Measurements of the (π^+, π^0) Reaction on Light Elements in the (3, 3)-Resonance Region*

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The cross sections for the reaction (π^+, π^0) on ^{7}Li, ^{10}B, and ^{13}C were measured over the energy range of 70 to 250 MeV by activation methods. The excitation functions were found to be flat with cross sections of about 2.5 mb for ^{7}Li, 0.4 mb for ^{10}B, and 1.0 mb for ^{13}C.

Few measurements of the pion single-charge-exchange reaction have been performed to date.[1-2] The experimental situation is summarized in Ref. 2. There is considerable theoretical interest in this reaction. While the plane-wave impulse approximation[3-5] for the (π^+, π^0) analog transition gives an excitation curve with a *maximum* near the energy of the (3, 3) resonance, multiple-scattering or distorted-wave calculations[7-12] which do include absorption give a *minimum* in the same energy region. The situation on pion single-charge exchange was thus confused[2]: There were opposing predictions for the excitation function, and the few data which existed agreed, if at all, with the less believable plane-wave calculations. Moreover, the dominance of the analog-state transition was questionable.

In this paper we report the measurement of the excitation function for the (π^+, π^0) reaction on ^{7}Li, ^{10}B, and ^{13}C inthe region of the (3, 3) resonance. We used the low-energy-pion channel at LAMPF, and obtained $(1-3)\times 10^7$ pions/sec on target with a momentum spread of $\pm 2\%$, and a beam spot of about 2×3 cm^2. We bombarded samples of isotopically enriched ^{10}B (99%) and ^{13}C (98%) and natural Li with positive pions ranging in energy from 70 to 250 MeV. For ^{13}C the beam intensity was measured by simultaneous bombardment of a ^{12}C sample followed by a measurement of the residual ^{11}C activity. [The cross section for the reaction ^{12}C$(\pi^+, \pi N)$ ^{11}C has recently been measured with high accuracy[13]]. We used the same runs to calibrate an argon-gas ionization chamber, which was then used as a beam monitor for the other reactions. In addition to pions the beam included muons, positrons, and protons. The contribution for the measured cross section from positrons and muons is expected to be negligible, and this expectation was confirmed for the range of 30–90 MeV.[2] Protons were deflected from the beam by a differential absorption method. Secondary protons, which were produced in the target, contribute to our measured cross section. We therefore estimated this contribution, using proton-production data,[14] energy-loss tables, and (p, n)-reaction cross sections,[15] and integrating over the actual target volume. This contribution was found to be about 20% for ^{7}Li, 10% for ^{13}C, and negligible for ^{10}B. These amounts were subtracted from the measured cross sections at all energies. (The uncertainty of the cal-effect might be twice as big.) A more exact subtraction will be possible when higher pion-beam intensities, which will make it possible to use thinner targets, become available.

The Li samples were disks of thicknesses ranging from 0.5 to 2 g/cm^2 and 5 cm in diameter. The ^{7}Be activity in the Li target was measured in a shielded 65-cm^3 Ge(Li) detector. The long half-life of ^{7}Be (53.28 days) enabled us to carry out the counting in a low-background area at sea level, far from the accelerator, each measurement lasting a few days. We counted the 478-keV γ rays resulting from a 10.4% branch of the ^{7}Be decay.[16] In this way we measured the sum of the reaction cross sections to the analog of the target ground state and to the first excited states. The detection efficiency, including the absorption in the target, was measured with standard sources.

The ^{10}B samples were of powder, 3 cm in diameter and 2 g/cm^2 thick, pressed into thin aluminum cans. An Al sample did not show any activity of the kind detected from ^{10}B. The ^{10}C nucleus from the reaction ^{10}B$(\pi^+, \pi^0)^{10}$C has two bound states, neither of which is an analog of ^{10}B. It has a half-life of 19.4 sec and decays[16] through the 717-keV state in ^{10}B. Two ^{10}B targets were mounted on the two ends of a physical pendulum and swung between the beam and a 65-cm^3 shielded Ge(Li) detector. This was done automatically once every 30 sec. The efficiency of the detector was measured with standard sources. Figure 1 shows γ spectra from irradiated ^{7}Li and ^{10}B targets.

The ^{13}C target consisted of powder 3.2 cm in diameter and 0.72 g/cm^2 thick, pressed into a thin beryllium can. No activity was found from a Be sample alone. The nucleus ^{13}N has only one bound state, which is the analog of the ground state of ^{13}C, so activity measurements yield the charge-exchange cross section just for the analog transition. The residual nucleus ^{13}N decays

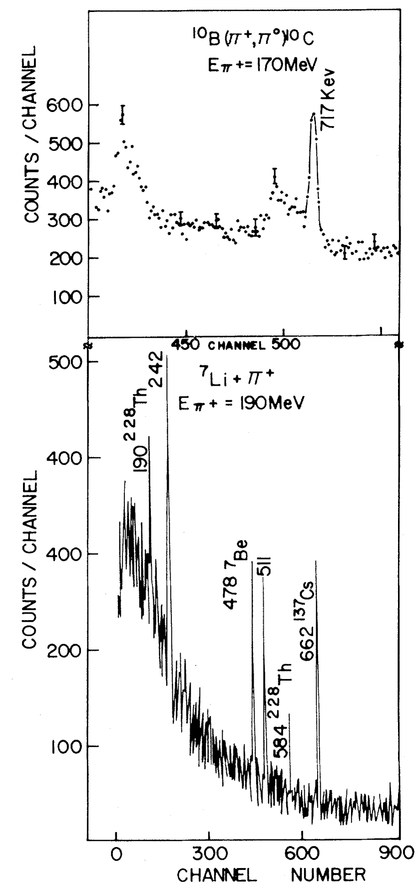

FIG. 1. γ spectra from targets of ^{7}Li and ^{10}B. The γ radioactivity from the ^{7}Li target was counted for 30 h, 120 days after the irradiation; the 478-keV line comes from the ^{7}Be activity. The radioactivity from the ^{10}B target was counted while the target was mounted on a physical pendulum. The 717-keV line comes from ^{10}C activity.

to ^{13}C with a half-life of 10 min. The β^+ activity was measured by detecting the annihilation γ rays in coincidence, with two NaI(Tl) detectors. The absolute efficiency of the system was measured with a plastic scintillator of the same size as the target, which was activated by reactions such as ^{12}C(n, 2n)^{11}C or ^{12}C(π^+, π^+n)^{11}C, and then counted in our system as well as in a β-γ coincidence system. The beam intensity as a function of time, as well as the coincidence counts, were recorded in a multiscaler. The bombardments were carried out for periods of about 15 min and the activity was then measured for about 3-4 h. In this ^{13}C measurement we observed both the 10-min β^+ activity of ^{13}N and the 20.4-min activity of ^{11}C. The last activity arises from reactions such as ^{12}C(π^+, π^+n)^{11}C on the 2% ^{12}C contamination in the target, and from reactions such as ^{13}C(π^+, pn)^{11}C. The decay curves were analyzed with a least-squares fitting program. A series of tests were conducted in order to verify the existence of the 10-min activity. In all attempts in which a 20.4-min activity was assumed to be present and another activity searched for, we always found that activity to have a half-life of 10 $\pm$ 2.5 min. The counting rates and statistical uncertainties at the end of each bombardment were then obtained with a χ^2 analysis, in which the half-lives of the two activities were fixed at 10.0 and 20.4 min. The normalized χ^2 values obtained from the fits were approximately unity. The fits were not improved when we tried to add a 2.1-min activity due to ^{15}O from reactions such as ^{16}O(π^+, π^+n)^{15}O. In Fig. 2 we show an example of the measured β^+ activity as a function of time. Also shown is a curve representing the 20.4-min ^{11}C activity.

The observed cross sections for the three charge-exchange reactions are shown in Fig. 3. Uncertainties in secondary-proton contribution, beam integration, and detection efficiency add up to a systematic error of 20%. The cross section is about 0.4 mb for ^{10}B, where two nonanalog states are bound. For ^{13}C the cross section is of the order of 1 mb and only one analog state is measured. These values are smaller by about a factor of 3 than those reported in Ref. 1. The cross section for ^{7}Li, in which we measured the cross sections for the (π^+, π^0) transition to the first excited state as well as to the ground state of ^{7}Be, is about 2.5 mb near the (3, 3) resonance, and is appreciably bigger than the cross section for ^{13}C In addition to the contribution from an excited state, the smaller absorption expected

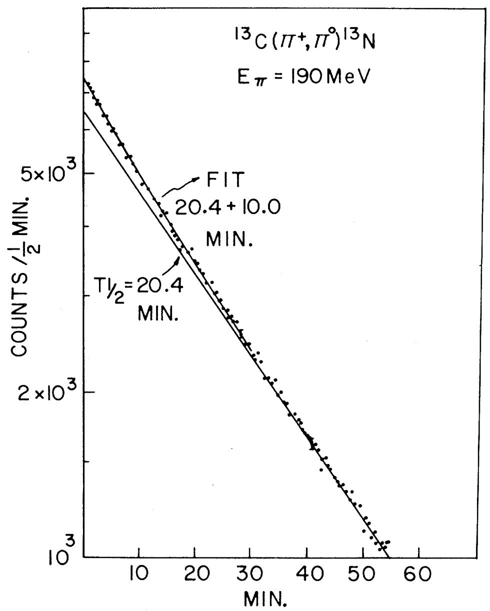

FIG. 2. β^+ decay curve, measured by the coincident detection of the annihilation γ rays. The fit has a normalized χ^2 value of 1.1. The lower solid line shows the contribution of the 20.4-min β^+ activity of ^{11}C. The rest is the 10-min ^{13}N activity.

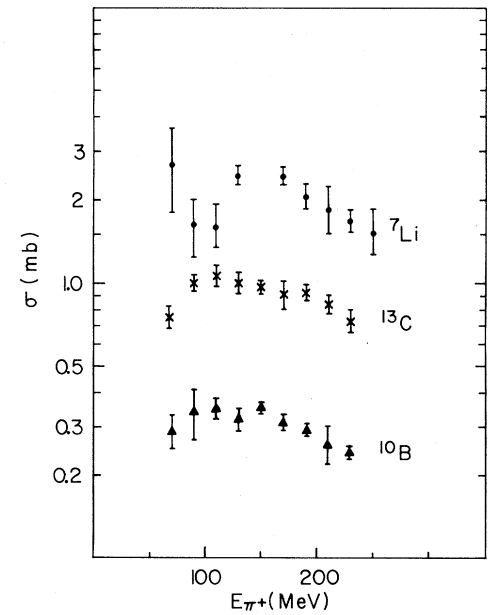

FIG. 3. Activation cross section for the (π^+,π^0) reaction on ^7Li, ^{10}B, and ^{13}C.

for lighter nuclei, as well as the contribution from the quadrupole form factor, may account[17] for the relatively larger cross section for ^7Li. From the three observed excitation functions we arrive at the following qualitative conclusions regarding (π^+, π^0) transitions in light nuclei: (1) Nonanalog transitions with $\Delta T = 1$ ($^{10}B \to {}^{10}C$) are relatively weak; (2) analog transitions [$^{13}C \to {}^{13}N$, and most likely also $^7Li \to {}^7Be$(g.s.)] are relatively strong; (3) nonanalog transitions with $\Delta T = 0$ [$^7Li \to {}^7Be$(excited state)] could still be strong; and (4) there is neither a marked maximum nor a marked minimum at the (3, 3) resonance. The absence of such a minimum casts some doubt on our present-day understanding of the pion-nucleus interaction.

Recent calculations,[18-20] which include absorption, and some of which go beyond first order, now predict somewhat larger cross sections than previously for the (π^+, π^0) analog transitions in the region of the (3, 3) resonance. The disagreement with experiment and the past confusion[2] have, therefore, been somewhat reduced. Still more charge-exchange data for transitions to single states, and better accuracy, as well as more complete calculations, are needed for a full understanding of pion single-charge exchange in light elements.

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Pion Charge-Exchange Scattering from Light Nuclei*

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The reactions $^7\mathrm{Li}(\pi^+,\pi^0)^7\mathrm{Be}$, $^{10}\mathrm{B}(\pi^+,\pi^0)^{10}\mathrm{C}$, and $^{13}\mathrm{C}(\pi^+,\pi^0)^{13}\mathrm{N}$ are examined using a full multiple-scattering formalism with a separable form assumed for the pion-nucleon t matrix. Spin-flip contributions are included. We find that the contributions arising from transitions to nonanalog final states in the case of $^{10}\mathrm{B}$ and $^7\mathrm{Li}$ are of the same order of magnitude as pure analog cross sections.

Pion-nucleus charge-exchange scattering has been studied as a means of probing nuclear structure details. Early theoretical works on this problem have used either optical models in a coupled-channel or distorted-wave formalism,[1] or multiple-scattering expansions, such as Glauber theory.[2] However, from the results of such calculations, it seems that those optical models incorporate too much absorption. The validity of applying the Glauber theory to pion-nucleus charge exchange is questionable, considering the lack of forward peaking in the pion-nucleon charge-exchange amplitudes contrary to a Glauber-theory assumption.

We have used a fixed-nucleon, full multiple-scattering treatment[3] free from the approximations of optical models and also free of the small-angle forward-peaked assumptions of Glauber theory. The basic features of the formalism are described by Gibbs, Jackson, and Kaufmann.[4] Here we use a separable form for the pion-nucleon t matrix,[5] instead of the pole approximation used there. This enables us to treat the off-shell properties of the pion-nucleon scattering more realistically. The t matrix used has the form

$$\langle\vec{q}|t(\omega)|\vec{q}\,'\rangle=\lambda_0(\omega)V_0(q)V_0(q')+\lambda_1(\omega)\vec{q}\cdot\vec{q}\,'V_1(q)V_1(q'), \qquad (1)$$

where

$$\omega=(k^2+\mu^2)^{1/2}$$

and

$$V_l(q)=\frac{k^2+\alpha_l^{\,2}}{q^2+\alpha_l^{\,2}},\quad \lambda_l(\omega)=\frac{\exp[2i\delta_l(\omega)]-1}{k^{2l+1}}. \qquad (2)$$

The parameters α_l have been determined by fits