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ANALYSIS OF (p, α) and $(p,{}^3\text{He})$ CROSS-SECTIONS TO CONTINUUM STATES BY THE FESHBACH-KERMAN-KOONIN MULTISTEP DIRECT THEORY

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Abstract

The cross-sections of several (p, α) and $(p,{}^3\text{He})$ reactions at high energies to continuum states are analysed in order to obtain information on clustering in nuclei.

1. Introduction

The presence of clusters of nucleons inside nuclei greatly enhances the cross-sections of cluster knockout and transfer reactions. It is therefore useful to study such reactions in order to determine the probabilities of various possible types of cluster.

The most probable cluster in nuclei is the alpha-particle, due to its high symmetry and binding energy. Alpha-transfer and alpha knockout reactions have therefore been extensively studied in order to determine the alpha-clustering probability (Hodgson, 1979, 1987, 1990, 1994).

One of the reactions most frequently used to study alpha-clustering in nuclei is the (p, α) reaction, and many analyses of the differential cross-sections and analysing powers of this reaction to discrete states have been made (Gadioli and Hodgson, 1989) using either the triton pick-up or the alpha-particle knock-out models. Both models give rather similar results (Gadioli *et al*, 1984), but nuclear structure arguments favour the pick-up model. For a long time the calculations gave absolute magnitudes for the cross-section that were far too low (Brunner *et al*, 1983; Hoyler *et al*, 1985) but detailed analyses (Walz *et al*, 1988) have largely removed the discrepancy, although some difficulties still remain (Kajihara, 1992).

Comparatively few analyses have been made of (p, α) reactions at higher incident energies that proceed to unresolved continuum states. Bonetti *et al* (1989) calculated the analysing power of the (p, α) reaction at 22 and 72 MeV on ^{58}Ni to both discrete and continuum states and found that for the reactions to continuum states only the knockout model gives analysing powers in accord with the data. The (p, α) reaction to continuum states is thus a suitable reaction for studying alpha-clustering in nuclei, and some recent analyses are described in Section 2.

The same experiments also gave the cross-sections of the $(p,{}^3\text{He})$ reaction on the same nuclei, and these were analysed using the deuteron-pickup model. This work is described in Section 3. Some conclusions are given in Section 4.

2. Analyses of (p, α) Reactions

At the higher incident energies corresponding to reactions to the continuum, the contributions of two, three and higher step processes become more important, and so it is appropriate to use multistep reaction theories. Quantum-mechanical theories of multistep reactions have been developed by Feshbach, Kerman and Koonin (1980) (FKK), by Tamura *et al* (1977ab, 1981, 1982) and by Nishioka, Weidenmüller and Yoshida (1988, 1990). These theories make somewhat different statistical assumptions, and they have been compared in detail by Koning and Akkermans (1991, 1993). They give the same result for the first step of the reaction, but differ for the second and higher steps. The FKK theory gives expressions for the cross-section that have a simple convolution structure which greatly facilitates the calculation of the contributions of the higher steps, and mainly for this reason it has been used more often than the other theories to analyse experimental data.

The first detailed analysis of double-differential cross-sections of (p, α) reactions using the FKK theory was made by Olaniyi *et al* (1995), using the data of Ferrero *et al* (1979). These data comprised double differential cross-sections on several nuclei for incident energies of 30 and 44.3 MeV. At these energies two-step processes are unlikely and the incident proton is captured into a bound state of the residual nucleus. There is, however, a large contribution from the compound nucleus process, so this was removed using the subtraction method (Demetriou *et al*, 1993). The remaining cross-section was analysed using the multistep direct FKK theory, which proved able to give a good fit to the data. The compound nucleus cross-section was calculated using the theory of Hauser and Feshbach (1952) and, when added to the multistep direct cross-section, gave a good overall fit to the angle-integrated energy spectra of the outgoing alpha-particles as shown in Fig.1. Pairing and spectator effects in (p, α) reactions were studied by Guazzoni *et al* (1996).

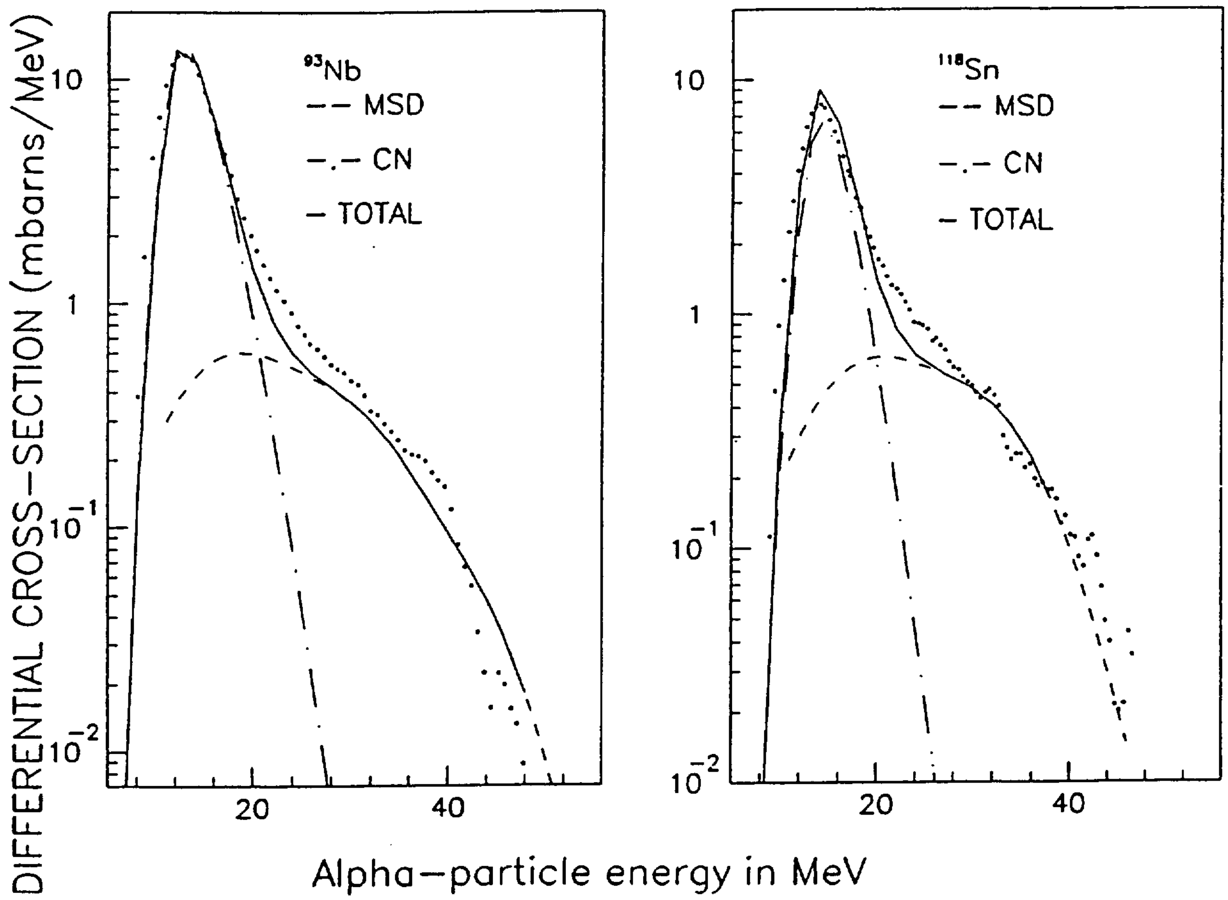

Fig. 1. Angle-integrated cross-sections for the (p, α) reaction on ^{93}Nb and ^{118}Sn at 44.3 MeV compared with zero-range FKK multistep direct (short-dash curves) and compound nucleus (long-dash curves) calculations. The full curves show the sum of the two components (Olaniyi *et al*, 1995).

A more detailed study of the energy dependence of the (p, α) cross-section was made by Demetriou and Hodgson (1996). As in the case of nucleon-induced reactions, the only energy dependence in the FKK theory is that of the effective interaction, and the folding model indicates that this is the same as that of the corresponding optical potential. In the case of the (p, α) reaction, this is the alpha-particle optical potential, and the effective interaction was indeed found to have the same, rather weak, energy dependence, within the experimental uncertainties.

As in previous analyses, it was found that the calculated cross-sections are relatively insensitive to the proton optical potential, but are very sensitive to that of the alpha-particle, even when they are in accord with the corresponding elastic scattering cross-sections. This is a serious difficulty in all analyses using optical potentials obtained from analyses of elastic scattering cross-sections. The reason for this sensitivity is to be found in the different contributions of the S-matrix elements to the elastic and non-elastic-reactions, so that a set determined from elastic scattering does not necessarily give the best physically-correct values for non-elastic reactions. The only way to tackle this problem phenomenologically is to choose the sets of proton and alpha-particle optical potentials also that give the best fit to the reaction data, and this procedure was adopted.

These calculations were subsequently extended to analyse the (p, α) cross-sections at 120, 160 and 200 MeV on ^{27}Al, ^{59}Co and ^{197}Au (Cowley *et al*, 1996). At these energies, multistep processes become increasingly important, and it is more likely that the incident proton remains in the continuum. The multistep processes can be readily calculated because of the convolution structure of the multistep direct FKK theory, but it is more difficult to include the effects of unbound protons in the final state. In these calculations the device was adopted of deepening the proton potential to make these protons just bound. This may be a reasonable approximation at energies just above the threshold, but it is likely that it becomes increasingly unsatisfactory at higher energies.

In these calculations, the two-step reactions (p, p', α) and (p, n, α) were included, and also the three-step (p, N, N', α) reactions, where N stands for a neutron or a proton. The multistep reactions require the nucleon-nucleon effective interaction, and its energy dependence was included in the calculations. The calculations were normalised to the experimental data at the highest outgoing energies, which are dominated by the one-step process. The normalisation factor includes the alpha-particle pre-formation factor in the target nucleus and the other uncertainties in the calculation. The results of some of these calculations are shown in Fig.2, and the contributions of the first, second and third steps to the ^{59}Co(p, α) reaction at 120, 160 and 200 MeV are shown in Fig.3.

3. Analysis of $(p, {}^3\text{He})$ Reactions

In the experiment of Cowley *et al* (1996), the emitted helions were resolved from the alpha-particles. These double-differential cross-sections for the $(p, {}^3\text{He})$ reaction to the continuum were also analysed using the FKK theory, assuming that the reaction mechanism is deuteron pickup.

The DWBA cross-section is given as a sum over all possible neutron-proton configurations and isospin transfers, with the appropriate Clebsch-Gordon coefficients. The form factor of the deuteron was obtained using the well-depth procedure with geometrical parameters adjusted so that the microscopic and macroscopic form factors are almost identical. The ^{3}He optical potential was chosen to give the best overall fit to both elastic scattering and reaction data. The cross-sections of the two-step $(p, p', {}^3\text{He})$ and three-step $(p, p', p'', {}^3\text{He})$ reactions were also calculated. The cross-sections were normalised to the data at the highest outgoing energy. Some typical results for the cross-sections are shown in Fig.4, and for the individual contributions of the one, two and three-step processes in Fig.5. 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 around 50 MeV where two- and three-step processes dominate the cross-section.

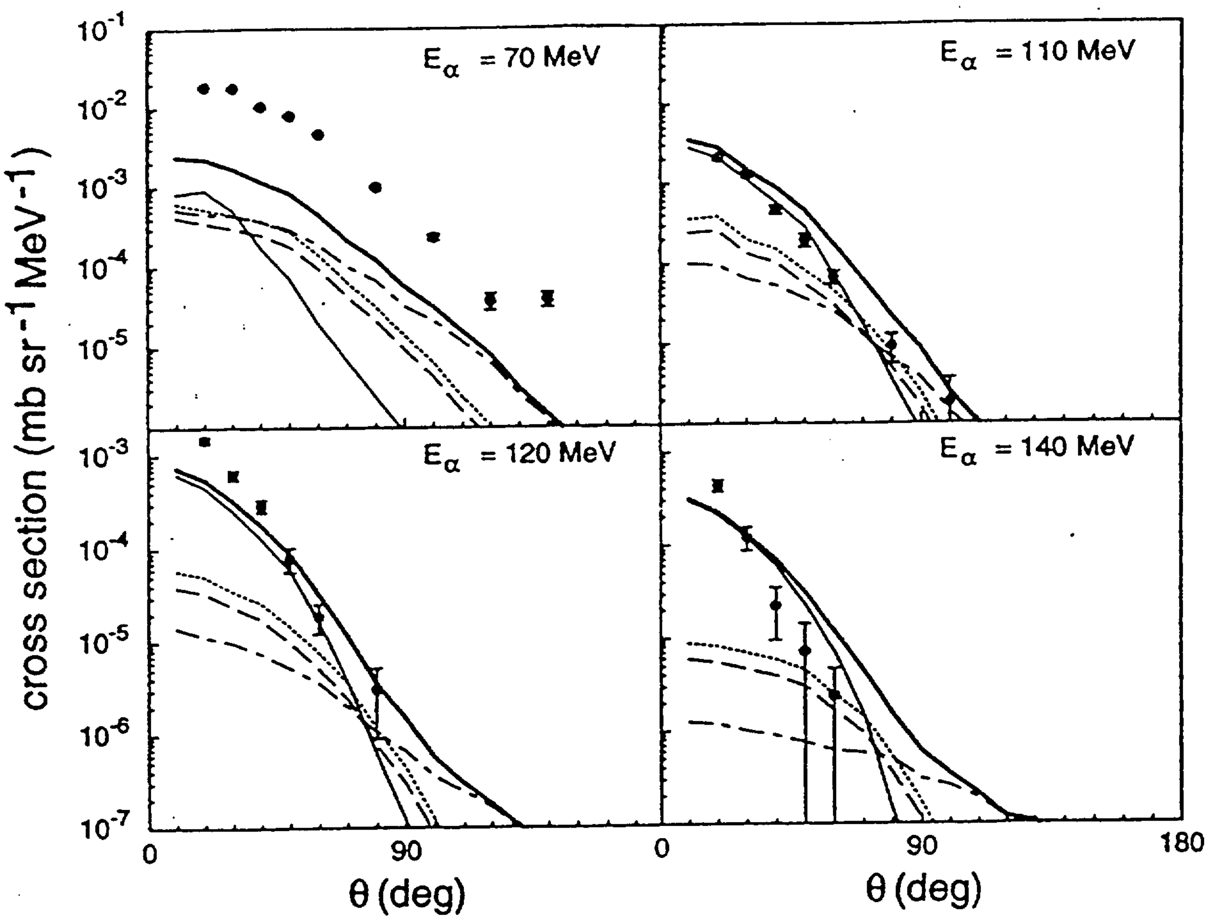

Fig. 2. Double-differential cross-sections for the ^{59}Co(p, α) reaction at an incident energy of 160 MeV compared with Feshbach-Kerman-Koonin calculations for one-step knockout (thin solid curves), the two-step (p, p', α) (dotted curves) and (p, n, α) (dashed curves) processes and the sum of the three-step contributions (dot-dashed curves). The sum of all these processes is given by the thick solid curves (Cowley *et al*, 1996).

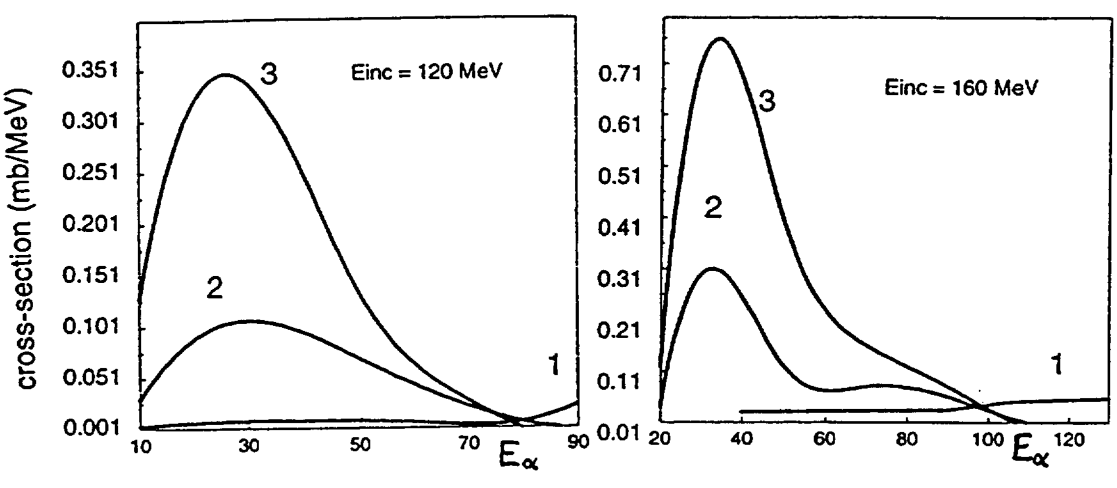

Fig. 3. The cross-sections of the first, second and third steps of the ^{59}Co (p, α) reaction for two incident energies as a function of the outgoing alpha-particle energy.

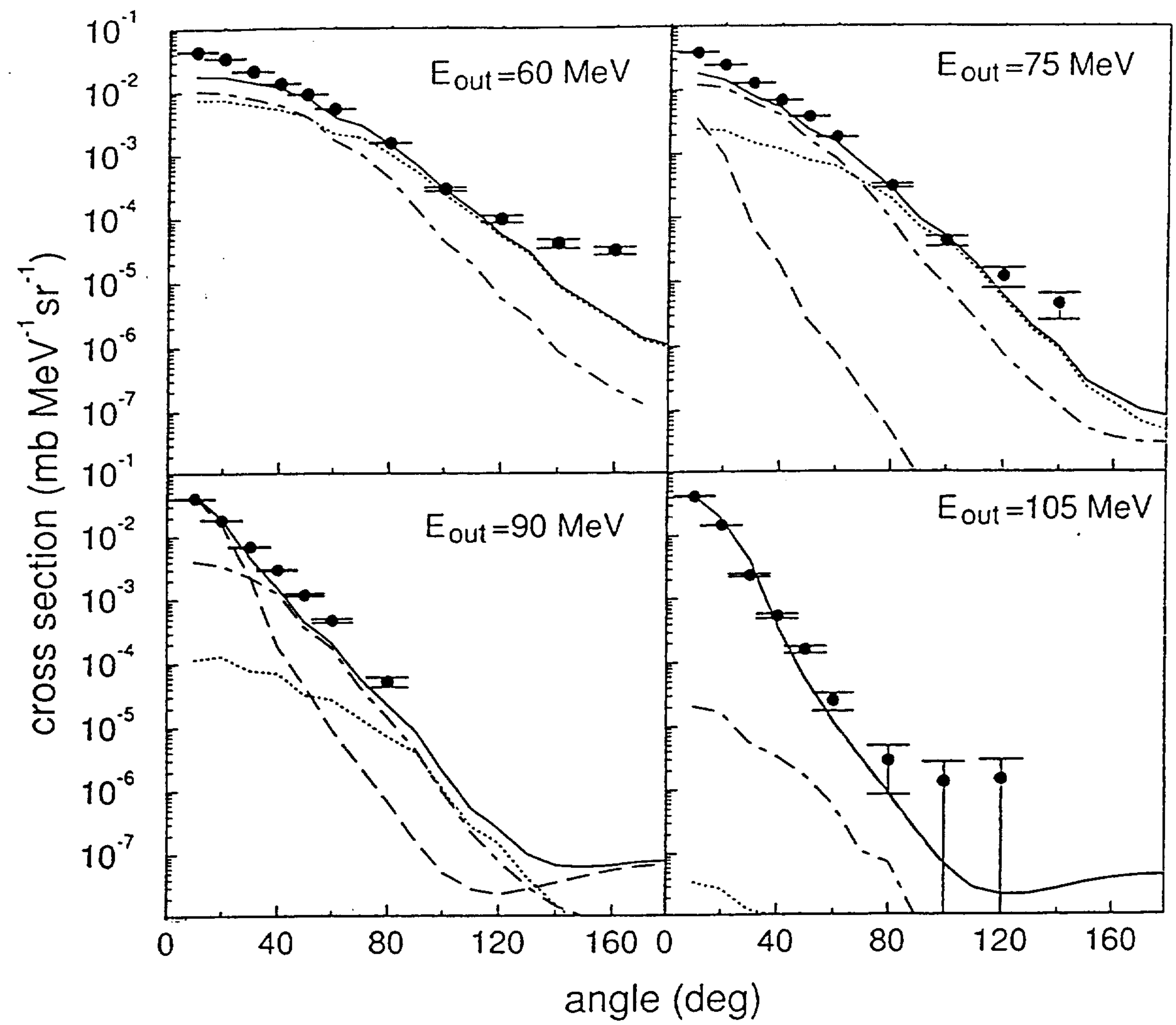

Fig. 4. Double-differential cross-sections for the $^{59}Co(p,{}^{3}He)^{57}Fe$ reaction at an incident energy of 120 MeV compared with Feshbach-Kerman-Koonin calculations for one step (long-dashed curves), two-step (dot-dashed curves) and three-step (dotted curves) processes. The sum of these contributions is shown by the solid curves (Cowley *et al*, 1997).

4. Conclusion

These studies of (p,α) and $(p,{}^{3}He)$ reactions to continuum states using the knock-out and pick-up models show that they are able to give a good account of the experimental cross-sections and, in the case of the (p,α) reaction, analysing powers. The comparison between the calculated analysing powers and the experimental data made by Bonetti *et al* (1989) definitely favours the knock-out model, and thus supports the concept of alpha-particle clustering in nuclei. It would, however, be desirable to have confirmation of this from analyses of (p,α) reactions on other nuclei. A more accurate theoretical analysis requires the formulation of the reaction with the incident proton remaining in the continuum.

While the concept of clustering is evidently applicable to alpha-particles, due to their high binding energy and thus good spatial localisation, the same can hardly be said for the deuteron cluster used in the analysis of $(p,{}^{3}He)$ cross-sections using the pick-up model. A deuteron is not small compared with the nucleus, and so the concept of clustering is less plausible.

All these analyses can give estimates of the clustering probability, and these should be compared with estimates obtained from theories of nuclear structure.

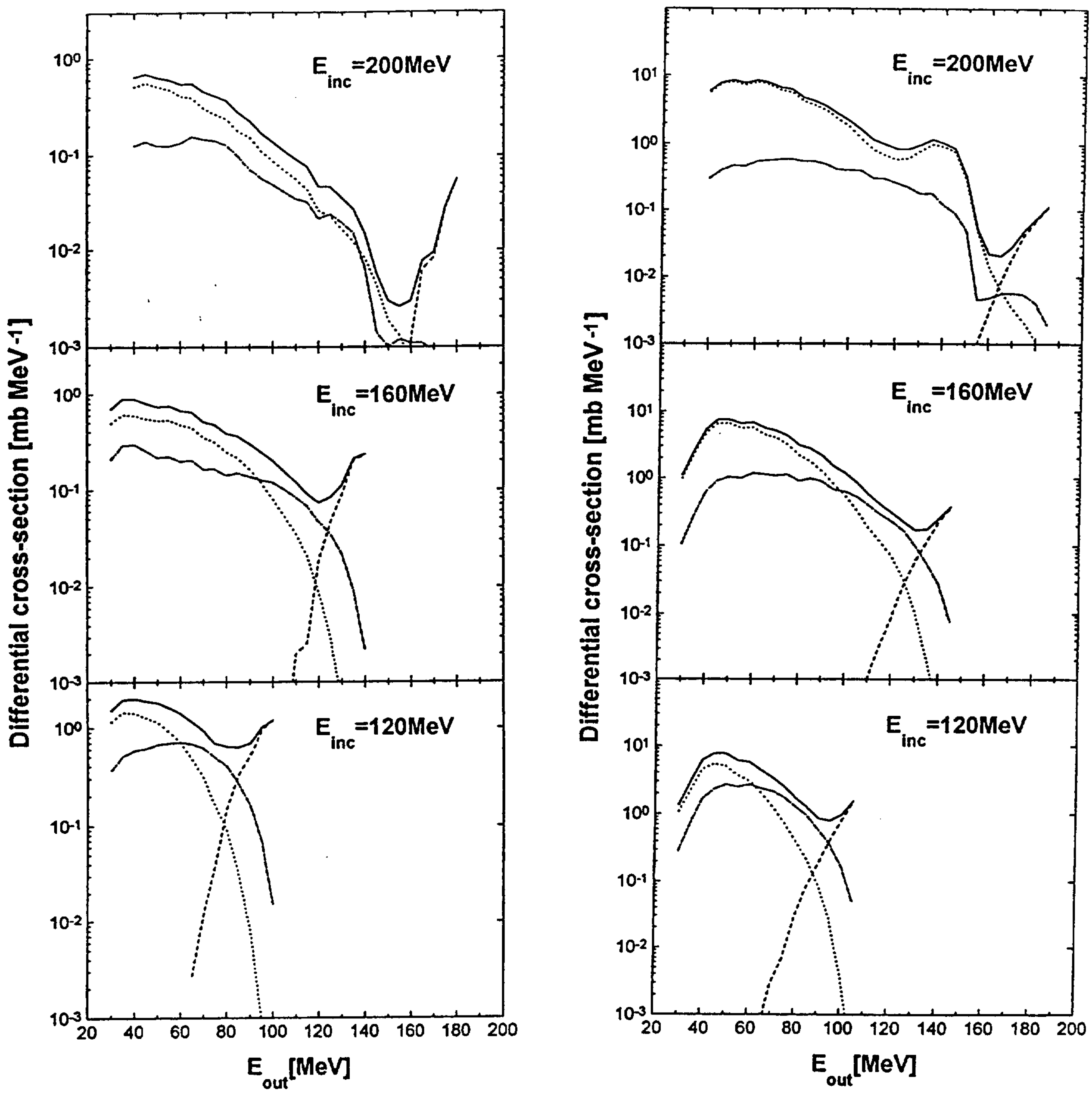

Fig. 5. The cross-sections of the first, second and third steps of the ^{59}Co(p, ^{3}He) and ^{197}Au(p, ^{3}He) reactions at 120, 160 and 200 MeV. The dashed lines show the one-step cross-sections, the dash-dotted lines the two-step, the dotted the three-step and the solid lines the total cross-sections.

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