Multistep direct mechanism in the ($\vec{p}$,^{3}He) inclusive reaction on ^{59}Co and ^{93}Nb at an incident energy of 100 MeV

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The inclusive ($\vec{p}$,^{3}He) reactions on ^{59}Co and ^{93}Nb were investigated at an incident energy of 100 MeV. Emission-energy distributions for cross sections as well as analyzing powers, were measured from a threshold of ~35 MeV, determined by the detector configuration, up to the kinematic maximum. An angular range from 15° to 140° (lab) was covered. The experimental distributions were compared with a multistep direct theory in which a reaction mechanism based on deuteron pickup is employed. Reasonable agreement between experimental double differential cross sections and analyzing powers and the theoretical expectation is obtained.

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I. INTRODUCTION

The identification of the reaction mechanisms leading to the emission of complex ejectiles initiated by medium-energy protons has been the object of many studies in recent years. Apart from the fundamental importance of insight into the mechanisms, the needs of applications such as medical therapy with proton beams, require a complete understanding of the physical process.

After the earliest studies of cross section angular distributions, the advent of polarized proton beams of high quality a number of years ago [1,2], promised a new tool with increased sensitivity to the details of the reaction mechanism. For example, it was shown by Bonetti *et al.* [3] that, whereas the experimental cross section angular distributions for the ^{58}Ni($\vec{p}$,α) inclusive reaction were in agreement with either a cluster knockout or a pickup mechanism, the analyzing power distributions could only be reproduced by calculations based on the former model. Clearly the analyzing power distributions are more sensitive to the details of the reaction mechanism than the cross sections alone.

The inclusive ($\vec{p}$,α) and ($\vec{p}$,^{3}He) reactions at incident energies of 65 [1] and 72 MeV [2] show unexpectedly large analyzing powers up to large scattering angles. The energy and angular distributions for these two studies were generally consistent with the expectation of a simple multiple scattering model in which very few steps appear to participate. The work of Renshaw *et al.* [4], on the other hand, measured zero analyzing power on ^{nat}Ag+$\vec{p}$ at 200 MeV for a variety of ejectiles with $Z \leqslant 7$, thus concurring with the conclusion from studies at even higher incident energy [6] that a simple mechanism such as direct cluster knockout, or a similar one-step reaction, is excluded. The two classes of contrasting results could perhaps be reconciled with the findings of Cowley *et al.* [5] who investigated inclusive emission of ^{3}He from ^{59}Co and ^{197}Au at incident energies between 120 and 200 MeV. This later study, however, was based only on the comparison of theory with experimental cross section distributions. Consequently it is of importance to confirm the validity of the conclusions derived from the work of Cowley *et al.* with an investigation of the analyzing power distributions.

In this work we investigate the inclusive ($\vec{p}$,^{3}He) reaction on ^{59}Co and ^{93}Nb at an incident energy of 100 MeV, and emission-energy distributions are measured for cross sections as well as analyzing powers. The choice of incident energy is determined by the existing analyzing power results for the inclusive ($\vec{p}$,^{3}He) reaction that are available below 72 and above 200 MeV. The expectation is that the analyzing powers should become negligible the closer the incident energy is to 200 MeV, thus favoring a much lower incident energy value for reasonably rapid collection of data with good statistical accuracy. The two target nuclei that were selected are assumed to be representative examples.

The experimental procedure is described in Sec. II. The experimental distributions are analyzed in terms of a multistep direct theory that assumes a deuteron pick-up reaction mechanism, as detailed in Sec. III. In Sec. IV the results are presented and Sec. V contains a summary and conclusion.

II. EXPERIMENTAL PROCEDURE

The cross sections and analyzing powers were measured at the National Accelerator Centre, Faure, South Africa, for inclusive ($\vec{p}$,^{3}He) reactions on ^{59}Co and ^{93}Nb at an incident energy of 100 ± 0.5 MeV, with the projectiles polarized to approximately 80%. The polarization of the incident beam was switched from up to down in 5 s intervals in order to reduce systematic errors on the analyzing power measurements. The difference in the polarization between the two orientations was always less than 8%. The accelerator and the main details of the experimental equipment have been previously described elsewhere [7].

Two detector telescopes, each consisting of a 500 μm

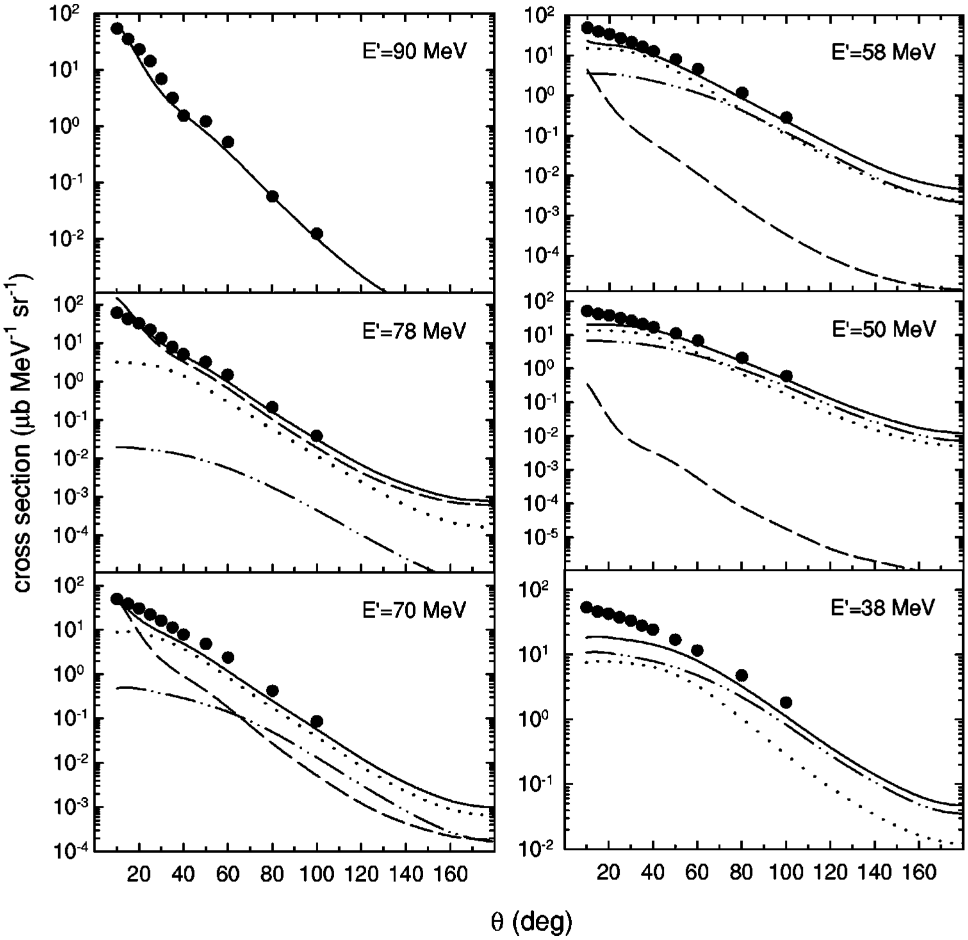

FIG. 1. Experimental lab double differential cross sections as a function of scattering angle θ for ^{59}Co($\vec{p}$,^{3}He) at 100 MeV incident energy and various outgoing energies E' (statistical uncertainties are smaller than the symbol size) compared with calculations for one step (— — —), two step (· · · · ·), and three step (— · · — · · —) contributions. The sum of the three contributions is given by continuous curves.

silicon surface barrier detector followed by a NaI(Tl) crystal connected to a photomultiplier tube, were used. Particle identification was achieved with a standard ΔE-E technique. This allowed the reliable separation of the ^{3}He particles of interest from other ejectiles, especially the adjacent α particles.

The two detector telescopes were collimated to the same nominal solid angle acceptance by means of Ta collimators, and used at symmetric scattering angles on opposite sides of the beam. This arrangement, together with the switching of the polarization state, is the standard method to minimize the systematic error on the analyzing power measurement.

Energy calibrations of the silicon surface barrier detectors were made with the aid of a ^{228}Th α-particle source, and the calibrations of the NaI(Tl) detector elements were based on the kinematics of the elastic scattering reactions ^{1}H$(p,p)^1$H and ^{12}C$(p,p)^{12}$C from a thin polyethylene target. These calibrations for protons in the telescope also provide energy values for ^{3}He, if the difference in the response of these ejectiles with the NaI(Tl) assembly is taken into account [8]. Gain drifts in the photomultiplier tubes of the NaI detectors were monitored by a light-emitting diode pulser system which allowed corrections to be made during analysis. These procedures lead to a 4% uncertainty in the energy scale for ^{3}He.

The self-supporting targets were metals of natural elements (100% occurrence of the isotope of interest) with thicknesses in the range of 1 to 5 mg/cm^2. The uncertainty in the thicknesses of the targets (up to 8%) is the main contribution to the systematic error on the cross section data.

III. THEORETICAL ANALYSIS

The ($\vec{p}$,^{3}He) double differential cross section and analyzing powers were calculated using the multistep direct theory of Feshbach, Kerman, and Koonin [9] assuming that the reaction mechanism is deuteron pickup. The formalism is given in our previous papers [5,10,11]. The extension of the theory to give analyzing powers is described by Bonetti *et al.* [12]. The analyzing power is defined by

$$A_y = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}, \tag{1}$$

where σ_L and σ_R are the double differential cross sections for the emission of the helions to the left and right of the incident particle beam, respectively.

Previous calculations of $(p,^3\text{He})$ cross sections [5] showed considerable sensitivity to the helion optical potentials, which were obtained by optical model analyses of elastic scattering from similar nuclei at similar energies. There is thus considerable uncertainty about the best phenomenological parameters to use. In addition, even if optical potentials obtained from analysis of data at the correct energy on the

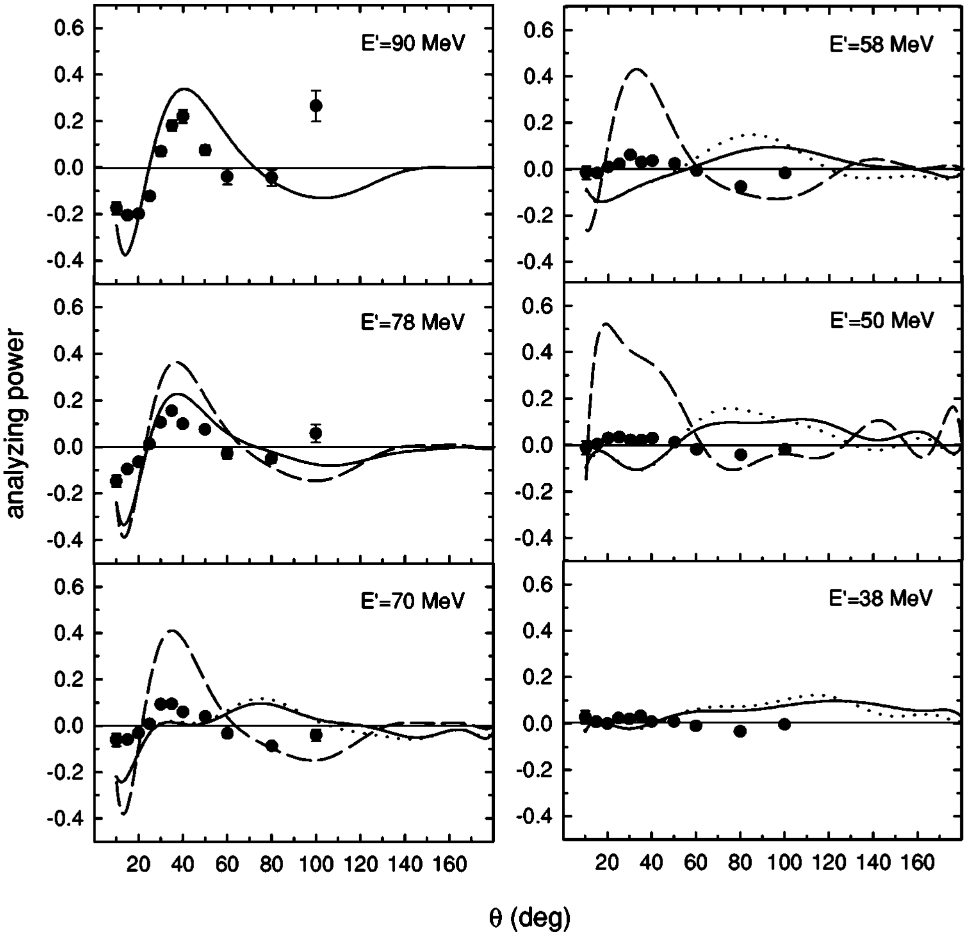

FIG. 2. Experimental analyzing powers as a function of scattering angle θ for ^{59}Co($\vec{p}$,^{3}He) at 100 MeV incident energy and various outgoing energies E' (data points with statistical error bars where they exceed the symbol size) compared with calculations for one step (— — —) and one + two step (· · · · ·) contributions. The sum of the contributions from three steps is given by continuous curves.

correct nucleus were available, they would not necessarily be the best ones to use for reaction calculations, as elastic scattering and reactions are sensitive to different matrix elements. We therefore sought to solve this problem by using a

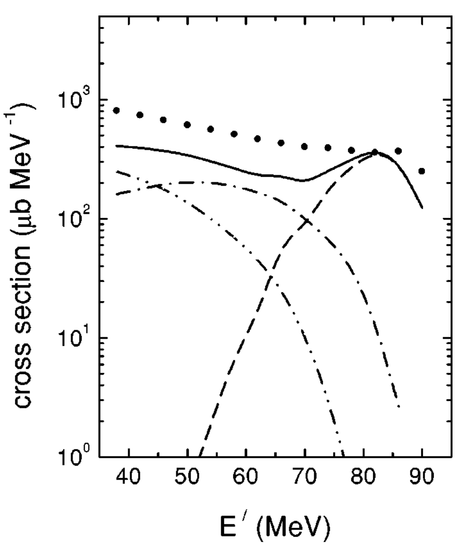

FIG. 3. Experimental lab angle-integrated cross sections for ^{59}Co($\vec{p}$,^{3}He) (solid circles) compared with the theoretical results for one step (— — —), two step (— · — · —), and three step (— · · — · · —) processes. The sum of the three contributions is given by the continuous curve.

microscopic optical potential for ^{3}He obtained by the double folding model [13,14] defined by

$$V_{\mathrm{DF}}(\mathbf{R})=\int d\mathbf{r}_1 d\mathbf{r}_2 \rho_{^3\mathrm{He}}(\mathbf{r}_1)\rho_A(\mathbf{r}_2)v_{eff}(\mathbf{r}_1+\mathbf{R}-\mathbf{r}_2), \tag{2}$$

where $\rho_{^3\mathrm{He}}(\mathbf{r}_1)$ and $\rho_A(\mathbf{r}_2)$ are the local density of ^{3}He and the target nucleus A, respectively, and $v_{\mathrm{eff}}(\mathbf{r}_1+\mathbf{R}-\mathbf{r}_2)$ is an effective nucleon-nucleon interaction. In the present calculations we use the DDM3Y effective nucleon-nucleon interaction originally introduced by Kobos *et al.* [15]. The DDM3Y effective interaction is real and energy dependent. Thus the helion potential is real and to this we added an imaginary part of the optical potential of the volume Woods-Saxon form. The double folding potential $V_{\mathrm{DF}}(\mathbf{R})$ thus has the form

$$V_{\mathrm{DF}}(\mathbf{R})=U_C^{\mathrm{DF}}(\mathbf{R})+U_{\mathrm{SO}}^{\mathrm{DF}}(\mathbf{R})\mathbf{L}\cdot\mathbf{S}+iW^{\mathrm{WS}}(\mathbf{R}), \tag{3}$$

where $U_C^{\mathrm{DF}}(\mathbf{R})$ and $U_{\mathrm{SO}}^{\mathrm{DF}}(\mathbf{R})$ are the central and the spin-orbit parts of the double folding potential, respectively, and $W^{\mathrm{WS}}(\mathbf{R})$ is the imaginary part of the potential.

To calculate the double folding potential we used the code MOPHE3 of Katsuma and Sakuragi [16]. For the ^{59}Co($\vec{p}$,^{3}He) reaction we used the following parameters for the imaginary part of the double folding potential: $V=96$ MeV, $r_i=1.0$ fm, and $a_i=0.6$ fm which we found to give a good fit

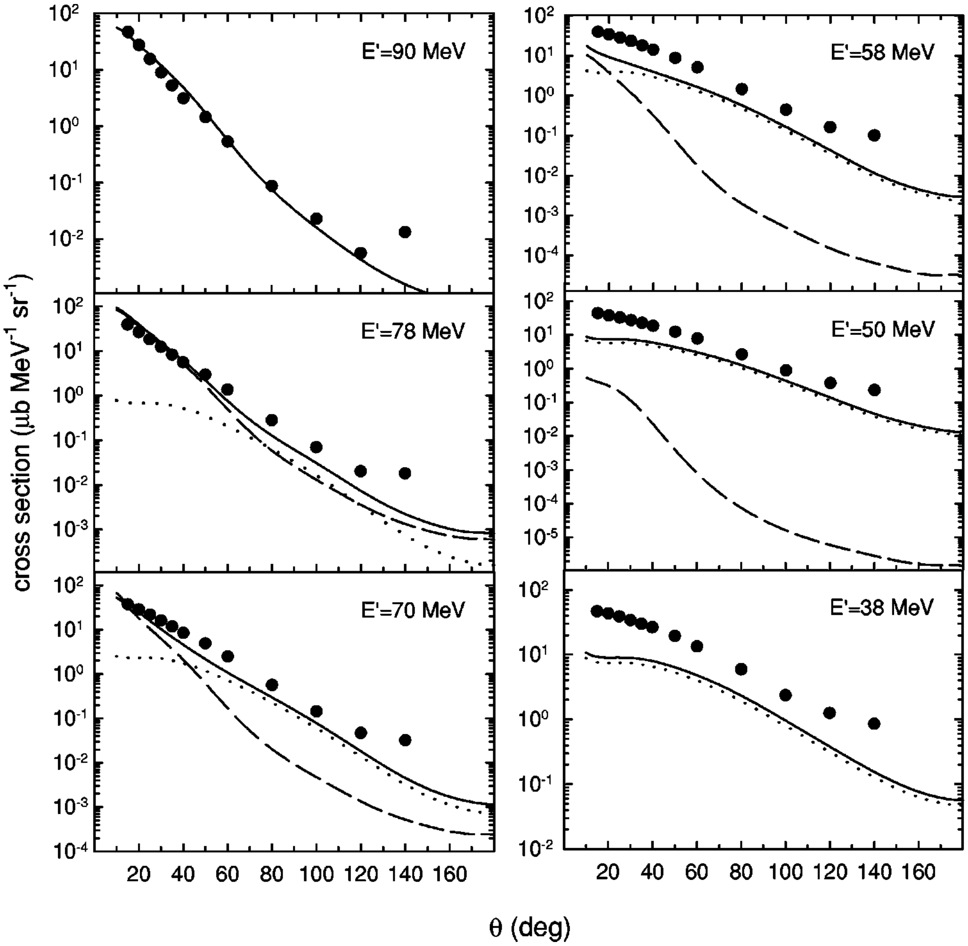

FIG. 4. Experimental lab double differential cross sections as a function of scattering angle θ for ^{93}Nb($\vec{p}$,^{3}He) at 100 MeV incident energy and various outgoing energies E' (statistical uncertainties are smaller than the symbol size), compared with calculations for one step (— — —) and two step (· · · · ·) contributions. The sum of the contributions is given by continuous curves.

to the cross sections and the analyzing powers for ^{59}Co at 90 MeV outgoing energy. For the protons we used the Walter and Guss [17] optical model parameters. The (p,p') and (p,p',p'') double differential cross sections which are needed for calculating the contributions of the second- and third-step processes were taken from Ref. [18].

The calculations for the ^{93}Nb($\vec{p}$,^{3}He) reaction were made in a similar way. The best fit of the theoretical results to the experiment was found when the central U_C^{DF} and spin-orbit part $U_{\mathrm{SO}}^{\mathrm{DF}}$ of the potential were scaled by factors of 0.5 and 35, respectively. The imaginary part W^{WS} was parametrized as follows: $V=36$ MeV, $r_i=1.5$ fm, and $a_i=0.3$ fm. Since suitable data for the ^{92}Mo(p,p') cross sections at 120 MeV are available [19] we use them to approximate the (p,p') cross sections which are needed to calculate the two-step contribution to the ^{93}Nb($\vec{p}$,^{3}He) reaction. Because the deuteron formation probability is not known, the differential cross sections for both reactions were normalized to the experimental data at an outgoing energy of 90 MeV.

IV. RESULTS

The double differential cross sections and analyzing power angular distributions for the reaction ^{59}Co($\vec{p}$,^{3}He) at 100 MeV incident energy and outgoing energies E' ranging from 90 to 38 MeV are shown in Figs. 1 and 2. It is seen that at 90 MeV, which is approximately the highest outgoing energy allowed by the kinematics of the reaction, the cross sections and the analyzing powers are both well reproduced by the first step of the pickup process. For lower outgoing energies the two-step $(p,p',{}^3\mathrm{He})$ and three-step $(p,p',p'',{}^3\mathrm{He})$ processes contribute increasingly to the total cross sections and analyzing powers. The calculations describe very well the shape of the double differential cross sections over the whole range of outgoing energies. The quality of the fit is also demonstrated by comparing the calculated and experimental angle-integrated cross section shown in Fig. 3.

It was previously conjectured [20] that the shortfall in the cross section in the lower energy region could be due to an underestimate of the two-step cross section. The calculated total cross section can indeed be brought into agreement with experiment by multiplying the two-step cross section by a substantial factor. However, further calculations showed that this destroys the agreement with the first peak of the analyzing power, so this explanation is excluded. It is possible that the shortfall is due to the sequential emission process, which is not included in our calculations.

The analyzing power is much more sensitive to the reaction mechanism, the nuclear structure information involved and the accuracy of the numerical calculations than the reaction cross section. At lower outgoing energies the magnitude of the analyzing power decreases rapidly, due to the contributions of the higher steps. A more detailed study of the

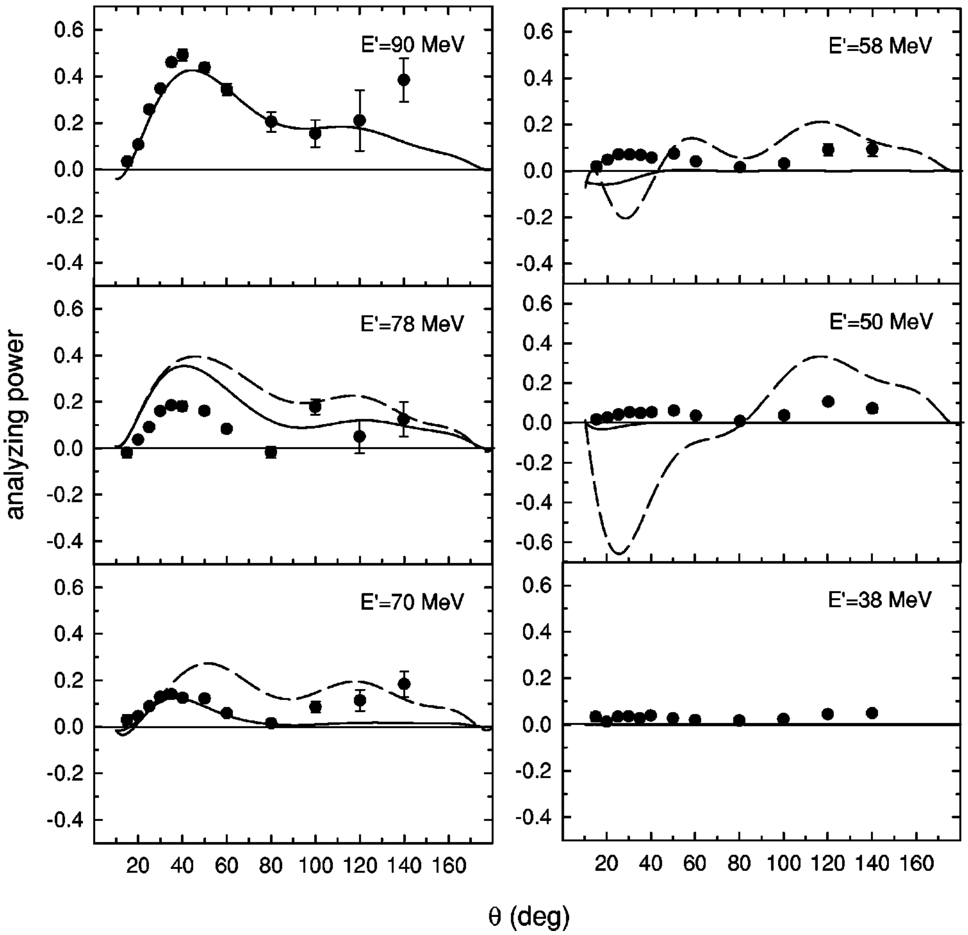

FIG. 5. Experimental analyzing powers as a function of scattering angle θ for ^{93}Nb($\vec{p}$,^{3}He) at 100 MeV incident energy and various outgoing energies E' (data points with statistical error bars where they exceed the symbol size) compared with calculations for one step (− − −) and the sum of the various steps (continuous curves).

multistep processes is needed to describe the experimental shape of the analyzing power at low outgoing energies.

The results for the ^{93}Nb($\vec{p}$,^{3}He) reaction are compared with the experimental data in Figs. 4 and 5. As before the theoretical calculations reproduce quite well the shape and the magnitude of the double-differential cross section, especially at the higher outgoing energies. The data for the analyzing powers at energy losses up to 30 MeV are also well described. At low outgoing energies the magnitude of the analyzing power decreases rapidly and the calculations reproduce this trend, although they do not describe accurately the angular variation of the analyzing power. Note that in Fig. 5 we do not show the one-step theoretical analyzing power at an emission energy of $E'=38$ MeV, as it clearly becomes irrelevant towards lower outgoing energies. At this lowest emission energy of 38 MeV the sum of the various steps is seen to be essentially zero.

V. SUMMARY AND CONCLUSIONS

The study of the differential cross sections and analyzing powers of the ($\vec{p}$,^{3}He) reaction on ^{59}Co and ^{93}Nb to the continuum at an incident energy of 100 MeV has supported and extended the previous analyses [5] of the differential cross section alone. The analyzing powers prove to be a sensitive measure of the contributions of the various one-step and multistep processes. The one-step process dominates for the reactions with the smallest energy loss (highest outgoing energies) and shows relatively large analyzing powers, well reproduced by our calculations. As the energy loss increases (lower outgoing energies), the contribution of the one-step process falls rapidly and the two-step process, and then the three-step process, become dominant. Since these multistep processes have small analyzing powers, the total analyzing power falls with outgoing energy, and this also is well reproduced by the calculations. The analysis of data from the two reactions give very similar results, showing that our results are characteristic of nuclei in general.

We have thus attained a good overall understanding of the physics of the reaction. The fits to the experimental data, however, are not perfect, but it is difficult to see how the calculation can be meaningfully improved, mainly because of the lack of an accurate knowledge of the optical potentials. Further parameter variation could well improve the overall agreement between theoretical and experimental results, but such a procedure would be of doubtful physical significance. Clearly a better understanding of the optical potentials would then allow the introduction of further refinements to the theory, such as an evaluation of the contribution of a sequential pickup process.

The results of this study are similar to, but more extensive, than those of the recent analysis [21] of the data of Lewandowski *et al.* [2] for the ^{58}Ni($\vec{p}$,^{3}He) reaction at 72

MeV. Naturally it would be desirable to extend this type of investigation to higher incident energy.

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