Inclusive $(p,^3\mathrm{He})$ reactions on ^{59}Co and ^{197}Au at incident energies of 120, 160, and 200 MeV

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Measurements of inclusive $(p,^3\mathrm{He})$ reactions on ^{59}Co and ^{197}Au at incident energies of 120, 160, and 200 MeV are compared with calculations based on a statistical multistep direct reaction theory. The angular range extends from 10° to 160° and emission energies exceeding 30 MeV were studied. It is found that the multistep contributions are dominant for all but the highest outgoing energies. This is in qualitative agreement with previous results for the inclusive (p,α) reaction at the same incident energies and targets. [S0556-2813(97)01004-2]

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I. INTRODUCTION

The statistical multistep direct theory, especially as formulated by Feshbach, Kerman, and Koonin [1], appears to describe the essential physical process whereby inclusive (p,p') reactions proceed [2]. As a result of this successful description, it has recently become of interest whether the emission of complex particles can also be accommodated by a similar theoretical approach. The implementation of the theory for such calculations suffers from additional complications that require further simplifying assumptions that are, *a priori*, of poorly known validity. Nevertheless, initial results for (p,α) inclusive reactions at 30 and 44 MeV [3], and also in the incident energy range 120–200 MeV [4], are encouraging. The latter study reveals that, as the incident energy is increased, higher-step contributions become more important than first-step knockout of clusters.

Renshaw *et al.* [5] found that the analyzing powers for mass fragments from H to Mg emitted in inclusive reactions of protons on $^{\mathrm{nat}}$Ag at 200 MeV are consistent with zero for emission energies up to 75% of the incident value. The conclusion is thus that neither ^{3}He and ^{4}He, which are of present interest, are produced appreciably by a direct mechanism. Consequently, this result of Renshaw *et al.* is consistent with our earlier finding based on a multistep direct analysis of the inclusive (p,α) reaction.

The reaction mechanism for the emission of ^{3}He induced by energetic protons may differ somewhat from that of the production of α particles. For example, it is reasonable to speculate that a pickup process would be more important for the formation of ^{3}He, whereas a knockout mechanism could dominate for α particles. However, for both species the projectile energy should dissipate in a series of nucleon-nucleon collisions to a value where either the pickup or knockout process becomes energetically favorable.

In this work we compare inclusive $(p,^3\mathrm{He})$ reactions on ^{59}Co and ^{197}Au at incident energies of 120, 160, and 200 MeV with the statistical multistep direct formulation. The results suggest that the theoretical treatment is appropriate, and that the dominant contribution at excitation energies of more than $\sim$30 MeV originates from the pickup of nucleons after at least two successive nucleon-nucleon collisions. In this respect the present results are qualitatively in agreement with the process leading to knockout of α particles at similar incident energies [4] from the same target nuclei.

II. EXPERIMENTAL PROCEDURE

The continuum energy spectra were measured at the National Accelerator Centre, Faure, South Africa, for inclusive $(p,^3\mathrm{He})$ reactions on ^{59}Co and ^{197}Au at incident energies of 120, 160, and 200 MeV simultaneously with (p,α) data [4] published previously. The projectile energy was accurate to $\pm$ 0.5 MeV. The accelerator and experimental equipment have been previously described elsewhere [6].

A detector telescope, consisting of a 150 μm silicon surface barrier detector followed by three Si(Li) detectors of 5 mm nominal thickness each, and a 2 mm silicon surface barrier veto detector, was used. Particle identification was achieved with a standard ΔE–E technique in which various combinations of the detectors in the telescope were used to measure energy loss and total energy of the ejectiles. This allowed the reliable separation of the ^{3}He particles of interest from other ejectiles, especially the adjacent α particles.

Energy calibration of the detector elements was based on the kinematics of the elastic scattering reactions $^1\mathrm{H}(p,p)^1\mathrm{H}$ and $^2\mathrm{H}(p,p)^2\mathrm{H}$ from a deuterated plastic target. The self-supporting targets were metals of natural elements (100% occurrence of the isotope of interest) of thickness in

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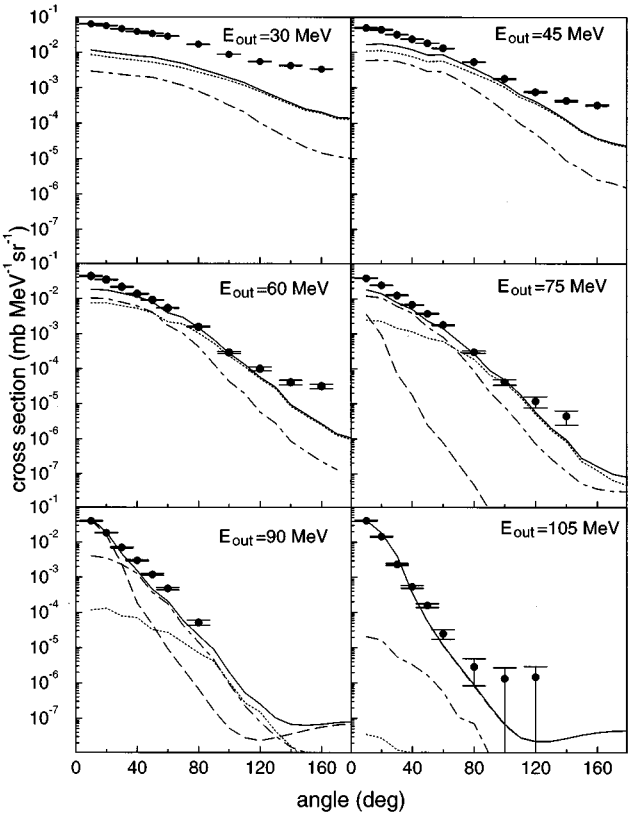

FIG. 1. Double-differential cross sections for the ^{59}Co(p,^{3}He)^{57}Fe reaction at an incident energy of 120 MeV and six outgoing energies, compared with Feshbach-Kerman-Koonin calculations for one-step (long-dashed curves), two-step (dot-dashed curves), and three-step (dotted curves) processes. The sum of the three contributions is given by the solid curves. The error bars reflect statistical uncertainties.

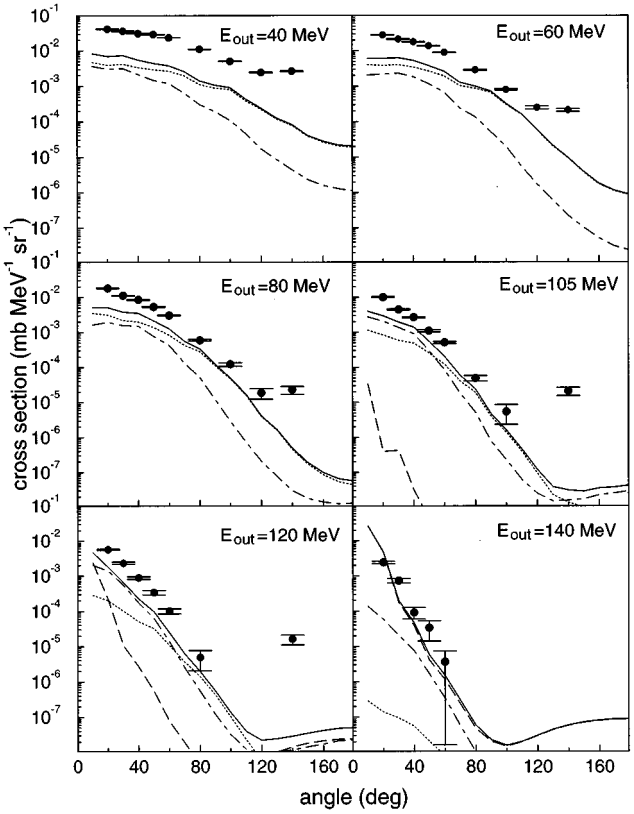

FIG. 2. The same as Fig. 1 for the ^{59}Co(p,^{3}He)^{57}Fe reaction at an incident energy of 160 MeV.

the range 1–4 mg/cm^2. The uncertainty in the thicknesses of the targets (up to 8%) is the main contribution to the systematic error on the data. For high emission energies the angular uncertainty of 0.1° also contributes significantly due to the rapid variation of the cross section with scattering angle.

III. THEORETICAL ANALYSIS

The (p,^{3}He) cross sections were calculated using the multistep direct theory of Feshbach, Kerman, and Koonin [1] assuming that the reaction mechanism is a deuteron pickup. The formalism is very similar to that already used to calculate the (p,α) cross sections [3,4], so here we give just a brief discussion related to the (p,^{3}He) reaction to the continuum.

The one-step double-differential cross section of a (p,^{3}He) transition to a continuum state with excitation energy E is given by

$$\frac{d^2\sigma(\theta,E)}{d\Omega dE}=\sum_{N,L,J}\frac{2J+1}{\Delta E}\frac{d\sigma^{\mathrm{DW}}}{d\Omega}(\theta,N,L,J,E), \qquad (1)$$

where the summation runs over the target states with single-particle energies within a small interval $(E-\Delta E/2, E+\Delta E/2)$ around the excitation energy E. The last factor in Eq. 1 is the DWBA differential cross section. In this analysis we assume that the target nucleus consists of a core to which a deuteron is bound in a shell-model state. The (p,^{3}He) reaction can then be described as a direct transition of a deuteron, considered as a single particle. We use this cluster approximation for simplicity and also because it has been found to give essentially the same results as a microscopic calculation. The distorted-wave Born approximation (DWBA) differential cross section is given by [7,8]

$$\frac{d\sigma^{\mathrm{DW}}}{d\Omega}(\theta,N,L,J,E)=\mathcal{N}\sum_{\{n_k\}}G^2(\{n_k\}^2)\frac{2J_f+1}{2J_i+1}\sum_{T=0,1}b_{ST}^2D_{ST}^2 \times\langle T_fT_{fz}TT_z|T_iT_{iz}\rangle^2\left(\frac{d\sigma}{d\Omega}\right)^{\mathrm{DWUCK}}, \qquad (2)$$

where the sum runs over all possible neutron-proton configurations $\{n_k\}$. Here $\mathcal{N}$ is a normalization constant whose value depends on the square of the fractional parentage coefficient for the two-nucleon removal [9], the optical model potentials and other unknowns. $G^2(\{n_k\}^2)$ is the spectroscopic factor for a proton and neutron to form a deuteron bound state with quantum numbers (N,L,J). The sum in Eq. (2) is over the transferred isospin T with the selection rule $S+T=1$. The quantity b_{ST}^2 is 0.5 for both values of S and T, and the values for the strengths of the proton-deuteron interaction D_{10}^2 and D_{01}^2 are 0.3 and 0.72, respectively [10]. The square of the Clebsch-Gordan coefficient depends on initial, transferred, and final isospins T_i, T, and T_f. The quantities J_f and J_i are

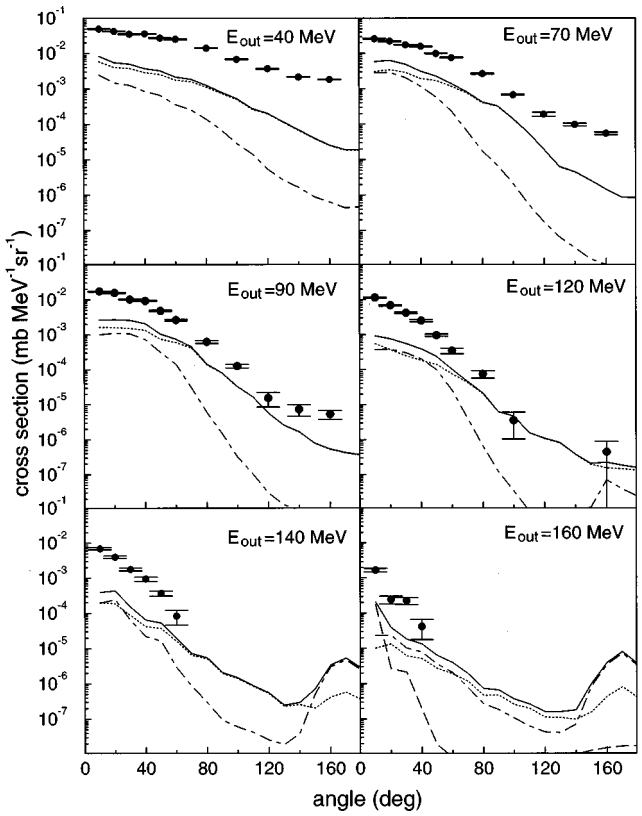

FIG. 3. The same as Fig. 1 for the ^{59}Co$(p,^3\mathrm{He})^{57}$Fe reaction at an incident energy of 200 MeV.

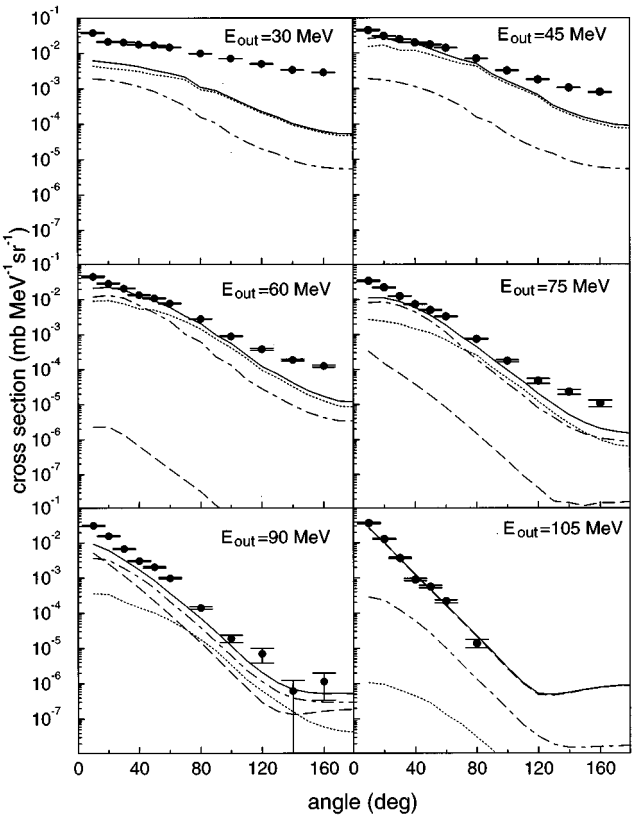

FIG. 4. The same as Fig. 1 for the ^{197}Au$(p,^3\mathrm{He})^{195}$Pt reaction at an incident energy of 120 MeV.

final and initial total angular momenta, respectively. The differential cross sections to particular (N,L,J,T) states are calculated using the code DWUCK [11]. The form factor of the deuteron is obtained using the ''well-depth'' procedure for a Woods-Saxon potential with geometrical parameters $r_0=$ 1.15 fm and $a=$ 0.76 fm [12,13], which are adjusted so that microscopic and macroscopic form factors are almost identical. The optical potentials used are those of Walter and Guss [14] and Madland-Schwandt [15,16] for protons, and of Willis *et al.* [17] and Fulmer and Hafele [18] for ^{3}He potentials for ^{59}Co and ^{197}Au, respectively. The calculated cross sections are rather insensitive to the proton potential but very sensitive to the ^{3}He potential. We therefore used the ^{3}He potential that gives the best overall fit to both elastic scattering and reaction data, since the elastic scattering data alone do not determine the potential with sufficient accuracy [19]. This potential is used for all outgoing energies since the ^{3}He potential, like that of the α particle, has a small energy dependence [20]. The convolution structure of the formalism allowed the calculation of multistep processes, in particular the two-step $(p,p',^3\mathrm{He})$ and three-step $(p,p',p'',^3\mathrm{He})$ reactions. The $(p,n,^3\mathrm{He})$ reaction was not included because it requires the pickup of a diproton.

For each incident energy, the reaction is dominated (at the highest outgoing energy) by the direct one-step reaction, and so the calculated cross sections were normalized to these data at 120 MeV. This normalization factor was then used for the reactions at all other outgoing and incident energies for each nucleus.

IV. RESULTS AND DISCUSSION

The results of these calculations are shown in Figs. 1–6. The theoretical angular distributions for various emission energies are compared directly with the experimental quantities, which are in the laboratory coordinate system. This procedure is reasonable because the systematic angular and absolute cross section uncertainties exceed the relatively small center-of-mass corrections for the target nuclei investigated in our work.

It is notable that as the energy transfer increases the two-step process becomes increasingly more important and becomes comparable with the one-step process for energy differences between incident and outgoing energies around 30 MeV. Thereafter the one-step cross section decreases rapidly with decreasing outgoing energy, finally becoming negligible for energy differences of around 50 MeV where two- and three-step processes dominate the cross section. At still lower outgoing energies, four-step and more complicated processes become important, particularly at large scattering angles. There is also a contribution from compound nucleus reactions, but the asymmetry of the measured cross sections shows that this is very small. These mechanisms, which were not included in our analysis, are expected to account for the remaining difference between theory and experiment at the lowest emission energies.

Renshaw *et al.* [5], who investigated intermediate-mass fragments induced by protons on $^{\mathrm{nat}}$Ag at 200 MeV, concluded that the direct process does not contribute significantly to the reaction. Their conclusion is supported by the very low analyzing powers observed at emission energies up

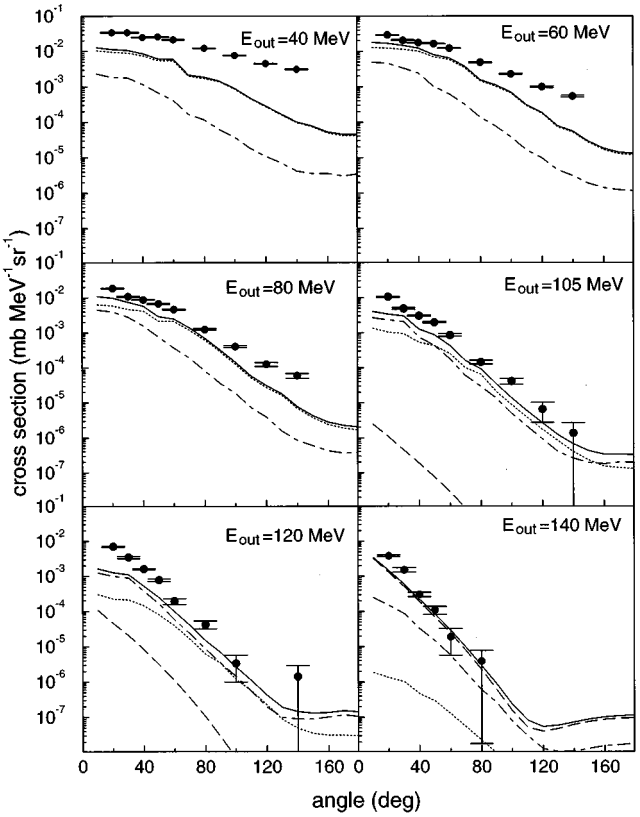

FIG. 5. The same as Fig. 1 for the ^{197}Au(p,^{3}He)^{195}Pt reaction at an incident energy of 160 MeV.

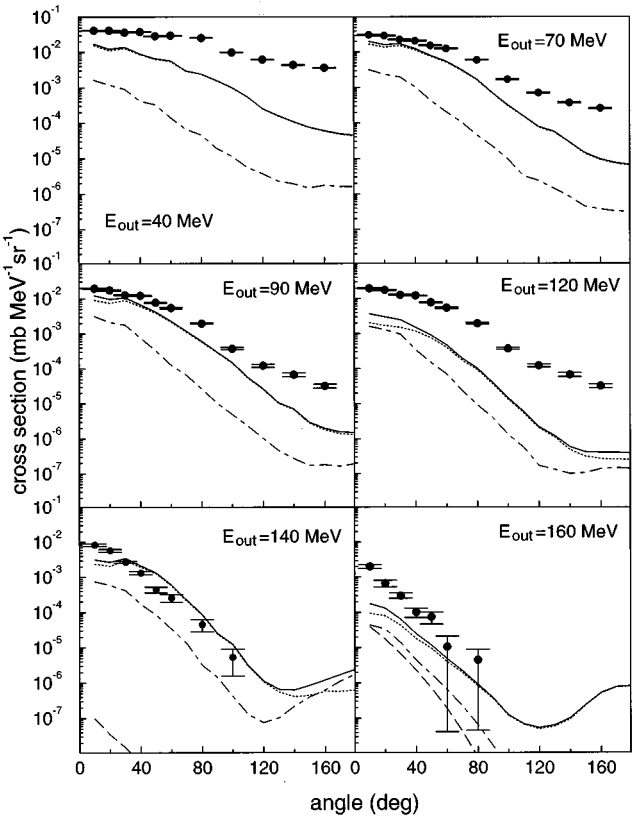

FIG. 6. The same as Fig. 1 for the ^{197}Au(p,^{3}He)^{195}Pt reaction at an incident energy of 200 MeV.

to 150 MeV for small scattering angles. That result is consistent with our findings, for example, as displayed in Fig. 6. Our study indicates that the one-step process consistently contributes several orders of magnitude less to the total cross section than the dominant three-step process, up to emission energies of 150 MeV. However, at an excitation energy of $\sim$20 MeV, the direct process does contribute greatly, as may typically be seen in Figs. 4 and 5.

V. SUMMARY AND CONCLUSIONS

Experimental cross sections for the inclusive reactions ^{59}Co(p,^{3}He) and ^{197}Au(p,^{3}He) at incident energies of 120, 160, and 200 MeV were interpreted with a statistical multistep direct formulation in which successive nucleon-nucleon collisions are finally followed by a pickup process that forms the ejectile. The comparison between experimental and theoretical angular distributions indicates that the theoretical treatment is probably a good representation of the first stages of the reaction. The pickup mainly occurs after two or more successive nucleon-nucleon interactions, except for high emission energies, where a direct process is more significant. The remaining differences between the theoretical and experimental results provide a strong incentive for more refined calculations.

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