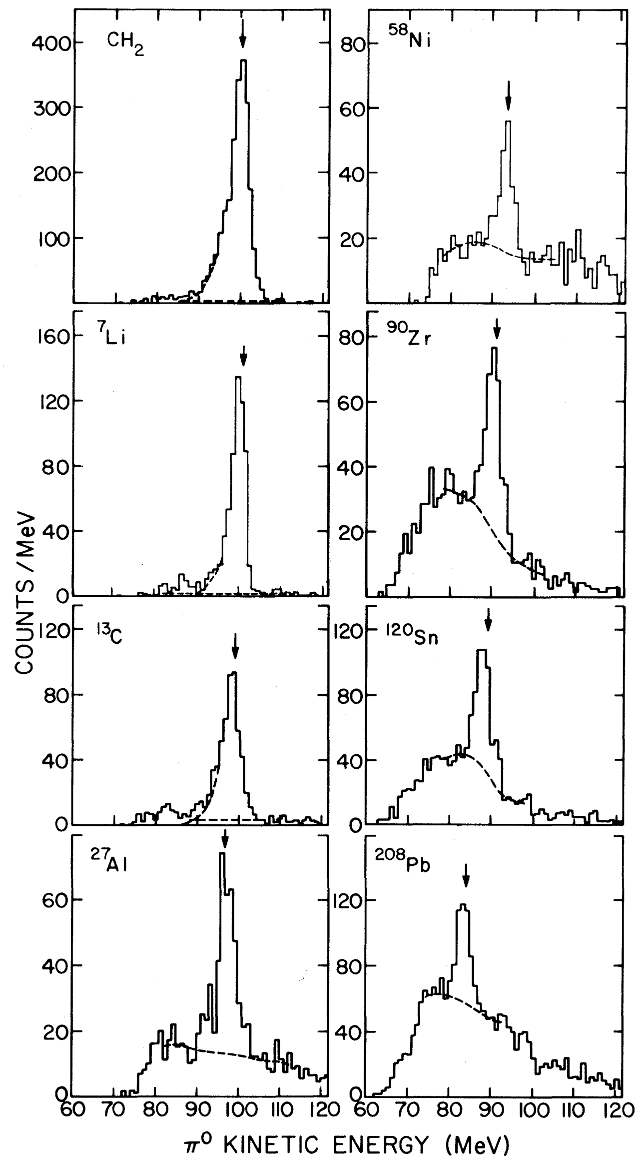

FIG. 1. Neutral-pion spectra measured for single-charge-exchange reactions at $T_\pi = 98$ MeV on targets of CH_2, ^{7}Li, ^{13}C, ^{27}Al, ^{58}Ni, ^{90}Zr, ^{120}Sn, and ^{208}Pb. The angular acceptance for each spectrum is 0° to 16°. The expected position of the isobaric analog state is shown by the arrow. The dashed lines show the assumed background shapes.

1.15 mb/sr for the $\pi^- p \rightarrow \pi^0 n$ reaction at 0° and $T_\pi = 97.5$ MeV, as given by the current energy-dependent phase-shift analysis of Dodder.[6] In view of this good agreement, also obtained for CH_2 runs at other energies, we used the calculated solid angle for the cross-section determinations.

The π flux determination was based on the measurements of ^{11}C activity induced in scintillator disks. The accuracy of this technique[7] is 7.4% for π^+ and 15% for π^- reactions at $T_\pi = 98$ MeV. The targets for the data runs had thicknesses 0.5–1.2 g/cm^2.

The measured spectra are shown in Fig. 1. The linewidths are 4–5 MeV full width at half maximum. These values are larger than our best achieved resolution of 2.5 MeV since, because of the low π^0 yield, we could not optimize beam, target, and spectrometer conditions. We identify the peak directly visible in each spectrum as the IAS of the target ground state. This identification rests on the close correspondence between the expected and observed peak position for all targets. The extraction of peak areas was subject to the uncertainty of background shape, which was estimated by using various polynomial fits and hand-drawn background lines together with line shapes determined with CH_2 targets. The combined fitting and statistical error is the dominant contribution to the relative error (column 3 of Table I) for targets with $A \geq 27$.

To obtain the 0° differential cross sections given in the table from the measured cross sections (column 2), which represent weighted averages over the angular range 0 to 16°, we assumed a $J_0^2(q\bar{R})$ angular dependence of the cross sections, as discussed below. The momentum transfer q was taken to be $\hbar|\vec{k} - \vec{k}'|$ where k is the incident π^+ wave number and k' is the outgoing π^0 wave number. The radii $\bar{R}$ used are given in the table. These were deduced from the first minima of the available elastic scattering data and checked against the optical-model calculations discussed below. The variation of the spectrometer acceptance with θ, as calculated by the Monte Carlo code and checked against runs with CH_2 targets, was represented by $f(\theta) = 0.60(0.071\theta)(1 - 0.071\theta) \times (1 - 0.023\theta)^2$ for $\theta \leq 14°$. A measured average cross section as given in column 2 of the table can be compared to any theoretical cross section by computing the average $\int (d\sigma/d\Omega) f(\theta) d\theta$ over the interval 0° to 14°.

The A dependence of the 0° differential cross sections is shown in Fig. 2. It may be qualitatively understood in terms of the analytic expression for pion IAS transitions given by the eikonal model of Johnson.[8]

$$\frac{d\sigma(q)}{d\Omega} = \frac{(ka)^2}{4\pi} \frac{\sigma_{\text{total}}}{N-Z} \left(\frac{\Delta\rho(\bar{R})}{\rho(\bar{R})}\right)^2 J_0^2(q\bar{R}),$$

where $\Delta\rho(r)$ is the valence neutron density, $\rho(r)$ is the total density, σ_{total} is the pion-nucleus total cross section, $a = \rho(\bar{R})/\rho'(\bar{R})$, $\bar{R}$ is the mean interaction radius $[\bar{R} \simeq (\sigma_{\text{total}}/2\pi)^{1/2}]$, and J_0 is a Bessel function of order 0. The conditions of the model are best satisfied close to the $\Delta(\frac{3}{2}, \frac{3}{2})$

TABLE I. The measured pion single-charge-exchange differential cross section at $T_\pi = 98$ MeV.

Target	$\langle d\sigma/d\Omega \rangle$[a] (mb/sr)	Error[b] (mb/sr)	Model-dependent extrapolation to 0° $\bar{R}$ (fm)	$d\sigma(0°)/d\Omega$[c] (mb/sr)
^{1}H	1.18	0.26		1.19 ± 0.26
^{7}Li	0.89	0.11	2.70	0.94 ± 0.19
^{13}C	0.43	0.06	3.32	0.47 ± 0.09
^{27}Al	0.13	0.03	4.23	0.15 ± 0.04
^{58}Ni	0.073	0.018	5.46	0.091 ± 0.026
^{90}Zr	0.31	0.05	5.96	0.40 ± 0.09
^{120}Sn	0.46	0.07	6.56	0.63 ± 0.14
^{208}Pb	0.22	0.05	7.88	0.34 ± 0.08

[a]Average over angular region 0°–16°.

[b]The error for ^{1}H is the absolute error. For the other targets, the relative error is given. The absolute error is given by adding in quadrature a 16% contribution from the π^+ flux and the solid-angle determination.

[c]Deduced 0° differential cross section, as discussed in text. The given errors are the absolute errors.

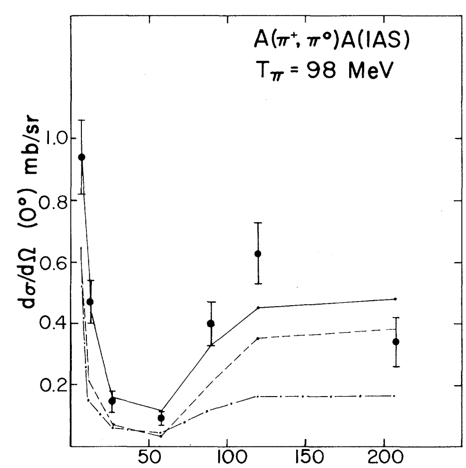

FIG. 2. The A dependence of the 0° differential cross sections for (π^+, π^0) reactions to the IAS. The error bars reflect the relative errors only. The solid line represents the function $13.4(N-Z)A^{-4/3}$ derived from the eikonal model (Ref. 8) and fitted to the data. Also shown are the results of first-order optical-model calculations with use of realistic densities (dashed line) and N/Z scaled neutron densities (dot-dashed line) with proton densities determined from electron scattering.

resonance. Since the π-nucleus interaction is already quite absorptive at 98 MeV, we apply the model here to extract the general N and A dependence. If one assumes the shape of the neutron and proton densities to be the same, i.e., $\Delta\rho/\rho = (N-Z)/A$, and that $\overline{R} \propto A^{1/3}$, the model predicts $d\sigma(0°)/d\Omega = g(N-Z)A^{-4/3}$, where g is a constant. This function, fitted to the data, is shown in Fig. 2. It is seen to describe quite well the general trend of the data.

For a more quantitative analysis we used a modified version of the optical-model program PIRK[9] to calculate the scattering amplitude in channels of good total isospin. The appropriate combinations of these amplitudes were used to calculate the charge exchange. Terms of U linear in density were determined from free pion-nucleon phase shifts. The resulting 0° differential cross sections are shown in Fig. 2. The two displayed calculations differ in the choice of ρ_n and ρ_p. We see that the calculations with realistic densities[10] are closer to the data, and are a factor of approximately 2 larger than the $\rho_n = (N/Z)\rho_p$ result. The reason for this is that $\Delta\rho(\overline{R})/\rho(\overline{R}) > (N-Z)/A$ for realistic densities. No ρ^2 terms were used for these calculations.

Discrepancies similar in magnitude to those found in ^{13}C remain between the data and lowest-order calculations.[1,11] Because of the strong sensitivity of charge exchange to $\Delta\rho/\rho$ one may suspect that the nuclear model is at fault. This is given some support in light nuclei,[12] where transition densities from large shell-model calculations tend to increase the charge-exchange cross sections uniformly by 30%. To study the dependence on the nuclear model for ^{120}Sn, we used empirical valence neutron occupation probabilities to redistribute particles in the Hartree-Fock orbitals. Little effect was observed. Although the contributions to the density of the individual orbits are altered by as much as 30% in the surface region, the net valence density remains nearly unchanged.

Higher-order terms may also contribute to the discrepancy.[4] These terms have received considerable attention lately, but little is known about their isospin dependence. We have been able to obtain a uniform upward shift of the cross sections by about a factor of 2 by adding isoscalar and isovector "ρ^2" terms which produce a 20% change in the magnitudes of the real and imaginary parts of U_0 and U_1 at the center of the nucleus. The cross section is approximately equally sensitive to the isoscalar and isovector "ρ^2" terms, and we could not determine them uniquely in the absence of better-quality elastic angular distributions. The ρ^2 piece of U_0 sensitively affects the charge-exchange amplitude through a second-order process in which one scattering occurs through the linear piece of U_1 and the other through the ρ^2 piece of U_0. The "ρ^2" terms of U_2 are relatively ineffective for single charge exchange.

In conclusion, we have observed the IAS for the first time in pion single-charge-exchange reactions on nuclei throughout the periodic table. These data are essential, together with corresponding elastic and double-charge-exchange scattering, in obtaining a unique characterization of the π-nucleus optical potential. Once U is better understood, there is the possibility of exploiting the great sensitivity to $\Delta\rho/\rho$ in single-charge-exchange scattering to determine neutron densities at the nuclear surface.

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Observation of Non-Lorentzian Spectral Line Shapes in Na–Noble-Gas Systems

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This Letter reports observations showing that the spectral line shape in the core region of collision-broadened lines contains a dispersion component in addition to the usual Lorentzian. The physical origin of this component is the finite *duration* of the collisions. For the Na D lines and Xe perturbers, the dispersion component produces an 8% asymmetry 0.1 Å from line center. Calculations based on recent line-broadening theories predict a dispersion component with an amplitude comparable to our experimental results.

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Weisskopf[1] showed that if radiating atoms were subject to collisions which destroy phase coherence then their emission profile would have a purely Lorentzian shape—the shape expected for quenching collisions.[2] Lindholm[3] and Foley[4] showed that this shape was also to be expected —although possibly displaced from the frequency of the unperturbed radiators—if the collisions only changed the phase by small amounts. Recently both Szudy and Baylis[5] and Kielkopf[6] have shown that the finite duration, T_d, of the collision modifies the Lorentzian line shape, the first correction being the addition of a dispersion component to the line shape. We report here a definitive experimental observation of this component[7]; it is in reasonable accord with the theory.

Our experiment determines the line shape in the near-wing region of the line. This is the region where the detuning from resonance Δ is less than the inverse of the collision duration T_d, but several times greater than the Doppler width $\Delta\omega_D$, so that negligibly few atoms interact resonantly. In this region the line shape is

$$I(\Delta)=\frac{1}{\pi}\frac{\gamma(\Delta)}{\Delta^2+\gamma^2}\left[1+\frac{3}{2}\frac{\Delta\omega_D^2}{\Delta^2}+\frac{2\delta_c}{\Delta}+\dots\right], \qquad (1)$$

where $\gamma(\Delta)$ is the amplitude, and the terms in brackets indicate the lowest-order corrections due to the Doppler width $\Delta\omega_D$ (half width at e^{-1} points), and the pressure shift δ_c. A purely Lorentzian line shape would be represented in the near-wing region by Eq. (1) with $\gamma(\Delta)$ constant; we find that $\gamma(\Delta)$ has a term linear in Δ, indicating that the line shape contains a dispersive component.

We have measured the line shape in the near-wing region of the Na D_1 and D_2 lines broadened by collisions with He, Ne, Ar, Kr, and Xe. The line shape is determined by monitoring light scattered out of a monochromatic laser beam versus laser frequency. The laser was a Coherent Radiation Model-599 single-mode cw dye laser with actively stabilized linewidth (±1 MHz) and output power (±0.5%). Light scattered at 90° from the incident laser direction was collected with $f/7$ optics, passed through a 100-Å-wide interference filter centered at 5900 Å, and imaged onto a photomultiplier used in photon counting mode. The incident laser was linearly polarized in the vertical direction, and the collection optics arm contained a linear polarizer rotated 54.7° from the vertical [where $P_2(\cos\theta)=0$], so that the collection optics system was insensitive to variations in the angular distribution of scattered light with laser frequency.[8,9] Frequency detunings were determined relative to the Lamb dip in a reference cell with 20 MHz error.

The target cell contained Na vapor at 390 K and

