even for such unreasonably large values of a as 0.3, although the back-angle excitation function does become strongly structured.

In summary, resonancelike structure is observed in the excitation function of the reaction $^{24}Mg(^{18}O, ^{14}C)^{28}Si$, where resonant behavior in the entrance and exit channels is not expected. While the angular distributions are well described by direct-reaction calculations, the resonant structure cannot be reproduced by such calculations at present. The relationship with the resonances in the reaction $^{24}Mg(^{16}O, ^{12}C)$ as well as the origin of the structure in both reactions remain unexplained.

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Energy Dependence of Pion Production by Protons on Nuclei

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The reactions $^{10}B(p,\pi^+)^{11}B$(g.s.) and $^{40}Ca(p,\pi^+)^{41}Ca$(g.s.) have been studied with proton beams in the energy range 140 to 200 MeV. Angular distributions at several energies, supplemented with fixed-angle cross-section data at several other energies, establish for the first time the energy dependence of these reactions in the near-threshold region.

The proton-induced pion production reaction, leaving a nucleus in a discrete final state, is known to exhibit distinct variations in character for different targets and residual nuclear states. If the production process can be sufficiently well understood, the reaction might constitute a useful spectroscopic tool for investigation of the high-momentum components of nuclear wave functions. The momentum transfer to the nucleus in this reaction is 2 or 3 times larger than the nuclear Fermi momentum. The reaction also may provide interesting new information about the production and propagation of pions in strong nuclear fields.

The experiments of Dahlgren *et al.*[1] and Höistad, Johansson, and Jonsson,[2] in particular, and more recent investigations[3-6] have stimulated a significant theoretical effort[7-14] to unravel the basic features of the production process. None of the interpretations so far can be regarded as entirely satisfactory because interrelated questions regarding the reaction mechanism, pion rescattering, and nuclear structure have so far allowed too much theoretical freedom with respect to the limited experimental data available.

The present work was motivated by the expectation that a thorough investigation of the energy dependence of the cross sections for a few final states as the threshold energy is approached would be of substantial benefit in determining a proper description for the production process. The energy dependence of the (p,π^+) reaction as a means of understanding the production process has in fact been the subject of several recent theoretical papers.[8,11,12,15] Brockman and Dillig[11] have argued that near-threshold measurements may be particularly useful in separating the contributions of one- and two-nucleon mechanisms and in testing various approximations.

The variable-energy proton beam at Indiana University Cyclotron Facility is singularly well suited to a detailed investigation of the energy dependence of the (p,π^+) reaction. The data we present overlap several earlier measurements but extend much closer to threshold, changing significantly the experimental picture of the energy dependence.

We have measured the $^{10}B(p,\pi^+)^{11}B$(g.s.) and $^{40}Ca(p,\pi^+)^{41}Ca$(g.s.) differential cross sections with two different magnetic spectrometers. The larger quadrupole-dipole-dipole-multipole (QDDM) instrument,[6] used here for the pion energy region above 9 MeV, is in routine use for precise proton elastic scattering studies, which confirm the solid angle and beam charge collection, giving total systematic uncertainties in the range (5–15)% for the absolute cross sections in the present pion measurements. The smaller instrument, used for pion energies below 13 MeV, consists of two opposing dipoles ($D\overline{D}$). It has a 3.5-msr solid angle, 77-cm flight path, and a mixed scintillator and silicon detector telescope at the nondispersed focal point. The $D\overline{D}$ was developed especially for (p,π^+) measurements and is described in detail elsewhere.[16] Systematic errors in the absolute cross sections measured with this instrument are believed to be less than 20%. Pions of energies between 9 and 13 MeV can be measured with both instruments and the overlapping data are in good agreement. This argues strongly for a correct absolute scale for data from either device.

Differential cross sections for the reaction $^{10}B(p,\pi^+)^{11}B$(g.s.) at seven proton energies are shown in Fig. 1 plotted against momentum transfer q. The proton energies are given at the target center. The figure shows that to a first approximation the shape is exponential with q below 540 MeV/c, and that while the yield at the smaller angles increases markedly with bombarding energy, the slope of the exponential changes only slightly over this substantial range of energies. Two of the distributions ($T_p = 153.8$ and 160.1 MeV) extend forward to 0° and offer little experimental evidence for a forward minimum due to the $|\vec{k}_\pi - \lambda(m_\pi/m_p)\vec{k}_p|^2$ factor, which comes from the nonrelativistic reduction of the pion production operator and appears as a multiplicative factor in the expression for the differential cross section given by the one-nucleon model (ONM) in the plane-wave approximation.[8,11]

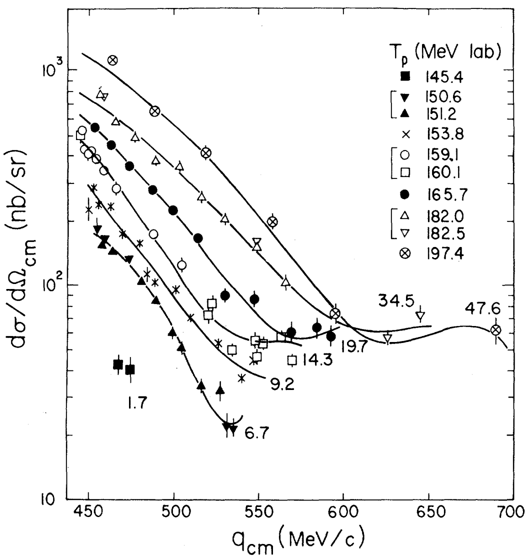

FIG. 1. The $^{10}B(p,\pi^+)^{11}B$(g.s.) differential cross sections at seven energies plotted as a function of momentum transfer. The curves are best fits to the data using a minimization of χ^2 with Legendre polynomials up to P_3. Each curve is labeled with the corresponding pion center-of-mass energy.

The energy dependence of the exponential portion of the boron angular distribution can be parametrized by a normalization factor (differential cross section at a fixed q) and a slope factor. For a fixed forward angle the reaction kinematics shows q changing only slowly with beam energy, so that the differential cross-section data at fixed laboratory angle are representative of the energy variation of this normalization factor. Figure 2(a) shows twelve $\theta_\pi(\text{lab}) = 25°$ measurements of the $^{10}B(p,\pi^+)^{11}B$(g.s.) cross section plotted against the pion center-of-mass momentum η_π (in units of $m_\pi c$). The range of pion energies in the center of mass extends from 1.7 to 47.6 MeV. Data points from Höistad[17] and Le Bornec *et al.*[3] are shown for comparison. Although the cross sections measured with the $D\overline{D}$ and QDDM spectrographs using quite different detectors agree well within the systematic measurement errors at $\eta_\pi(\text{c.m.}) = 0.37$, they are larger than those measured by Höistad[17] and Le Bornec *et al.*[3] by factors of 1.7 ± 0.6 and 5 ± 1.7, respectively.

Phase-space, Coulomb, and angular-momen-

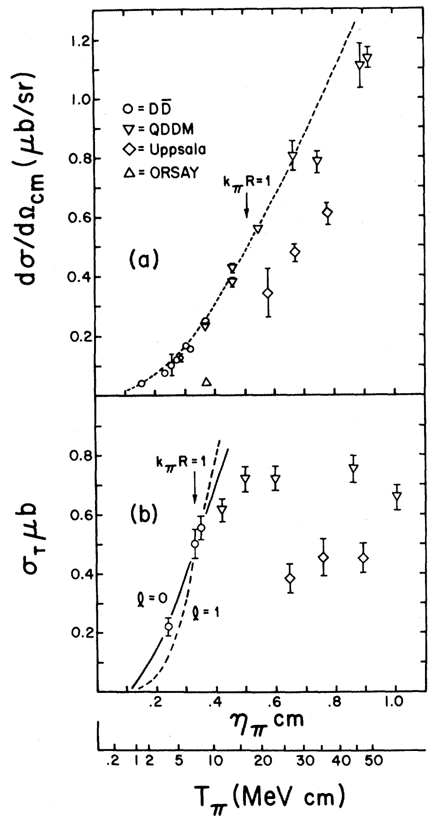

FIG. 2. (a) The dependence of the $^{10}B(p,\pi^+)^{11}B$(g.s.) differential cross section at θ_π(lab) = 25° on pion center-of-mass momentum (in units of $m_\pi c$). Where not shown, the error bars are smaller than the data points. (b) The dependence of the $^{40}Ca(p,\pi^+)^{41}Ca$(g.s.) total cross section on pion center-of-mass momentum. The curves are explained in the text.

tum–barrier factors appear to dominate the energy variation of the reaction $^{10}B(p,\pi^+)^{11}B$(g.s.) below 200 MeV. To illustrate this behavior, we construct a test for additional variation by noting that in its absence a simple connection may be established between the threshold energy dependence and the shapes of the angular distributions. If s-, p-, and d-wave pions are emitted, the $\cos\theta$ term, for example, in a fit to the cross section will have contributions from s-p and p-d interference with different energy dependences. Measurements at two energies suffice to determine both unknown constants A and B in the form $A(p_0p_1)^{1/2}+B(p_1p_2)^{1/2}$, where the combined phase-space–exterior penetrability factors $p_l=(k_\pi/k_p)\times\{F_l^2+G_l^2\}^{-1}$ (with the Coulomb wave functions F_l, G_l evaluated at $R=1.25A$ fm) contain all of the energy variation. The curve in Fig. 2(a) was generated from similar terms up to $\cos^3\theta$ by fits to data at $T_p=154$ and 166 MeV. The figure shows that reasonable agreement is obtained with all of the data up to $k_\pi R\sim 1$. The highest energies may begin to show a decrease of a few percent in the production amplitude.

Differential cross sections for the reaction $^{40}Ca(p,\pi^+)^{41}Ca$(g.s.) at seven bombarding energies are shown in Fig. 3. The 182.5-MeV curve is the 185-MeV angular distribution of Dahlgren *et al.*[1,17] normalized to our four data points. The 154-MeV data of Le Bornec *et al.*[4] [multiplied by a factor of 2.2 to normalize to our θ_π(lab) = 25° point] were used to determine the shape of the 153-MeV curve at forward angles.

The $^{40}Ca(p,\pi^+)^{41}Ca$(g.s.) angular distributions exhibit a well-defined and systematic variation in shape with changing bombarding energy which is in sharp contrast to the behavior of the reaction $^{10}B(p,\pi^+)^{11}B$(g.s.). The deep minimum seen near 60° at 185-MeV bombarding energy[1] becomes deeper (ratio $\sigma_{90°}/\sigma_{min}$ approached 100:1 at T_π = 7.6 MeV) and moves toward forward angles as the energy is lowered toward threshold. The yield at 90° stays nearly constant until T_π(c.m.) is below 10 MeV. The momentum transfer q at the forward minimum varies linearly with p_π according to $dq/dp_\pi = 0.82\pm 0.09$ over a range including the 148-, 153-, 160-MeV energies shown here and the three higher energies quoted in Ref. 17. The energy dependence of the depth and position of the first minimum was not reproduced in the distorted-wave Born-approximation calculations of Höistad.[17] Some features of the data were reproduced in similar calculations by Tsangarides, Wills, and Bent.[18] Calculations of this type are extremely sensitive to details of the pion-nucleus optical potential.

The motion of the minimum in these data can confuse the interpretation[8,12] of the energy dependence of forward-angle cross sections for this nucleus. The total cross sections obtained by integration of the differential cross sections are shown plotted against pion momentum in Fig. 2(b). The measurements of Höistad[17] are shown for comparison. For this case, in contrast with Fig. 2(a), Coulomb penetrability arguments can explain the energy variation only for the lowest energy points. The penetrability factors p_0 and p_1 defined above are plotted in Fig. 2(a) normalized to the data at $\eta_\pi = 0.35$. The yield is seen to be falling well below these curves beginning at about $k_\pi R = 1$.

In summary, we have established the near-threshold energy dependence of the reactions

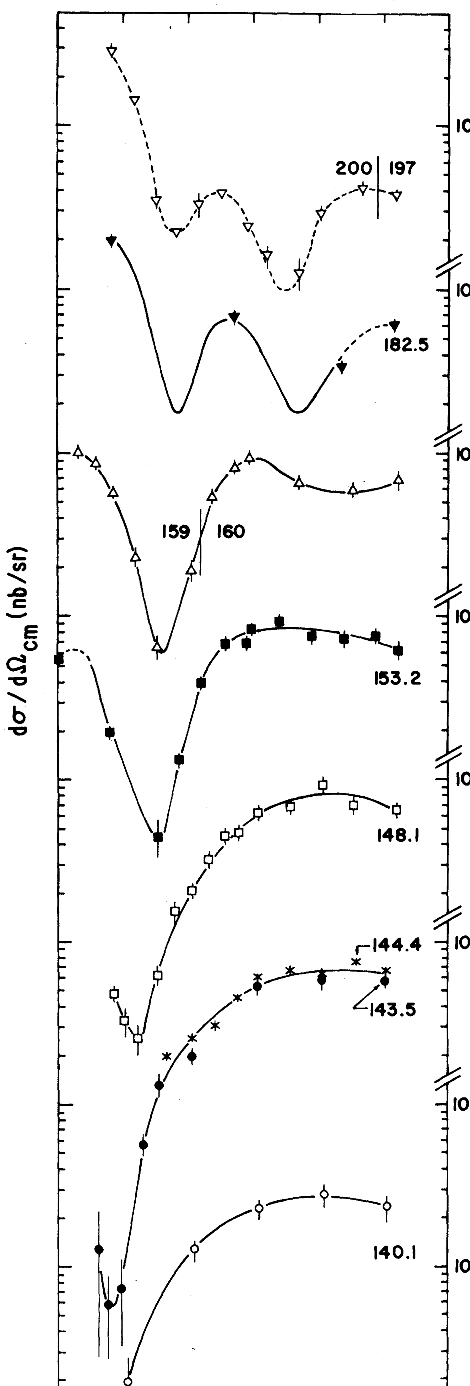

FIG. 3. The $^{40}Ca(p,\pi^+)^{41}Ca$(g.s.) differential cross sections at seven energies. Note the motion of the minimum toward forward angles as the energy approaches threshold and the near constancy of the 90° yield except at the lowest and highest energies. Smooth curves have been drawn through the data points to guide the eye.

$^{10}B(p,\pi^+)^{11}B$(g.s.) and $^{40}Ca(p,\pi^+)^{41}Ca$(g.s.) as well as the correct normalization for these cross sections, by the use of two independent measurement techniques that agree in the region of overlap. Our angular distribution measurements, which extend into the near-threshold region where the pion Coulomb penetrability might be expected to dominate, demonstrate a very different energy dependence for ^{10}B and ^{40}Ca targets. The measurements cover a sufficiently wide energy range to offer a stringent test for the numerous theoretical explanations of the (p,π^+) reaction. Detailed calculations based on various reaction models will be required to determine the extent to which the new data can clarify our understanding of the production process.

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True Absorption and Scattering of 125-MeV Pions on Nuclei

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The cross section for absorption of 125-MeV positive and negative pions in Li, C, Al, Fe, Nb, and Bi was measured. The results were obtained by combining a transmission experiment, a measurement of the angular distribution for pion scattering, and an estimate of the charge-exchange cross section. Information about inelastic scattering and decomposition of the total pion-nucleus cross section into its contributions from the major channels is also obtained.

Pion-nucleus reactions have been widely investigated in recent years. Yet very little is known about the process of true pion absorption in flight, one of the special features of the pion as a nuclear probe, where there are no pions in the final state. Also, since pion absorption is a large part of the reaction cross section, it affects strongly all other reaction channels and the elastic-scattering process. The available experimental information from direct measurements of the cross section for pion absorption in flight is limited to positive-pion absorption in the deuteron[1] and in carbon at 130 MeV.[2] Some early measurements in emulsions and cloud chambers were also done.[3] There is no information about the dependence of the absorption cross section on the energy and charge of the incident pion and the atomic number of the target.

In this work we present the results of experiments in which the cross sections for positive- and negative-pion absorption in nuclei were measured. These cross sections were obtained by combining the results of two separate experiments. Both experiments were carried out at the $\pi M3$ channel of the Schweizerisches Institut für Nuklearforschung accelerator at a bombarding energy of 125 MeV. The targets studied were Li, C, Al, Fe, Nb, Bi, and CH_2.

The first experiment was done using a standard transmission technique of the kind used for measurements of total cross sections. The pion beam hit the target after passing through two plastic scintillators used to monitor the beam flux. Protons present in the beam were eliminated by degraders positioned inside the beam transport channel. Muon and electron contaminations in the beam were measured by time of flight. Five plastic scintillation counters of disk shape were positioned on the beam axis behind the target position. The counters covered the solid-angle range of 0.1–0.7 sr and by changing the distance from the target, the measurements were taken at nine different solid angles for Li, C, Al, and Fe and thirteen for Nb and Bi. The disk counter which is

