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Abstract:

Double scattering of 51 MeV deuterons on carbon shows strong vector polarization effects. Tensor polarization effects are found to be small. Optical model predictions by SATCHLER could be confirmed qualitatively. Quantitatively, there are significant discrepancies.

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Double scattering experiments with deuterons are less numerous than those with spin=1/2 particles. Due to additional tensor polarization effects intensities must be determined not only at azimuth angles $\emptyset = 0$ and π, but at $\pi/2$ (and or $3\pi/2$) also. This requires axial symmetry of the secondary beam with respect to the intensity and to the beam divergence, which is difficult to achieve with the necessary precision.

The interpretation of deuteron double scattering experiments [1] in the low energy region is difficult because of possible compound nucleus contributions. The two early double scattering experiments [2] at high energies suffer from a lack of energy resolution. The present double scattering experiment performed at the Karlsruhe isochronous cyclotron uses energies where compound nucleus contributions should be small and where separation of elastic from inelastic scattering is still possible with plastic scintillators. No deuteron polarization data for this energy region are available so far.

In order to get information on the spin dependent terms of the optical model we performed double scattering experiments for deuteron scattering on carbon with a primary deuteron energy of 51.5 MeV. The experimental setup [3] uses a first scattering chamber, a quadrupole triplet focusses the scattered deuterons into another scattering chamber. This chamber can be rotated around the axis of symmetry of the secondary beam. A circular diaphragm in front of the second target provides axial symmetry in intensity on the second scatterer. Axial symmetry in divergence is monitored by two counters positioned directly in the secondary beam and fixed to the rotating scattering chamber. The parameters A and B of azimuthal asymmetry, defined by $N \sim 1 + A\cos\emptyset + B\cos 2\emptyset$, are taken for two symmetrically located counter telescopes as well as for the monitors mentioned above. The asymmetries in the telescopes were found to depend linearly on the asymmetries in the monitors. Linear interpolation of the telescope asymmetries to zero monitor asymmetries results in the experimental azimuthal asymmetry due to spin dependent components of the nuclear interaction.

The experimental setup was tested with double scattering of 100 MeV α-particles. The resultant effective deviations from ideal symmetry were found to be $\varepsilon_A = 0.015 \pm 0.014^\circ$ for A and $\varepsilon_B = 0.010 \pm 0.009^\circ$ for B. The corresponding systematic errors to be expected for deuteron scattering are

$$\Delta_{A,B} = \frac{d\ln\sigma}{d\Theta}\,\varepsilon_{A,B}, \tag{1}$$

where σ is the differential scattering cross section and Θ the polar angle for the second scattering.

Measurements extended over several months. An overall χ^2 test yielding $\chi^2 = 271.4$ for 274 degrees of freedom shows the consistency of the results.

The asymmetry parameters A and B depend on the deuteron energies E_1 and E_2 and on the polar scattering angles Θ_1 and Θ_2 in the CM-system for the first and the second scattering, respectively. The first scattering acts as a polarizer, the second one as an analyzer. Using the notation of LAKIN [4], the asymmetry parameters A and B are given by

$$A = \frac{2((iT_{11})_1\,(iT_{11})_2 - (T_{21})_1\,(T_{21})_2)}{1 + (T_{20})_1\,(T_{20})_2}, \tag{2}$$

$$B = \frac{2(T_{22})_1\,(T_{22})_2}{1 + (T_{20})_1\,(T_{20})_2}.$$

Here, the tensor components T_{jk} with subscript 1 and 2 describe the spin orientation in the laboratory system created by the first scattering and by the time reversed second scattering for unpolarized incident particles, respectively.

During each experiment for a fixed primary angle Θ_1 the azimuthal asymmetries A and B are measured as a function of Θ_2. In two experiments, significant polarization effects were observed.

For the first experiment, Θ_1 was chosen near a pronounced interference minimum in the differential cross section (Fig. 1). The resulting azimuthal asymmetries as a function of Θ_2 are shown in Fig. 2. At $\Theta_2 \approx \Theta_1$, a positive value of A was obtained. For this secondary angle, B is zero within statistics. A negative maximum in A was found at $\Theta_2 = 57.6^\circ$.

For the primary angle of the first experiment the polarization was expected to vary rapidly with angle and energy. This was not the case with the angular region of the observed negative minimum. Hence, a second experiment at $\Theta_1 = 57.6^\circ$ was performed (Fig. 3). Under this primary angle, a pronounced maximum in A appears at $\Theta_2 = 43^\circ$. As to B, the largest deviation from zero (-0.030 ± 0.008) is found in a region of maximum slope $d\ln\sigma/d\Theta$ at about 23°. Here, according to (1), instrumental asymmetries reach $\Delta_B = -0.015 \pm 0.014$. So, within statistics, our results in B are not inconsistent with a vanishing difference between the experimental points and the expected instrumental asymmetries.

The tensor components T_{jk} in (2) for elastic scattering of 51.5 MeV deuterons on carbon have been calculated by SATCHLER [5]. He analyzed the differential cross section data measured by SCHMIDT-ROHR et al. [6] and BRÜCKMANN et al. [7] using an optical potential [8] with a Saxon-Wood-type real central term, a Thomas-type imaginary central term, and a real Thomas-type LS term. A search routine applied to the data for scattering angles between 15 and 160° yielded the model parameters. Some of the resultant optical model parameter sets are given in Table I. A good fit was obtained even without any spin dependant term. All these parameter sets give nearly the same fit shown in Fig. 1.

The azimuthal asymmetries A predicted by the corresponding potentials in Table I are shown in Figs. 2 and 3 also. Only for potential 1 the energy dependence of polarization has been taken into account (curves 1e). A comparison with our results shows qualitative agreement in A. However, a significant difference in magnitude is observed for $\Theta_1 = 57.6^\circ$ and $\Theta_2 = 43^\circ$. This discrepancy coincides with a small deviation of the fit from the experimental differential cross section in Fig. 1.

For a first interpretation of our results we neglect the energy dependence of the expansion coefficient T_{jk} in (2). As to B, the experimental values for $\Theta_2 \approx \Theta_1 = 22.8$ and 57.6° give statistical upper limits for T_{22} with $|T_{22}| < 0.07$ in both cases. This upper limit is not inconsistent with the results of SCHWANDT and HAEBERLI [9], who have shown the need for a tensor term in the optical potential to describe elastic scattering of polarized deuterons below 12 MeV. The maximum value for $\Theta < 60^\circ$ predicted by the potentials of Table I is $T_{22} = -0.005$ (pot. 2 at 22°).

Neglecting tensor components T_{2k} also, according to (2) the absolute value of iT_{11} can be calculated for $\Theta_1 = \Theta_2 = 57.6^\circ$. This yields a scale factor of +2.41 to be applied to the A scale of Fig. 3. Thus, one obtains iT_{11} as a function of Θ_2. The sign of the scale factor was chosen in order to get consistence with the calculated iT_{11} values in angular regions, where agreement between predicted asymmetries and experiment was found. Under these assumptions one obtains a maximum analyzing power $(iT_{11})_2 = -0.448 \pm 0.050$ (Basle convention) at $\Theta_2 = 43^\circ$ for $E_2 = 41$ MeV. This is 75% of the absolute maximum value compatible with vanishing tensor components T_{2k}. Under these conditions, carbon seems to be a good analyzer for deuteron vector polarization with an extrapolated differential cross section of about 40 mb/sterad.

Taking into account the calculated energy dependence of iT_{11} for $\Theta = 57.6^{\circ}$ the scale factor mentioned above would become +1.64. In this case one gets a mean value of $V_s = 7.3 \pm 0.8$ MeV for the LS term. This value was obtained by comparing the expected asymmetries for potential 1 and 3 (Table I) with the experimental value of A at $\Theta_1 = \Theta_2 = 57.6^{\circ}$. The indicated error contains statistics, uncertainty in the radial dependence of the LS term, and the uncertainty in T_{2k}.

Absolute calibration and energy dependence of iT_{11} are under investigation.

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Captions of Figures:

Figure 1: Differential cross section for elastic deuteron scattering on carbon at 51.5 MeV. Experimental data [6] and optical model fit [5].

Figure 2: Parameters A and B for the azimuthal asymmetry, defined by $N \sim 1 + A\cos\emptyset + B\cos 2\emptyset$, as a function of the polar angle Θ_2 for the second scattering and for $\Theta_1 = 22.8^{\circ}$. The curves are optical model predictions deduced from the corresponding potentials in Table I.

Figure 3: As figure 2, but for $\Theta_1 = 57.6^{\circ}$.

Table I: Optical model parameter sets obtained by SATCHLER [5] to fit the differential cross section [6], [7] for elastic deuteron scattering on carbon at 51.5 MeV, in the notation of [8]. χ^2 relates to 66 degrees of freedom.

Pot.No.	V	r_o	a_o	$4W_d$	r'^{*}	a'	V_s	r_s	a_s	σ_R	χ^2
1	86.0	1.024	0.766	33.0	1.343	0.757	4.16	r_o	a_o	790	47
2	"	"	"	"	"	"	"	1	0.5		
3	91.8	0.965	0.807	34.3	1.374	0.732	6.76	r_o	a_o	787	54
-	82.9	1.059	0.740	32.3	1.297	0.802	0	-	-	800	55

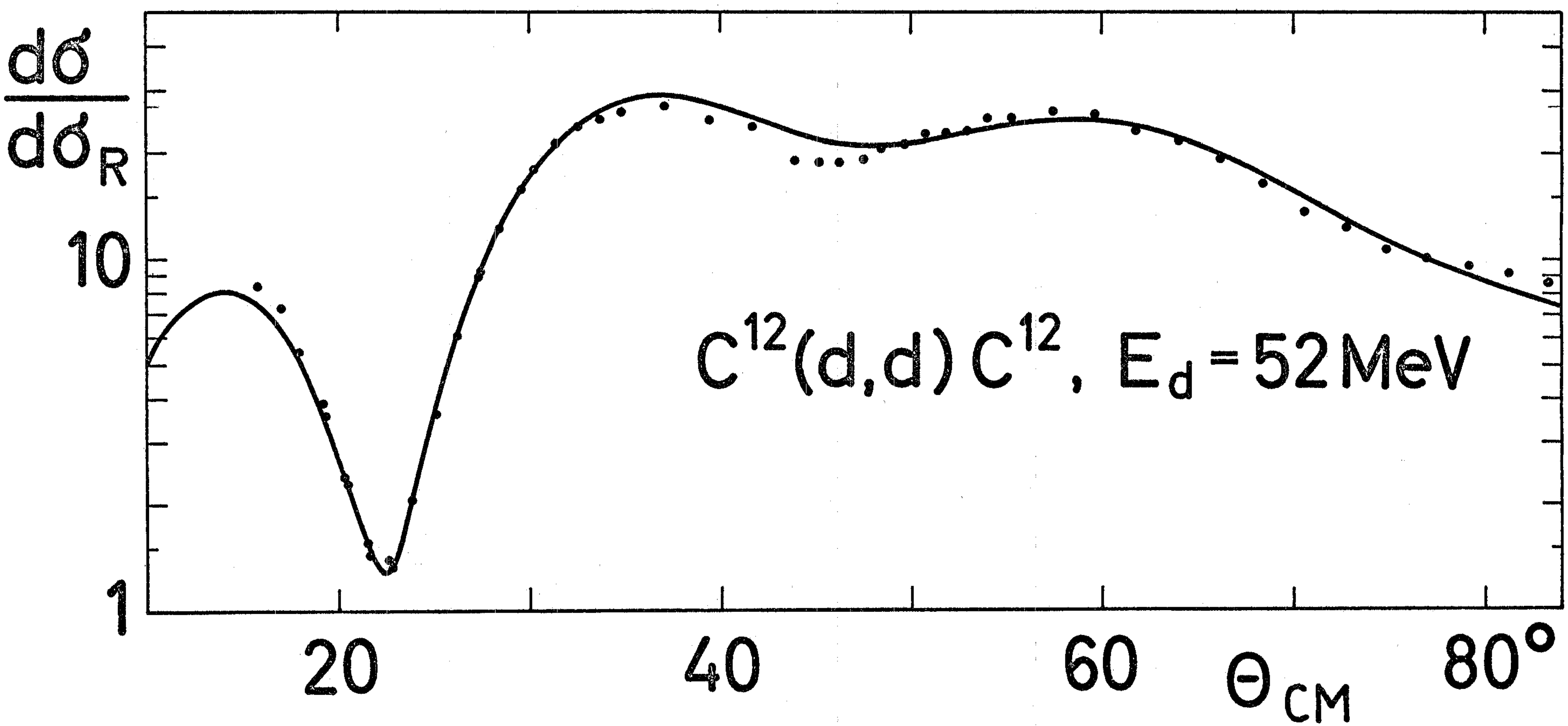
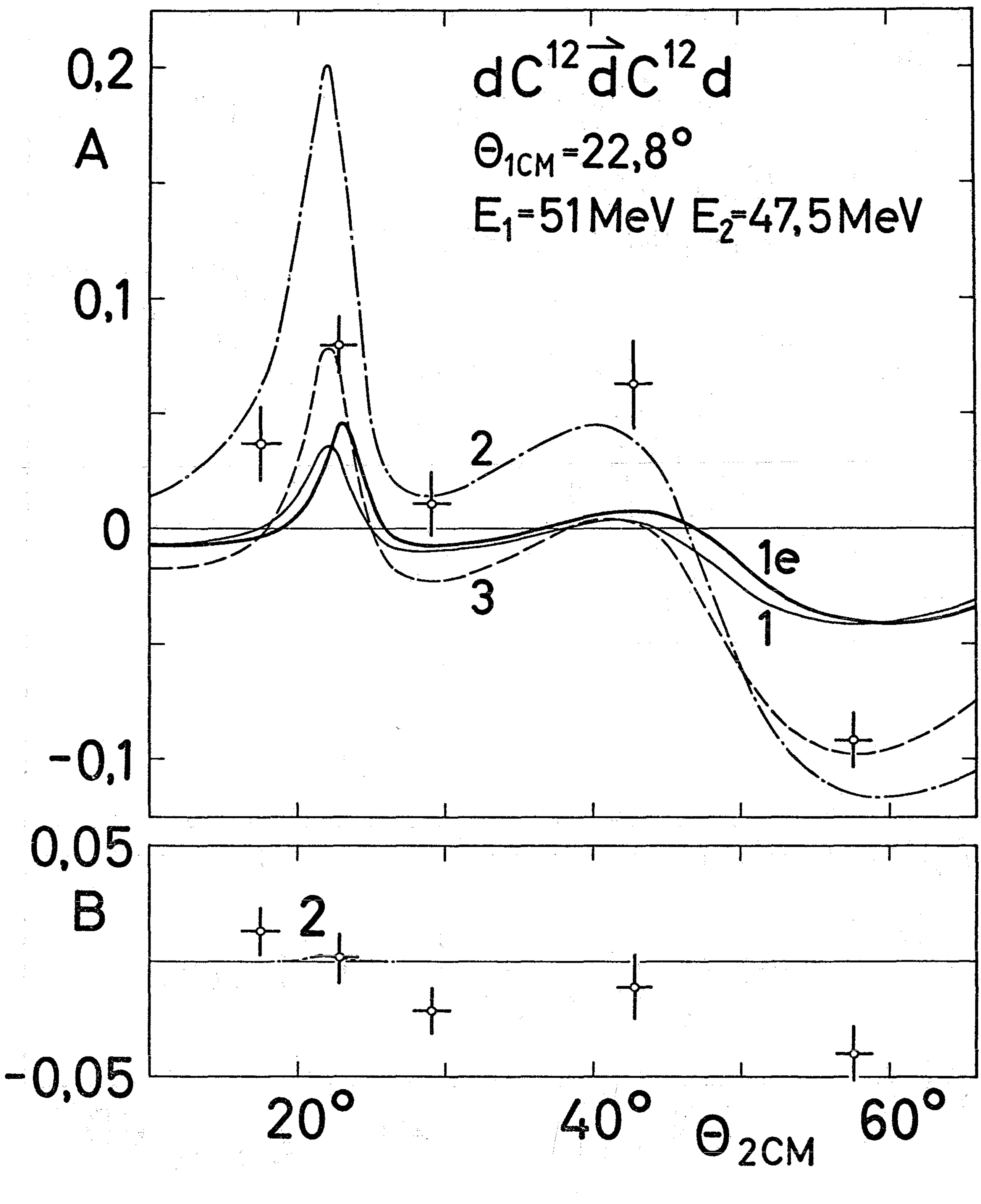


Figure 1



$dC^{12}\vec{d}C^{12}d$
$\Theta_{1CM}=22,8°$
$E_1=51\,MeV$ $E_2=47,5\,MeV$
0,2
A
0,1
0
-0,1
2
3
1e
1
0,05
B
-0,05
20°
40°
Θ_{2CM}
60°

Figure 2

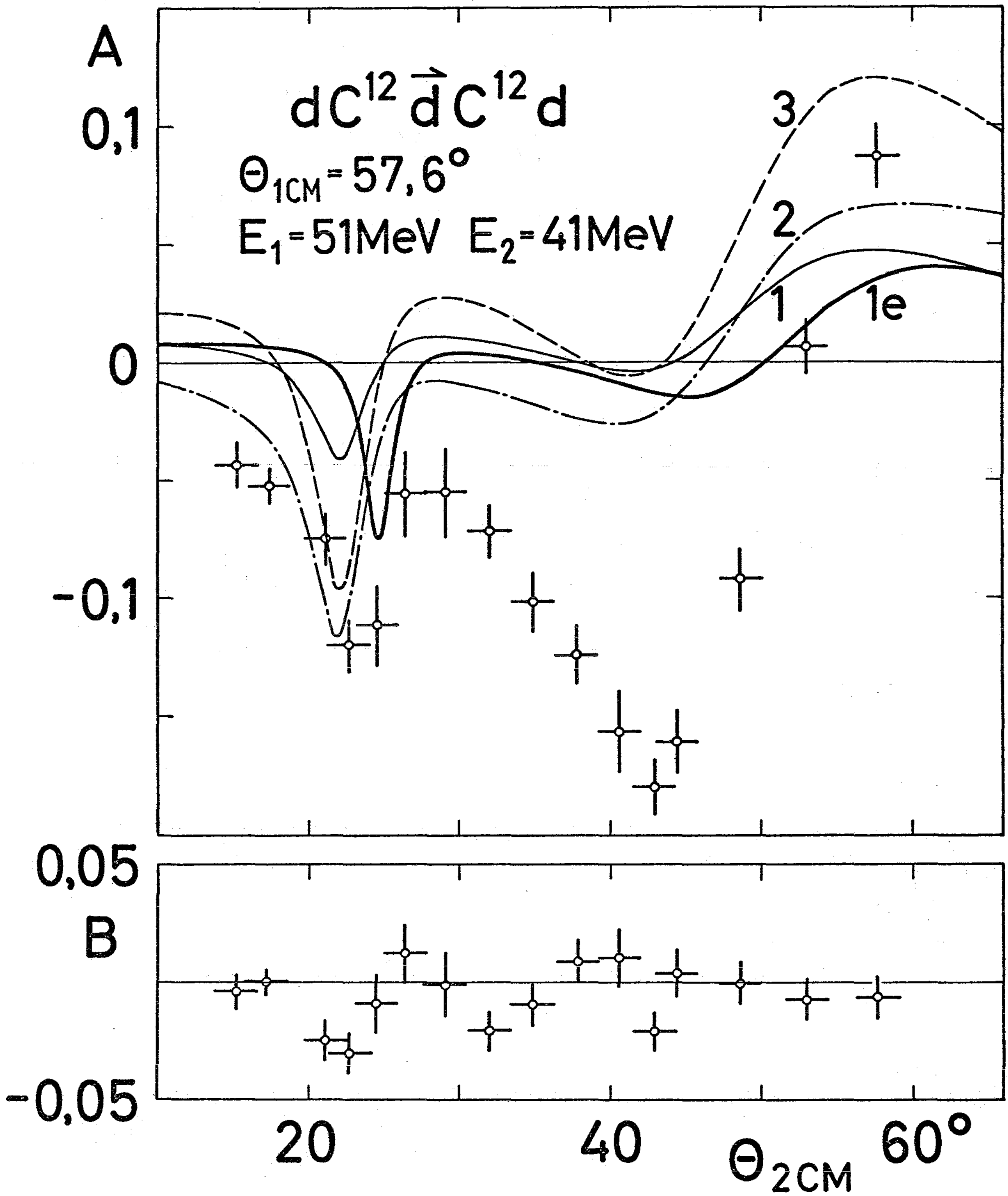

A
dC¹² d⃗ C¹² d
Θ1CM = 57,6°
E1 = 51MeV E2 = 41MeV
0,1
0
-0,1
3
2
1
1e
0,05
B
-0,05
20
40
60°
Θ2CM

Figure 3