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Inclusive (p,α) reactions on ^{27}Al, ^{59}Co, and ^{197}Au at incident energies of 120, 160, and 200 MeV

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Measurements of inclusive (p,α) reactions on ^{27}Al, ^{59}Co, and ^{197}Au at incident energies between 120 and 200 MeV are compared with the trend expected from systematics and also with calculations based on a statistical multistep direct reaction theory. Although reasonable agreement is obtained between the experimental angular distributions and the predictions of the parametrized systematics at various emission energies, significant discrepancies are nevertheless observed. Calculations with the quantum-mechanical multistep formulation confirm that the higher-step contributions are more important at these incident energies than found in a previous study at lower projectile energies. [S0556-2813(96)03007-5]

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I. INTRODUCTION

Inclusive nucleon emission induced by protons at incident energies in the range 100–200 MeV is described reasonably well [1–3] by quantum-mechanical formulations such as the statistical multistep theory [4] of Feshbach, Kerman, and Koonin. For composite ejectiles, such as α particles, the reaction mechanism is not understood to the same extent and it needs to be determined whether the dominant process corresponds to the knockout of preformed α clusters, or alternatively to pickup of nucleons as the projectile traverses the nuclear medium. For reactions to discrete states at lower incident energies the pickup reaction mechanism is probably more important, whereas there is evidence that the knockout reaction dominates in reactions to the continuum at higher incident energies [5]. Therefore it is important to investigate whether the recent [6] successful description of the inclusive (p,α) reaction on ^{93}Nb, ^{107}Ag, ^{118}Sn, ^{165}Ho, and ^{169}Tm, at incident energies of 30 and 44 MeV, in terms of the quantum-mechanical multistep formulation of α knockout, can be extended to higher incident energies and to other nuclei.

Whether the inclusive (p,α) spectra follow the systematics of the phenomenological parametrization [7] of Kalbach in this energy range is also of interest, as it may provide guidance to a formal theoretical treatment of the reaction process. For angular distributions of inclusive spectra for ^{197}Au(p,p') at incident energies of 100 and 200 MeV, it was found previously [8] that the Kalbach systematics describe the experimental quantities very well. At incident energies between those two values, however, small but significant discrepancies are encountered. It was suggested that the observed differences could be eliminated by a simple modification of the parametrization that introduces a smooth transition from the lower incident energy to the upper value, instead of the sharp discontinuity in the original formulation. Nevertheless, the need for such a modification is not firmly established, as the deviation between the original parametrization and the experimental data is relatively minor. For the present investigation, which also includes the (p,α) inclusive reactions on ^{197}Au, it is important to determine whether a discrepancy similar to that found for (p,p') applies and, if so, whether the same modification to the parametrization improves the situation.

In this paper we investigate the (p,α) inclusive reactions between 120 and 200 MeV on ^{27}Al, ^{59}Co, and ^{197}Au. We compare the angular distributions between 10° and 160° with the predictions of the phenomenological parametrization of Kalbach [7]. The (p,α) results for ^{59}Co are also compared with calculations based on the statistical multistep direct mechanism in which a preformed α cluster is knocked out by the incident proton.

II. EXPERIMENTAL PROCEDURE

The continuum energy spectra were measured at the National Accelerator Centre for inclusive (p,α) and $(p,^{3}\mathrm{He})$ reactions on ^{27}Al, ^{59}Co, and ^{197}Au at incident energies of 120, 160, and 200 MeV. The accelerator and experimental equipment have been described elsewhere [9].

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. This arrangement was chosen instead of the telescope with a NaI scintillator used for our previous (p,p') inclusive studies [1–3,8–10], because for

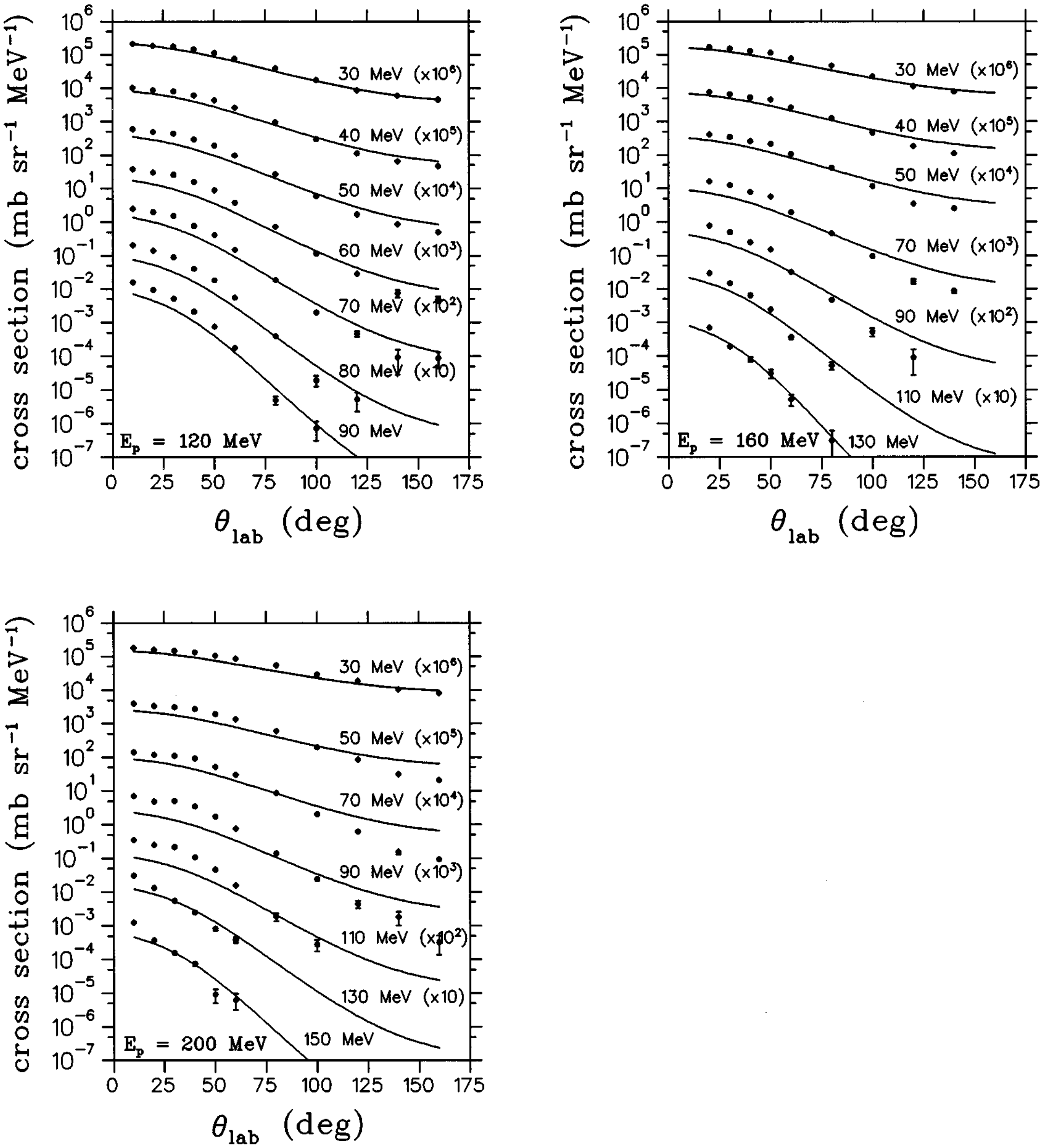

FIG. 1. Laboratory angular distributions for the inclusive reaction $^{27}\mathrm{Al}(p,\alpha)$ at incident energies E_p of 120, 160, and 200 MeV and various emission energies, as indicated. The distributions have been multiplied by the indicated factors for the purpose of display. Data are shown with error bars where these exceed the symbol size. The curves are distributions, predicted by the Kalbach systematics, normalized to the experimental data.

acceptable count rates of the composite ejectiles, the proton rate would be high enough to lead to gain instabilities in a scintillator-phototube assembly.

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 α particles of interest from other ejectiles, especially ^{3}He.

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 the range of 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.

III. RESULTS AND DISCUSSION

The experimental angular distributions for the (p,α) reaction on ^{27}Al, ^{59}Co, and ^{197}Au at incident energies of 120, 160, and 200 MeV are shown in Figs. 1–3. These distributions have been multiplied by the indicated factors for the purpose of display. Data are shown with error bars where these exceed the symbol size.

A. Comparison with parametrized systematics

It is found that the shapes of the experimental (p,α) distributions are reproduced reasonably well by the predictions

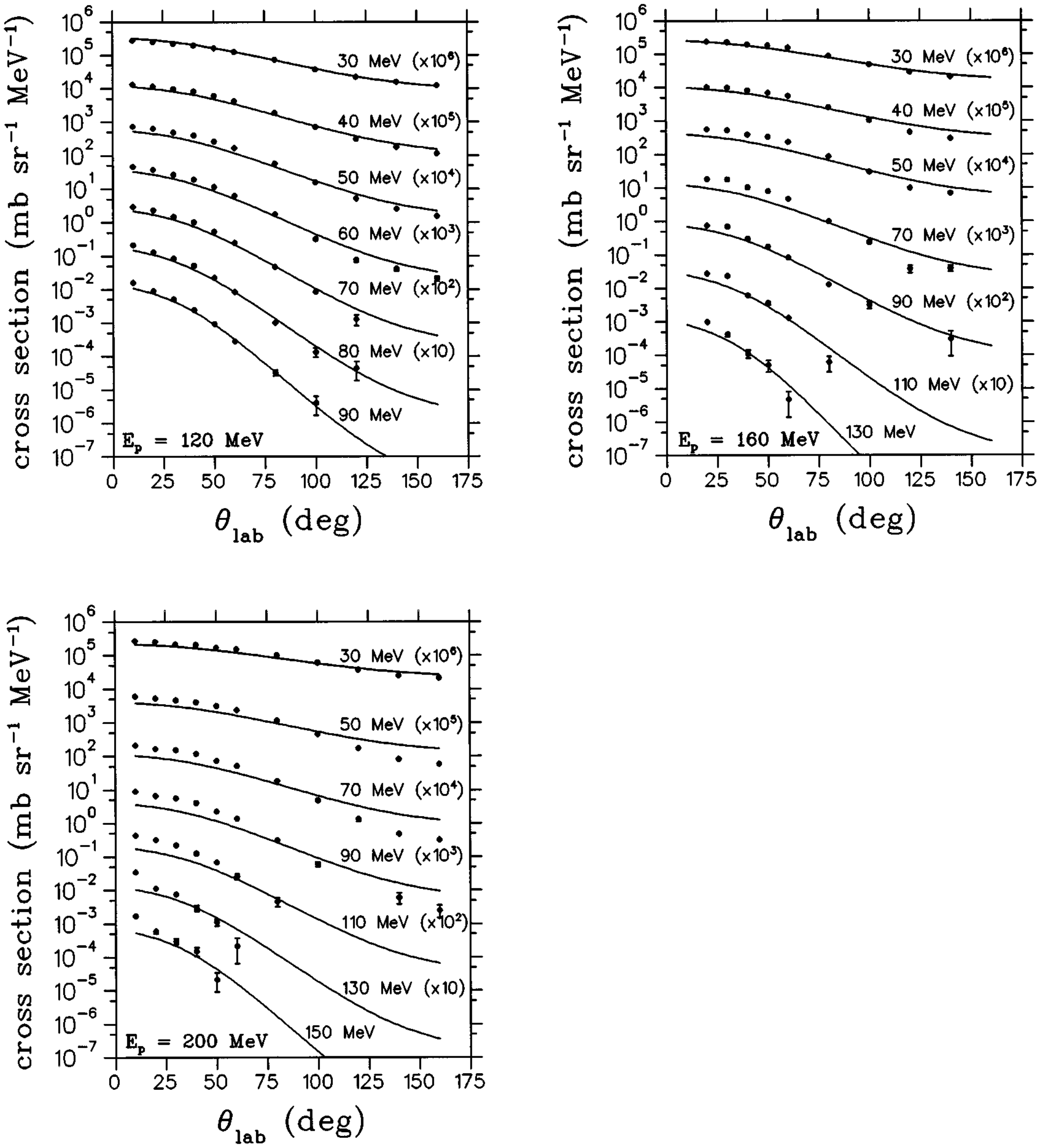

FIG. 2. Laboratory angular distributions for the inclusive reaction ^{59}Co(p,α). For other details, see caption to Fig. 1.

of the Kalbach parametrization, in which the calculated distributions are normalized to the experimental data for each distribution. However, in spite of the encouraging agreement between the experimental data and the phenomenological formulation, as seen especially for the results on ^{197}Au in Fig. 3, systematic deviations are encountered. The best agreement between the formulation and the (p,α) data is obtained for ^{197}Au at 120 MeV. As the incident energy is increased, the slopes of the predicted curves deviate increasingly from the measured distributions for this target. For the two lighter target masses (Figs. 1 and 2) the deviation becomes more severe with decreasing target mass, especially at high emission energies.

The results of the comparison for the (p,α) reaction on ^{197}Au are very different from those found previously [8] for the (p,p') reaction. For the latter reaction a difference between the data and the phenomenological systematics was only encountered for incident energies intermediate between 100 and 200 MeV, and the deviations could be correlated with the known [8] discontinuity in the parametrization. In the present investigation, however, the influence of the discontinuity in the parametrized systematics appears to be negligible and the agreement with the experimental data is even better at 120 and 160 MeV than at 200 MeV.

B. Comparison with calculations of the multistep direct reaction theory

The (p,α) cross sections were calculated using the multistep direct theory of Feshbach, Kerman, and Koonin [4] extended by Olaniyi *et al.* [6] and Guazzoni *et al.* [11]. The formalism is summarized in these two papers, so here we show how the theory is further developed to include the multistep processes that are increasingly important at higher energies.

In these calculations, following the work of Bonetti *et al.* [5,12], it is assumed that the (p,α) reaction takes place by a knockout process. The incident proton collides with a pre-

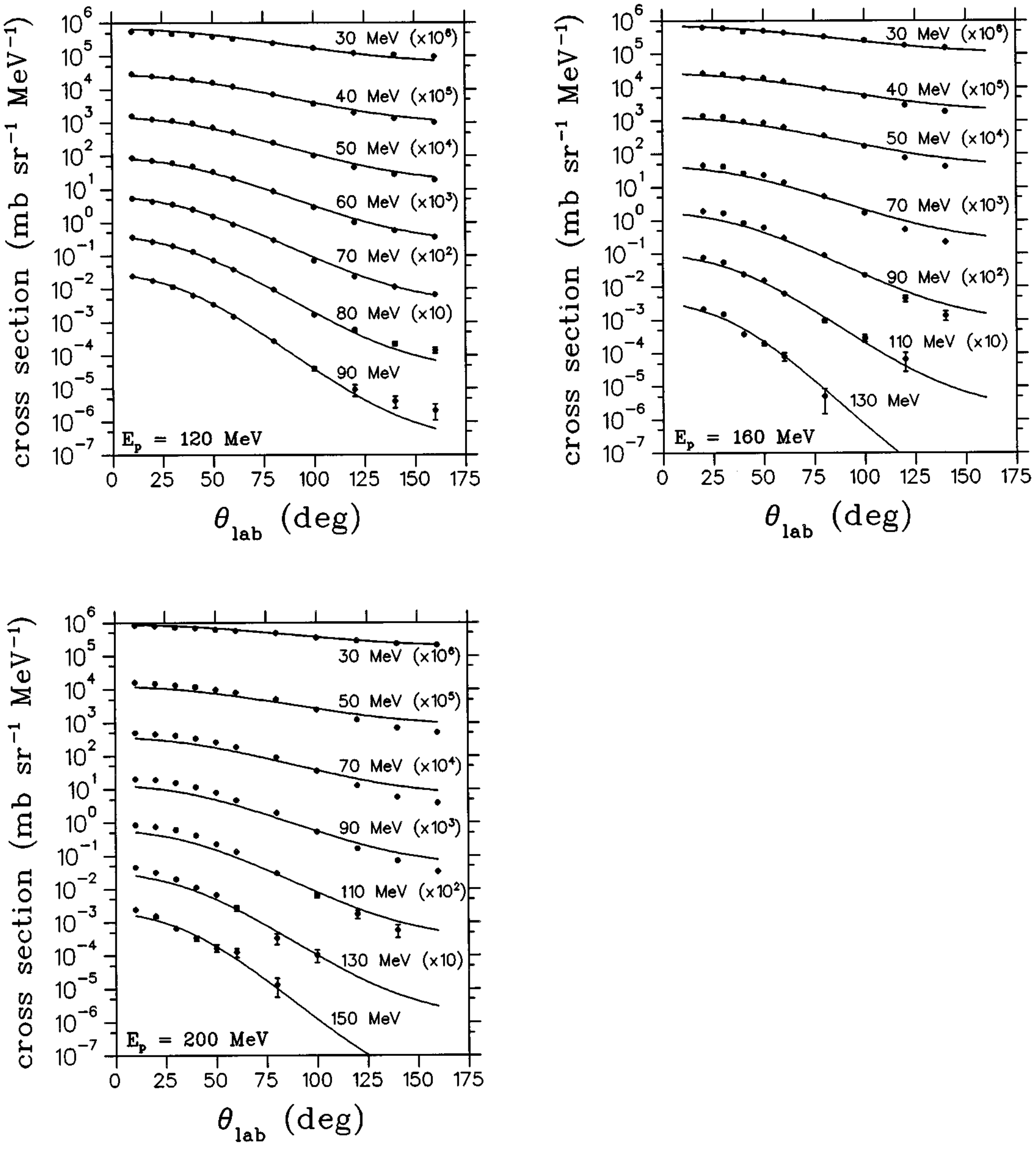

FIG. 3. Laboratory angular distributions for the inclusive reaction ^{197}Au(p,α). For other details, see caption to Fig. 1.

formed α-particle in the target nucleus, knocks it out and is captured by the residual nucleus. Olaniyi *et al.* [6] estimated the contribution of two-step processes and found them to be rather small at 44 MeV, the highest energy studied. As the incident energy increases, the multistep processes become more probable, and must certainly be included at the energies considered here. The calculation was therefore modified to include the $(p,p')(p',\alpha)$ and $(p,n)(n,\alpha)$ two-step processes and the four $(p,N)(N,N')(N',\alpha)$ three-step processes. These processes contribute incoherently and, as they each include just one nucleon-alpha interaction and one α-particle preformation factor, the cross sections include the same (unknown) normalization factor. This is not the case, for example, for processes like $(p,\alpha)(\alpha,\alpha')$ which contain additional unknown factors, in this case the strength of the α-α interaction.

In the previous calculations [6] it was assumed that the proton is captured into a bound state of the residual nucleus, but as the energy increases it is more likely that both the proton and the α particle are unbound after the interaction and so this possibility was also included in the calculations. Phase space arguments indicate that the proton is likely to be unbound for incident energies above 100 MeV, particularly for low ejectile energies. For calculational convenience we represent the unbound proton wave functions by quasibound ones calculated with a Woods-Saxon potential, the depth of which is adjusted to give a small proton binding energy (0.2 MeV).

As in the previous calculations, we use the computer program DWUCK4 [13] which, however, calculates only the direct terms of the DWBA transition amplitude. This may be used for the (p,α) knockout reaction, which is an exchange reaction, because the direct and exchange amplitudes give the same angular distribution for a zero range interaction.

The orbital angular momentum L of the preformed α particle was assumed to be zero, as in the work of Tamura *et al.*

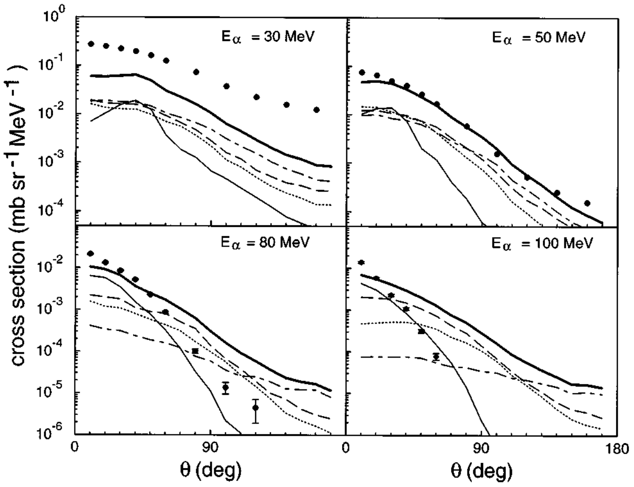

FIG. 4. Comparison between measured and theoretical angular distributions for the reaction ^{59}Co(p,α) at an incident energy of 120 MeV for various α-particle emission energies E_α. The thin solid curves are first-step (p,α) knockout contributions. The contributions for $(p,p')(p',\alpha)$ (dotted curves) and $(p,n)(n,\alpha)$ (dashed curves) are indicated separately, with a single dot-dashed curve representing the sum of three-step contributions. The summed cross sections are shown as thick solid lines. The results of the theoretical calculations are compared directly with the experimental data in the laboratory coordinate system because the effect of center-of-mass motion is negligible compared to the influence of experimental errors.

[14]. Calculations with $L=4$ gave a very similar angular distribution. The nucleon optical potentials used were those of Walter and Guss [15] for $E<50$ MeV and of Schwandt *et al.* [16] for $50<E<200$ MeV. The optical potential of Avrigeanu *et al.* [17] was used for the α particles. The single-particle state densities were taken to be $g_N=A/13$ and $g_a=g_N/4$. The exciton number in the expression for the spin cutoff parameter was taken to be $n=2$ for the residual nucleus after the one-step (p,α) reaction.

The effective nucleon-nucleon interaction had the Yukawa form with radius 1 fm, and its strength V_0 was fixed by the fit to ^{58}Ni(p,p') inclusive cross sections at the appropriate energy. The difference in V_0 [2,18] for (p,p') and (p,n) reactions was included in the calculations of the multistep processes. The (N,α) interaction was taken to be zero range. Only the $(p,p')(p',p'')(p'',\alpha)$ three-step process was calculated, and the resulting cross section was multiplied by four to take account of the other three processes. This calculation is affected by the energy dependence of the nucleon-nucleon effective interaction, which was included in the calculations [19].

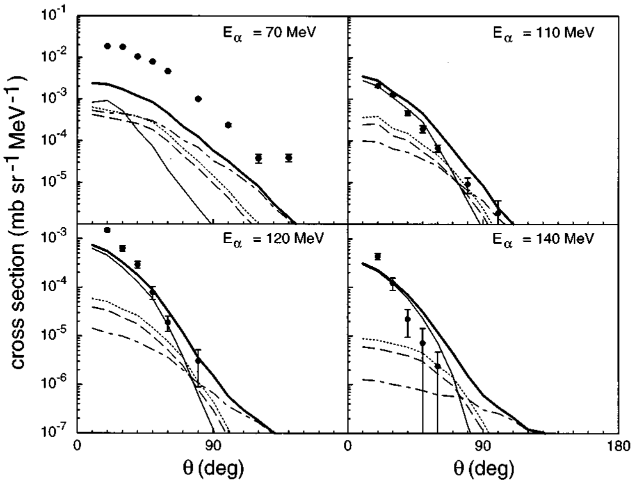

FIG. 5. Comparison between measured and theoretical angular distributions for the reaction ^{59}Co(p,α) at an incident energy of 160 MeV for various emission energies. See also caption to Fig. 4.

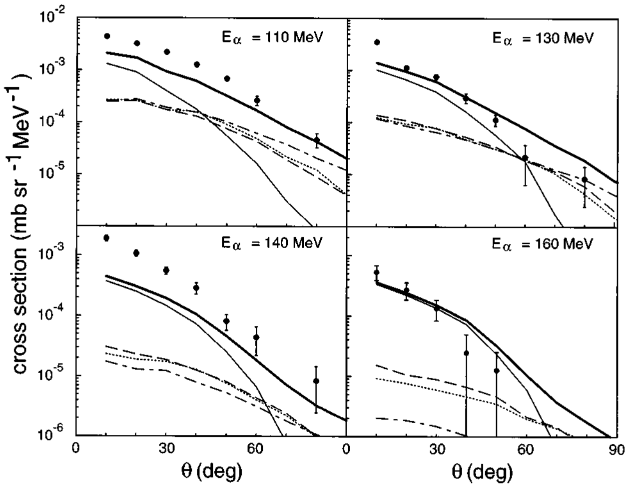

FIG. 6. Comparison between measured and theoretical angular distributions for the reaction ^{59}Co(p,α) at an incident energy of 200 MeV for various emission energies. See also caption to Fig. 4.

In all the calculations the normalization factor was adjusted to give the best overall fit to the double differential cross sections at all outgoing energies for a particular reaction. The results for ^{59}Co(p,α) at 120, 160, and 200 MeV are shown in Figs. 4–6 with the contributions of the one-, two-, and three-step processes shown separately. On the whole the fit is reasonable considering the approximations made, although there are some notable discrepancies that deserve further study. The $(p,p')(p',\alpha)$ and $(p,n)(n,\alpha)$ two-step processes dominate at the higher ejectile energies and have similar angular distributions. As expected, the three-step processes become progressively more important as the ejectile energy decreases, and the angular distributions become less forward peaked as the number of steps decreases. Similar conclusions were reached by Tamura *et al.* [14] from their analysis of the ^{93}Nb(p,α) reaction at an incident energy $E_p=65$ MeV and emission energy $E_a=45$ MeV. Some additional calculations with bound protons only gave much reduced cross sections at low outgoing energies that did not fit the data, showing that it is essential to include the unbound proton configurations.

IV. SUMMARY AND CONCLUSIONS

Good agreement was obtained between predictions of the parametrized systematics of Kalbach [7] and the experimental angular distributions of inclusive (p,α) reactions on ^{27}Al, ^{59}Co, and ^{197}Au at incident energies of 120, 160, and 200 MeV over a large range of emission energies. The discrepancies that are encountered are found to become more noticeable with increasing incident energy, and also with decreasing target mass number.

Calculations based on the statistical multistep direct reaction theory of Feshbach, Kerman, and Koonin [4] reproduces the measured (p,α) angular distributions reasonably well. Further calculations with exchange matrix elements treating the unbound proton configuration in a rigorous way are necessary for a more accurate analysis. The present calculations are sufficient to show that the overall features of the (p,α) data can be described by the multistep theory, and in particular that the second- and higher-step contributions to the reaction at the incident energies explored in this work are more important than at the lower incident energies studied previously.

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