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The Analyzing Powers of $(p,^3He)$ Reactions

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Abstract

Several studies of analysing powers have shown that they provide information on the reaction mechanism. We have analysed data for $(p,^3He)$ reactions using the Feshbach-Kerman-Koonin multistep theory with the deuteron pick-up model. It is found that the analysing powers are sensitive indicators of the contributions of successive steps to the reactions.

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1 Introduction

There have been relatively few measurements of the analyzing powers in reactions leading to the emission of composite particles in the continuum, but already they have yielded important information on the nuclear reaction mechanism. It has been shown for example that the analyzing powers of the (p,α) reaction on 72 MeV by ^{58}Ni could be fitted with the knock-out mechanism but not with the pick-up [1]. The attempt to describe the analyzing power of $^{58}Ni(p,^3He)$ reaction at $72MeV$ incident energy to the continuum assuming $(p,d)(d,^3He)$ reaction mechanism within the exciton model was unsuccessful [2].

The $(p,^3He)$ cross-sections of Cowley et al [3] have been successfully analyzed using the deuteron pick-up model, but corresponding analyzing powers are not available. The previous analysis of the cross-sections of the $(p,^3He)$ reaction [3] showed that the cross-section for small energy loss is dominated by the first step of the reaction and that as the outgoing energy decreases the contribution of the second step rapidly increases and soon dominates.

The aim of the present study is to verify the deuteron pickup as a mechanism of the $(p,^3He)$ reaction and study the multistep contribution to the analyzing power by analyzing the data of Lewandowski et al [4] for $(p,^3He)$ reactions at $72\ MeV$ incident energy. We made the calculations as the first stage of a series of calculations of analyzing powers and as a preliminary to our analysis of the new data from the National Accelerator Centre in Faure, South Africa [5].

The method of analysis is described in Section 2 and the results are given in Section 3. Our conclusions are given in Section 4.

2 Method of Analysis

According to the statistical direct theory of Feshbach, Kerman and Koonin (FKK) [6, 7] the double-differential cross-section of a multistep reaction can be written as:

$$\left(\frac{d^2\sigma}{d\Omega dE}\right) = \left(\frac{d^2\sigma}{d\Omega dE}\right)^{one-step} + \left(\frac{d^2\sigma}{d\Omega dE}\right)^{two-step} + ... \tag{2.1}$$

The one step double-differential cross-section of the $(p,^3He)$ transition to a continuum state characterized by the an excitation energy E has the form [3] :

$$\left(\frac{d^2\sigma}{d\Omega dE}\right)^{one-step} = \sum_{N,L,J} \frac{2J+1}{\Delta E}\left(\frac{d\sigma}{d\Omega}\right)^{DWBA}, \tag{2.2}$$

where ΔE is a small energy bin around E. The differential cross-section of the $(p,^3He)$ reaction in the Distorted-Wave Born Approximation (DWBA) [8] is presented as follows:

$$\left(\frac{d\sigma}{d\Omega}\right)^{DWBA} = N\sum_{\{n_k\}} G^2(\{n_k\}^2)\frac{2J_f+1}{2J_i+1}. \sum_{S,T=0,1} b^2_{ST}D^2_{ST}\langle T_f T_{f_z} T T_z \mid T_i T_{i_z}\rangle^2 \left(\frac{d\sigma}{d\Omega}\right)^{DWUCK}. \tag{2.3}$$

We assume that the target consists of a core to which a deuteron is bound in a shell model state. The $(p,^3He)$ reaction is described as a direct deuteron pick-up reaction. The sum in (2.3) runs over all possible neutron-proton configurations $\{n_k\}$. N is the normalization constant, $G^2(\{n_k\}^2)$ are the spectroscopic factors for a proton and neutron to form a deuteron bound state with quantum numbers (N, L, J). Macroscopic form factors for the deuteron in the target nucleus have been applied. They are obtained using "well-depth" procedure for a Wood-Saxon potential with geometrical parameters adjusted so that microscopic and macroscopic form factors are almost identical [9]. In the present work the possible deuteron states are included explicitly. The distorted wave functions were calculated using the optical model with a potential of the form:

$$V(\mathbf{r}) = V_c(r) + U\ f(r) + i\ W_V\ f(r) + i\ W_S\ g(r) + V_S\ \frac{1}{r}\frac{df(r)}{dr}\ L.S\ , \qquad (2.4)$$

where $V_c(r)$ is the Coulomb potential, $f(r) = \left[1 + \exp\left(\frac{r-R}{a}\right)\right]^{-1}$, $R = r_0 A^{1/3}$ and $g(r)$ is the radial derivative of $f(r)$.

The second step contribution to the cross-section is calculated using the standard FKK procedure [10].

The extension of the FKK theory to include analyzing powers is described by Bonetti et al [11]. The analyzing power is defined by:

$$A_y = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}\ , \qquad (2.5)$$

where σ_L and σ_R are the left and right cross-sections, respectively. The sum of σ_L and σ_R define the double differential cross-section of the reaction. As in the multistep direct theory (MSD) each left and right cross-section can be written in the form:

$$\sigma_{L,R} \equiv \left(\frac{d^2\sigma}{d\Omega dE}\right)_{L,R} = \left(\frac{d^2\sigma}{d\Omega dE}\right)_{L,R}^{one-step} + \left(\frac{d^2\sigma}{d\Omega dE}\right)_{L,R}^{two-step} + ... \qquad (2.6)$$

If we denote by A_i the analyzing power of the $i-th$ step:

$$A_i = \frac{\sigma_L^{i-step} - \sigma_R^{i-step}}{\sigma_L^{i-step} + \sigma_R^{i-step}}\ , \qquad (2.7)$$

the analyzing power of the multistep reaction can be written as a sum over the contributions for each step:

$$A_y = \frac{A_1\sigma^{one-step} + A_2\sigma^{two-step} + ...}{\sigma^{one-step} + \sigma^{two-step} + ...} \qquad (2.8)$$

In these calculations the total analyzing power includes the one- and two-step contributions. The left and right cross-sections are obtained from the DWUCK4 [12]. To calculate the two-step double- differential cross-section the experimental (p,p') cross-sections at 65 MeV incident energy are used [13]. As the available data are for energy loss above 12 MeV we extrapolated the (p,p') double-differential cross-sections for smaller energy losses. The use of experimental (p,p') cross-sections implies that the contributions of some higher step processes are also included.

3 Results

We calculate the cross-sections and the analyzing powers for ^{58}Ni, ^{90}Zr and ^{209}Bi since the required data for the double differential (p,p') cross-sections are readily available. Calculations have been performed with several ^3He optical potentials [14, 15, 16]. We have chosen the optical potential which gives the best overall fit of both differential cross-section and analyzing power. The results for the Perey ^3He optical potential [14], and the Madland and Schwandt proton potential [17, 18] are shown in Figs.1-3. The calculated cross-sections are normalized to those with the highest outgoing energy of $50MeV$.

Although the results show considerable sensitivity to the ^3He optical potentials, some general trends can be seen. The contribution of the second step increases the total cross-section and decreases the total analyzing power, reproducing the shape of the experimental data as the outgoing energy decreases. This consideration applies especially to the lighter nuclei. In the case of heavy nuclei like ^{209}Bi, where the statistical MSD theory of Feshbach -Kerman-Koonin is expected to work best, the calculated differential cross-section and analyzing powers reproduce the shape and the magnitude of the experimental data quite well.

4 Conclusions.

The analyzing power is a very sensitive indicator of the reaction mechanism. The results show that the statistical multistep direct formalism with the deuteron pickup process is applicable to the $(p,^3He)$ reaction . The comparison with the experimental data shows that the multistep process becomes important when the outgoing energy decreases and that it reduces the analyzing power significantly.

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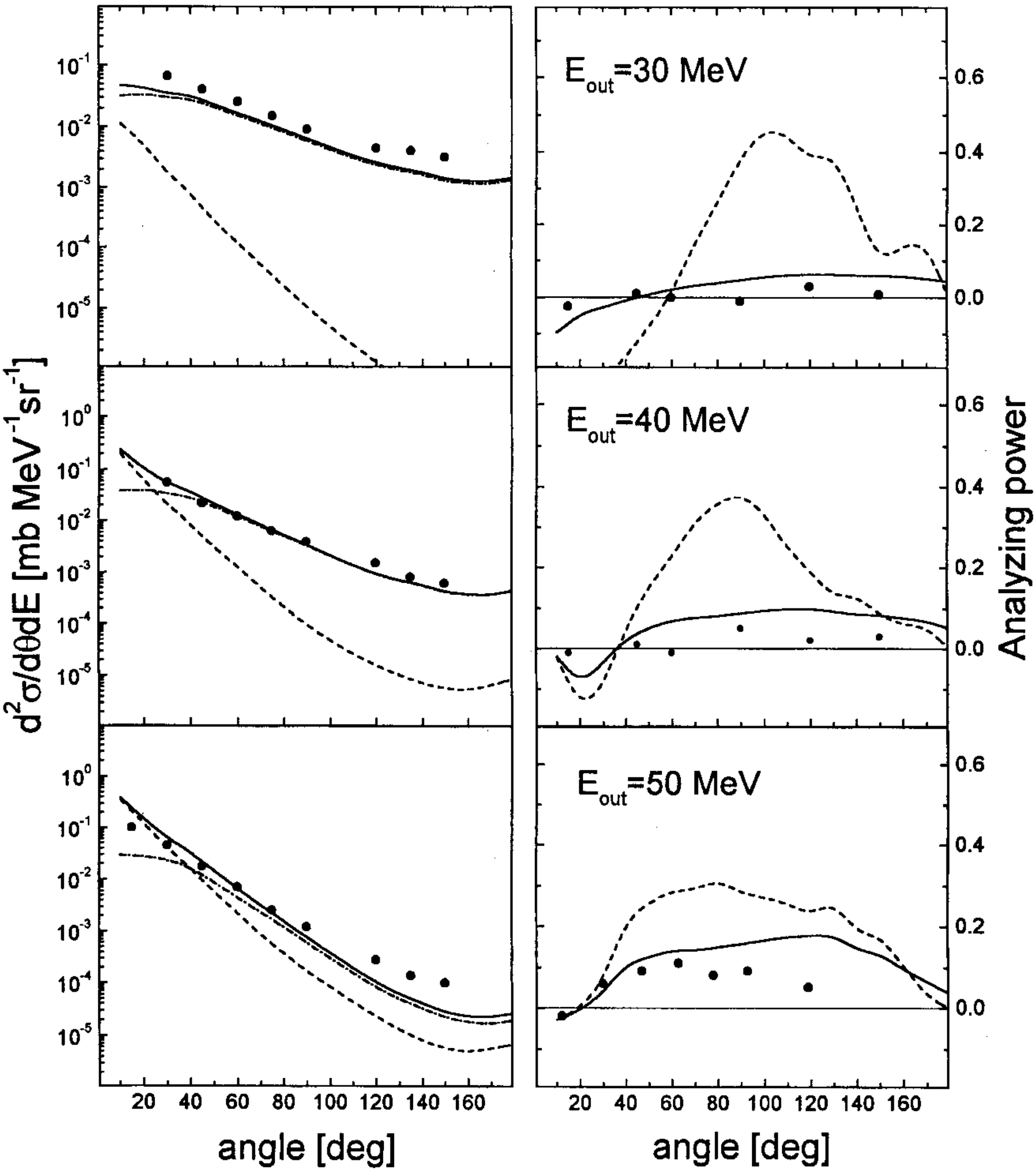
Figure Captions.

Fig.1. Double – differential cross sections and analyzing powers for the $^{58}Ni(p,^3He)^{56}Co$ reaction at an incident energy of $72MeV$ and three outgoing energies, compared with Feshbach–Kerman–Koonin calculations for one-step (dashed curves) and two–step (dot–dashed curves) processes. The sum of the two contributions is given by the solid curves. The experimental data are from [4].

Fig.2. The same as Fig.1. for the reaction $^{90}Zr(p,^3He)^{88}Y$.

Fig.3. The same as Fig.1. for the reaction $^{209}Bi(p,^3He)^{207}Pb$.



d²σ/dθdE [mb MeV⁻¹sr⁻¹]
Analyzing power
E_out=30 MeV
E_out=40 MeV
E_out=50 MeV
angle [deg]
angle [deg]

Fig.1

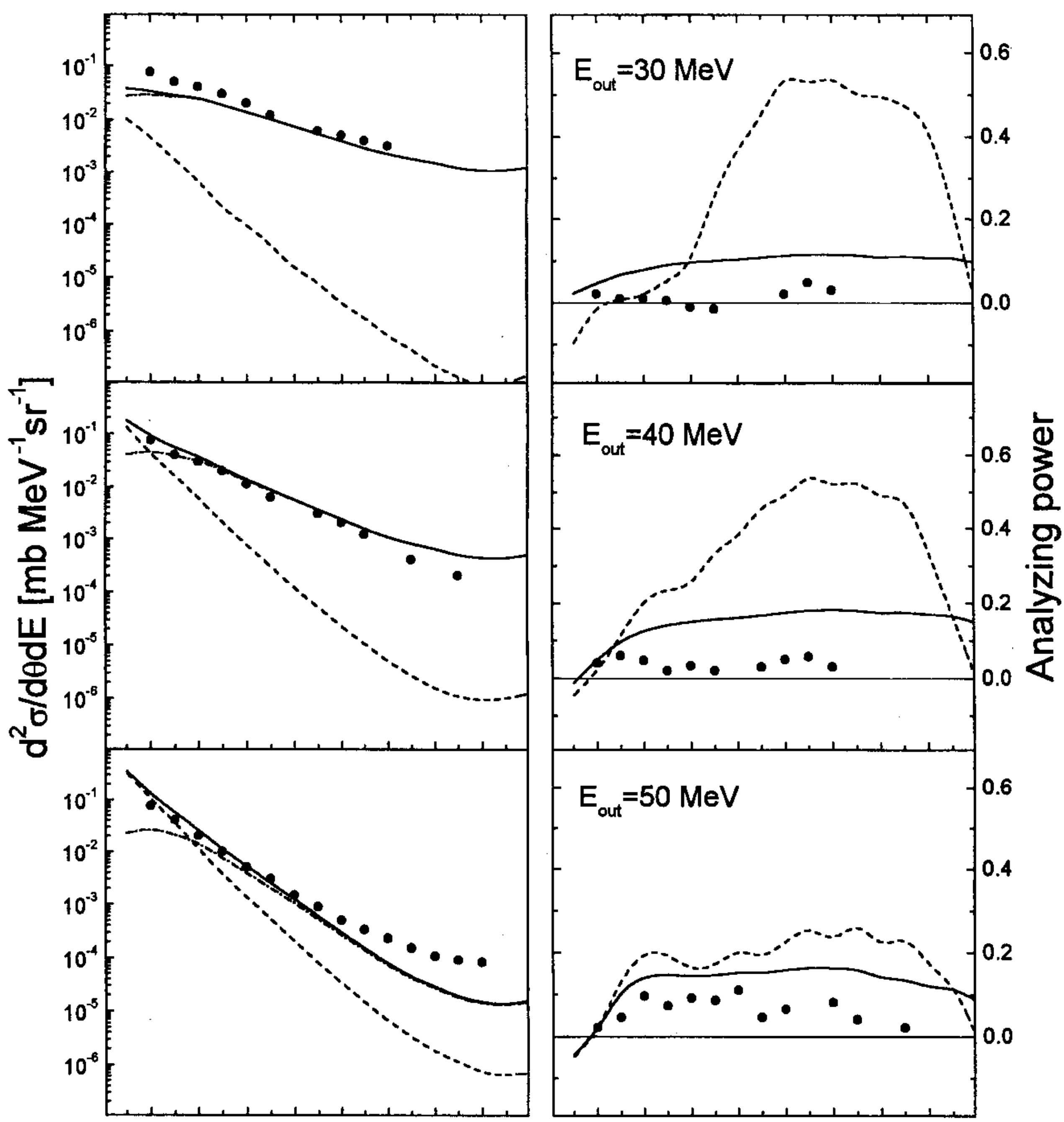
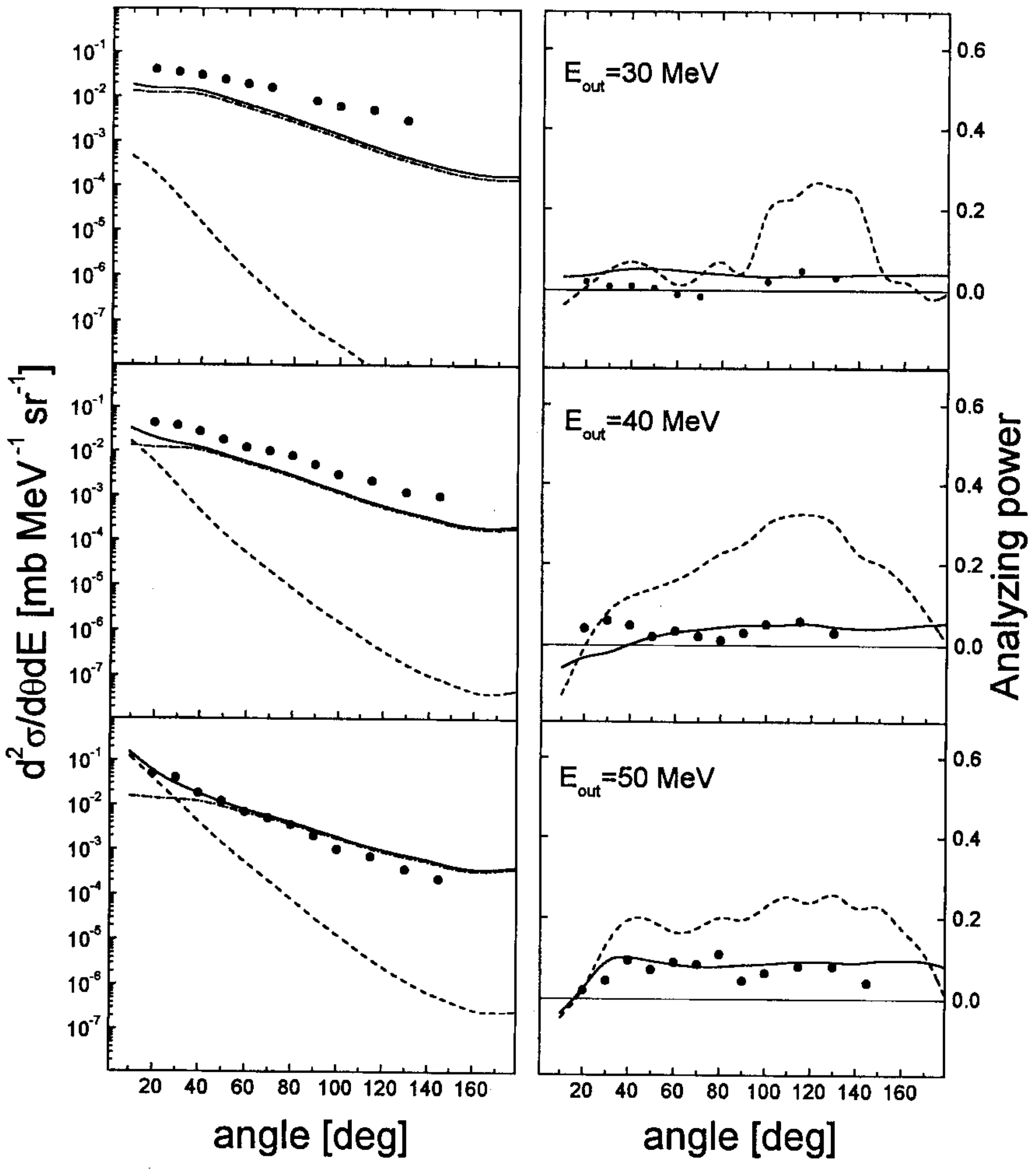

E_out=30 MeV
E_out=40 MeV
E_out=50 MeV
d²σ/dθdE [mb MeV⁻¹sr⁻¹]
Analyzing power
angle [deg]
angle [deg]

Fig.2



E_out=30 MeV
E_out=40 MeV
E_out=50 MeV
d²σ/dθdE [mb MeV⁻¹ sr⁻¹]
Analyzing power
angle [deg]
angle [deg]

Fig.3