above 6 MeV, and a comparable magnitude for the cross section. The Orsay results[3] indicate strong population of two groups of states centered around 6.5 and 8.5 MeV. A slightly improved fit to the distribution of events in Fig. 5 can be achieved by assuming population of these two groups of excited states with relative probabilities of 0.7 and 0.3, respectively, as shown by the dotted line in Fig. 5(b).

There are too few events in Fig. 4 to determine reliably the angular distribution of the differential cross section for population of the group of states between 6.5 and 10.5 MeV excitation energy. The events shown in Fig. 4 suggest a fairly isotropic angular distribution, with perhaps some peaking in the forward direction.

In summary, we have shown that the extremely small yield pionic fusion process $^{12}C(^{3}He,\pi^{+})^{15}N$ can be observed close to threshold by detection of the ^{15}N recoil ions. The kinematic projection of the recoil ions into a forward cone gives this technique unusually high efficiency. At 181.4 MeV bombarding energy, the angle integrated cross section for production of excited states in ^{15}N between 6.5 and 10.5 MeV is 1.3 ± 0.3 nb. The ground state of ^{15}N is very weakly populated. The pion angular distribution for the strong group is peaked somewhat in the forward direction.

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A MICROSCOPIC MODEL OF THE (p,π) REACTION

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The purpose of this work is to develop the capability for reliable (p,π) calculations based on a realistic, microscopic meson-exchange model of the A(p,π)A+1 reaction in the form of a thoroughly tested computer code that is fast and flexible with regard to nuclear structure and other physics input.

Our model includes both the one-nucleon mechanism (ONM), in which the pion is produced directly from the projectile in a stripping- or bremsstrahlung-like process (Fig. 1a), and the resonant p-wave rescattering part of the two-nucleon mechanism (TNM), in which the pion is produced in a single "hard" collision between the incident proton and one target nucleon (Fig. 1b). Effects due to "soft" proton-nucleus and pion-nucleus interactions before and after the production process are included via local mean-field corrections

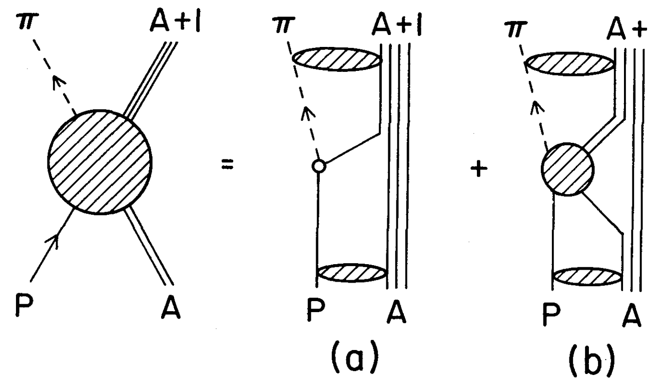


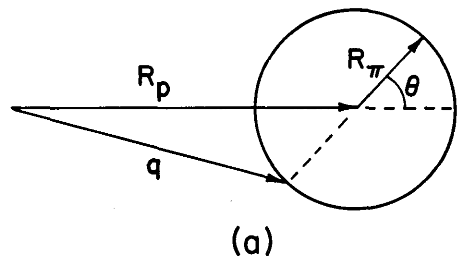
Figure 1. One-nucleon (a) and two-nucleon (b) decomposition of the (p,π) amplitude.

(distortions). The intermediate delta in the two-nucleon mechanism is treated as static with possible inclusion of a local density approximation for the delta-nucleus interaction.

During 1986, our efforts were devoted to extending and refining the model, locating and correcting errors in the coding, and testing the results against hand calculations for the case of the $^3He(p,\pi^+)^4He$ reaction in the zero-range, plane-wave limit.

At the end of 1985, our model included only the two-nucleon mechanism. We ignored the one-nucleon (bremsstrahlung) contribution initially because of the high momentum transfer of the (p,π) process. For bombarding energies from pion-production threshold up to 250 MeV, the (p,π) reaction is characterized by momentum transfers $\underline{q} = \underline{k}_p - \underline{k}_\pi$ to the residual nucleus between 375 and 670 MeV/c for the $^3He(p,\pi^+)^4He$ reaction, and between typically 470 and 900 MeV/c for much heavier nuclei (Fig. 2). In the plane wave Born approximation (PWBA), the cross section for the (p,π) reaction is proportional to the square of the momentum-space wave function of the captured nucleon, which is very small far above the Fermi momentum (~250 MeV/c), particularly for a harmonic oscillator wave function. We see from Fig. 2 that the momentum transfer in the A(p,π)A+1 reaction is always large compared to the Fermi momentum, even at threshold. Thus, it has long been thought[1] that the one-nucleon mechanism contribution to the (p,π) process should be small. Our results[2] at the end of 1985 indicated that this may not be so.

During 1986, we added the one-nucleon mechanism to our code and found, for the $^3He(p,\pi^+)^4He$ case, that it dominates the two-nucleon mechanism when appropriate proton and pion distortions and non-static corrections are included in the one-nucleon process. Distortions change the one-nucleon mechanism towards a multi-nucleon mechanism by explicitly introducing momentum sharing between the (bound) projectile and the



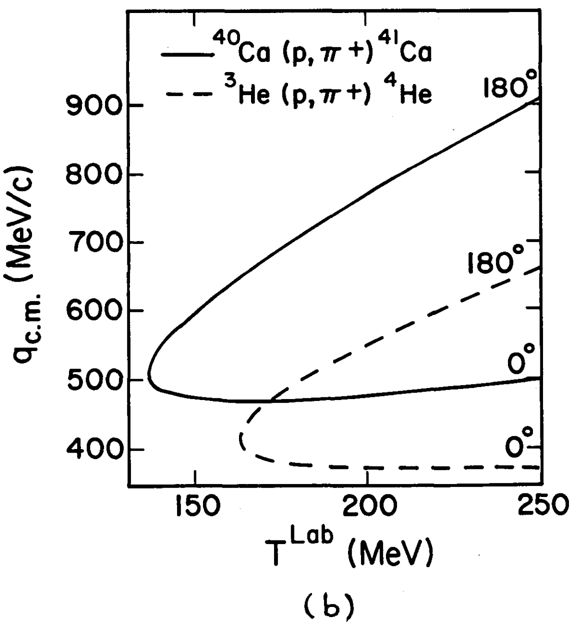


Figure 2. Kinematics of the A(p,π)A+1 reaction.

residual nucleus. The Fourier transform of the bound state wave function is then replaced by a folding of this Fourier transform with the momentum distribution of the distorted waves for the proton and the pion, and the resulting spreading in momentum components leads to a calculated cross section that has almost completely lost the features of the PWBA result. It is possible that this dominance of the one-nucleon mechanism does not hold for heavier nuclei. This expectation is based on experimental results showing comparable excitation of both single-particle and two-particle one-hole states, for example in the $^{12}C(p,\pi^+)^{13}C$ reaction.[3,4] In contrast to the data, the one-nucleon mechanism strongly discriminates between the excitations of pure one-particle and more complicated nuclear states. Yet, the ONM may never be negligible. It thus appears that both the one-nucleon and the two-nucleon mechanisms must be included in realistic (p,π^+) calculatons. Since the one-nucleon mechanism does not contribute to negative pion production, the (p,π^-) reaction will be useful in testing separately the two-nucleon part of our code.

In addition to adding the one-nucleon term to our code, a number of other improvements and tests were made during 1986:

- the one-nucleon and the two-nucleon terms were checked separately against hand calculations for the case of the $^3He(p,\pi^+)^4He$ reaction in the zero-range, plane-wave limit;
- improved pion distorted waves were generated, which no longer show any remnant of the "Kisslinger singularity";
- improved proton distorted waves were generated using DWUCK4 instead of SNOOPY (the latter did not generate accurate plane waves when the optical potentials were set to zero);
- an option was developed for reading in realistic bound-state wave functions that reproduce electron elastic-scattering data (up to this point, we had used harmonic oscillator wave functions, which were thought to be adequate in the two-nucleon mechanism, due to the momemtum sharing);
- the shell-model code OXBASH[5] was used to calculate the spectroscopic amplitudes that determine the relative weights and phases of the one- and two-nucleon terms;
- the stability of the radial integrals was checked by adding to the Gauss-Hermite numerical integration scheme used in the original version of the code (this was chosen to match the harmonic oscillator wave functions) options for Gauss-Laguerre and Gauss-Legendre integration;
- a number of small, but important, errors in the coding (for example, the sign of the analyzing power) were found and corrected.

All of these improvements caused significant changes in the $^3He(p,\pi^+)^4He$ calculations, usually in the direction of improved agreement with data, lending credence to the model. The sensitivity of the (p,π) reaction to so many things, all of which must be right at the same time, explains why it is so difficult to achieve agreement between theory and experiment.

The program ORCHID for carrying out calculations based on the model described above was designed to maximize flexibility with respect to the nuclear structure and reaction mechanism input and to minimize the execution time, while keeping core size requirements within reason, so that systematic testing of the physics involved in the (p,π) process will be possible with readily available computing facilities. Our present version of the code runs on a DEC/VAX 8600.

time and core requirements. Integer arithmetic is utilized as much as possible (e.g., for most of the angular momentum coefficient generation, conversion of phase arithmetic into integer arithmetic modulo 4, etc.), since it executes faster than real arithmetic, and the use of complex arithmetic is minimized, since it executes slowly. The program calculates all quantities that are used repeatedly only once and stores them using a fairly complex indexing scheme (particularly for the 9j symbols) for fast retrieval and minimum storage requirements. These include all radial integrals and all angular momentum coefficients. Integration schemes are chosen to match the functional form of the integrand for fast convergence.

To illustrate the speed of the program, a finite-range $^{3}He(p,\pi^{+})^{4}He$ calculation at T_p=200 MeV involving both the one-nucleon and two-nucleon terms, proton and pion distorted waves, and outgoing pion partial waves up to $\ell_{\pi}(max) = 6$, requires about three minutes of CPU time on a DEC/VAX 8600. A $^{14}C(p,\pi^{-})^{15}O$ calculation to a high-spin (13/2) final state requires more time (~ 30 minutes) because of the more complicated angular momentum coupling.

We chose the $^{3}He(p,\pi^{+})^{4}He$ reaction for initial testing of our model because of the simplicity of analytical calculations for this case, which were used extensively to check various pieces of the code, and the short computational time, which made possible the hundreds of test calculations required for development, testing and debugging of the code.

Fig. 3 shows the results of calculations for the $^{3}He(p,\pi^{+})^{4}He$ reaction and IUCF data.[6] The agreement between theory and experiment is quite good with respect to the shapes of the differential cross section and analyzing power angular distributions, but the by about a factor of 4. An understanding of the origin of this discrepancy will require careful examination of the model sensitivities. Preliminary investigations show that most things that increase the cross section tend to spoil the shapes of the angular distributions. We have found, however, that increasing the πNN coupling constant not only increases the cross sections but also improves markedly the angular distributions of both the differential cross sections and the analyzing powers by changing the interference between the one- and two-nucleon mechanisms (which results from the fact that $f_{\pi NN}$ appears only once in the one-nucleon mechanism and three times in the two-nucleon mechanism). This is shown in Fig. 3 by the dashed

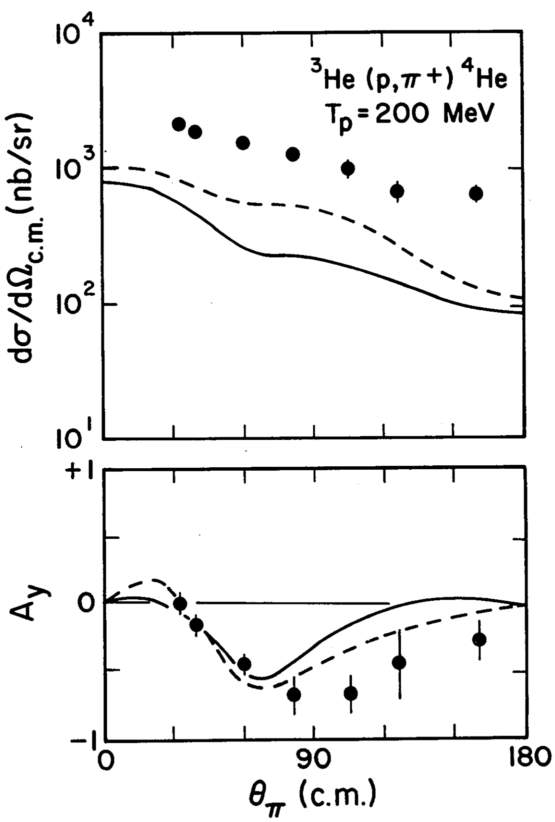


Figure 3. Data for the $^{3}He(p,\pi^{+})^{4}He$ reaction and calculations for two different values of the πNN coupling constant.

lines, which were calculated with a coupling constant 45% larger than that used for the solid lines. Medium modifications of the πNN coupling constant are implied by some interpretations of the EMC effect.

We feel that we have, at last, a reliable code that includes the most important physics of the (p,π) reaction in the near-threshold region. In addition to investigating the questions mentioned above, we hope to apply the model in the near future to the (p,π^-) reaction (for which only the two-nucleon mechanism contributes) and to other (p,π^+) reactions, and to extend the model to higher energies for interpretation of TRIUMF and future Cooler experiments. Finally, it is planned to document the code and to make it as user friendly as possible, so that it will be useful to the scientific community at large.

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STUDY OF HIGH-SPIN STATES AND THREE-QUASIPARTICLE (p,π) TRANSITIONS ON LIGHT TARGETS

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(p,π) reactions necessarily involve large momentum transfer, typically greater than 500 MeV/c. An important part of the reaction operator has the effect on the target of creating a hole and inserting two nucleons, thus creating three- (or one-) quasiparticle states relative to the target. The amount of momentum transfer for each of the three nucleon states involved is about the same as in the inelastic scattering regime where high-spin states are selectively excited, so it is not strange that there is a tendency for high-spin states to be strong in (p,π) reactions. The most striking experimental evidence for the three-quasi-particle mechanism comes from the (p,π^-) reaction in particular from the analyzing powers and intensity ratios observed by Jacobs et al.,[1] in $^{12,13,14}C(p,\pi^-)$ ground-state transitions, especially from the strong population of $19/2^-$ and $15/2^-$ states by Vigdor et al.[2] in $^{48}Ca(p,\pi^-)$ and reactions on neighboring targets, and the correspondence of the latter with the model calculations of Brown, Scholten, and Toki.[3]

(p,π^+) reactions should also strongly populate two-particle, one-hole states of high spin through similar mechanisms. The largest elementary cross section for pion production is pp→pn (T=0), so the strongest (p,π^+) transitions should proceed through