A detailed description of our microscopic model of the \( A(p, \pi)A + 1 \) reaction was prepared during 1987 and is now published. This model is based on mesonic and isobaric degrees of freedom and includes explicitly both the one-nucleon (pionic stripping) mechanism (ONM) and the resonant p-wave rescattering part of the two-nucleon mechanism (TNM). Higher order processes are included through proton-nucleus and pion-nucleus optical-model distortions. Numerical calculations are carried out with the computer program ORCHID, which has been extensively tested to insure that it is a correct implementation of the model — without recourse to experimental data, so that comparisons between theory and experiment can provide meaningful tests of the physics contained in the model. Preliminary calculations of the \( ^3\text{He}(p, \pi)\gamma^4\text{He} \) reaction showed the relative importance of various individual amplitudes and the sensitivities of the calculations to distortions and the bound-state wave functions. From these results, the following conclusions were drawn.

- The ONM and TNM amplitudes are comparable in magnitude for the \( ^3\text{He}(p, \pi)\gamma^4\text{He} \) reaction at \( T_p = 200 \) MeV.
- The ONM amplitudes are very sensitive to the bound-state wave functions (bswf), as well as to the proton and full pion distortions. Non-resonant pion distortions, on the other hand, have little effect, supporting the assumption that the non-resonant pieces of the TNM rescattering operator can be neglected.
- Non-static corrections to the ONM operator are important.
- The TNM amplitudes are less sensitive than the ONM amplitudes to the bswf and distortions.
- The TNM is dominated by the pion-exchange projectile-emission (PE) amplitudes. The target-emission (TE) amplitudes for pion exchange are much smaller than the PE amplitudes, and the contributions of \( \rho \)-meson exchange are almost negligible, because the PE and TE amplitudes for \( \rho \)-meson exchange, though individually large, effectively cancel each other due to the short-range nature of the \( \rho \)-meson.

Since our first paper, we have examined in more detail the approximate equivalence of two different descriptions of the \( ^3\text{He}(p, \pi)\gamma^4\text{He} \) reaction: one in which the pion is produced directly from the projectile in a stripping- or bremsstrahlung-like process and all higher-order processes are included via full proton and pion optical-model distortions; and the other in which the first re-scattering of the pion is treated microscopically. Using the Lippmann-Schwinger equation, the one-nucleon mechanism calculated with full
pion distortions can be split up into a ONM term with non-resonant distortions and the projectile-emission part of a two-nucleon mechanism with full distortions. The near equivalence of these two calculations is shown in Fig. 1, where the solid curves are the ONM calculations with proton and full pion distortions, and the dashed curves are the equivalent microscopic calculations involving the coherent sum of the ONM amplitude with proton distortions and non-resonant pion distortions, and the pion-exchange projectile-emission part of the TNM amplitude with proton distortions and full pion distortions. The agreement between the DWBA and microscopic calculations is striking. It gives us confidence in the relative phases of the ONM and PE contributions in our microscopic approach and the correctness of the individual components of the calculations.

The calculations shown in Fig. 1 do not include the contributions from target-emission and $\rho$-exchange. The solid curves in Fig. 2 represent the full TNM calculations with target-emission and $\rho$-exchange turned on. Comparing these results with the dashed curves in Fig. 1, we see that these additional contributions have only a small effect. The small contribution from $\rho$-meson exchange results from the cancellation between the PE and TE amplitudes due to the short-range nature of the $\rho$-meson interaction\(^1\). For pion-exchange, the TE contribution is in itself small compared to the ONM and PE contributions, which dominate the \(^3\text{He}(p, \pi^+)^4\text{He}\) reaction at \(T_p = 200\) MeV, as is shown in Fig. 2. The smallness of the $\pi$-exchange, TE and $\rho$-exchange contributions explains why the full ONM calculation reproduces so well the main features of the experimental data. We note, however,
that the microscopic calculation, in which the first pion rescattering is treated explicitly, gives a substantially better description of the analyzing powers. The explicit treatment of the first pion rescattering is an improvement over the distorted wave ONM approach, because it allows the far off-shell nature of the pion before the first rescattering to be dealt with explicitly. In addition, it allows target-emission and \( \rho \)-exchange contributions to be included in the calculations.

The internal consistency of the calculations shown in Fig. 1, together with the extensive analytical tests performed previously\(^1\), affirm that our model is correctly implemented by the computer program ORCHID. The discrepancies between the full calculations and the experimental data\(^2\) shown in Fig. 2 indicate, therefore, that some physics is either missing or incorrectly included in the model. There are several possibilities:

- Inadequacy of optical-model distortions for such light systems;
- Lack of \( \Delta \)-dominance at \( T_p = 200 \text{ MeV} \) \( [T^\text{cm}_\pi = 25.7\text{ MeV}] \);
- Sensitivity to D-state admixtures in the bound-state wave functions.

Preliminary calculations indicate that the effects of neglected D-state admixtures in the bound-state wave functions are probably too small to account for the disagreements between the calculations and the data. It seems more likely that an optical model approach to describing the initial and final state interactions may be inadequate for systems as light as Helium, or that the two-nucleon reaction mechanism is not dominated by intermediate \( \Delta \) formation at such low energies. Studies of the energy dependence of the reaction (see the following contribution by Bent et al. in this Annual Report) shed some light on these questions.
ENERGY DEPENDENCE OF THE $^3\text{He}(p,\pi^+)^4\text{He}$ REACTION

R. D. Bent

Indiana University Cyclotron Facility, Bloomington, Indiana 47405

P. W. F. Alons

Indiana University Cyclotron Facility, Bloomington, Indiana 47405
and NIKHEF, P.O. Box 41882, 1009 DB Amsterdam, The Netherlands

M. Dillig

Institute for Theoretical Physics, University of Erlangen-Nurnberg
Erlangen, W. Germany

We have described previously our microscopic model\(^1\) of proton-induced nuclear pion production and its application\(^{1,2}\) to the $^3\text{He}(p,\pi^+)^4\text{He}$ reaction at $T_p^{\text{lab}} = 200 \text{ MeV}$. Recently, we have examined the energy dependence of the various components of the calculations from the near threshold region [$T_p^{\text{lab}} = 178 \text{ MeV}, T^{\text{cm}} = 10.5 \text{ MeV}$] to an energy at which the $\Delta_{1232}$ resonance should clearly dominate the reaction mechanism [$T_p^{\text{lab}} = 300 \text{ MeV}, T^{\text{cm}} = 93.6 \text{ MeV}$]. The full calculations are compared with existing differential cross section and analyzing power data\(^3\) at $T_p^{\text{lab}} = 178$ and 200 MeV, and with cross section data\(^4,5\) from the time-reversed $^4\text{He}(\pi^-,n)^3\text{H}$ and $^4\text{He}(\pi^+,p)^3\text{He}$ reactions at equivalent proton laboratory energies of 229, 262, 296 and 329 MeV, assuming charge symmetry and detailed balance. The only energy above 200 MeV at which both differential cross section and analyzing power data are available is 800 MeV\(^6\), far above the region of applicability of our model.

Our microscopic model of the A(p,π)A+1 reaction is based on mesonic and isobaric degrees of freedom and includes explicitly both the one-nucleon mechanism (ONM) and the resonant p-wave rescattering part of the two-nucleon mechanism (TNM). Higher order processes are included through proton-nucleus and pion-nucleus optical-model distortions. For the present calculations, the proton distortions were obtained using optical model potentials that give a good description of proton elastic data at 178 MeV\(^7\) and at 200 and 300 MeV\(^8\), and then interpolating for 250 MeV. The pion distorted waves were generated using the pion-nucleus optical model code DWPIES (which is described in Ref. 1) and including second-order parameters determined by systematic fits to a large body of $\pi$-elastic data\(^9\). The second-order parameters are well known up to only 80 MeV pion energy, so an extrapolation was required to obtain the parameters for $T_p = 300 \text{ MeV}$, which is equivalent to a laboratory pion energy of 103 MeV. An energy-dependent pion self-energy was included in the two-nucleon mechanism.