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A Study of Nucleon-Nucleon Spin-Orbit Force in Quark Model*

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Abstract

Spin-orbit interactions between two quarks due to the one-gluon exchange, confinement potential, σ exchange of chiral field and two-gluon exchange are considered in our calculation. As a consequence the spin-orbit energy splitting of 1P state in the baryon spectrum and the $^3P_2$ phase shifts of N-N scattering can unifiedly be explained.

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1 Introduction

As well known, the quark potential model is quite successful not only in studying the structure of the heavy quarkonium[1], but also in explaining the baryon spectra[2] and the short range repulsion of the nucleon- nucleon interaction[3]. But in this model the spin orbit interaction is still an open problem. Theoretically the one-gluon exchange quark- quark interaction has a spin-orbit term V_{LS}^{OGEP}, as well as the Lorentz scalar confinement potential leads to a spin-orbit term V_{LS}^{conf} as a relativistic effect, which has the opposite sign to the V_{LS}^{OGEP}. When one further considers the coupling of the chiral field[4], the σ exchange also offers a spin-orbit term V_{LS}^{σ}, but the effect of this term is rather weak. Empirically, it is known that the effect of the spin-orbit term in the baryon spectrum is negligibly small[2]. It seems that we can describe the spin-orbit energy splitting of the single excited baryon system by considering V_{LS}^{OGEP} and V_{LS}^{conf}, because these two terms cancel each other and give a small contribution to the single-baryon spectrum[5]. But if we extend this spin-orbit interaction model to study the nucleon-nucleon spin-orbit interaction, a serious problem appears: the cancellation mentioned above also occurs in the two-nucleon system, so that the contribution of the spin-orbit interaction is too small to explain the experimental $^3P_2$ phase shifts in the N-N scattering. Even we leave out V_{LS}^{conf} and consider the spin-orbit interaction of one gluon exchange V_{LS}^{OGEP} only in the study of N-N spin-orbit interaction, the result shows that the effect is still too weak. Some calculations[4,6,7] showed that one needs a spin-orbit interaction which is 6-8 times stronger than that from the one gluon exchange to reproduce $^3P_2$ phase shifts. This indicates that it is difficult to describe the spin-orbit splitting in single baryon spectrum and the $^3P_2$ phase shifts of N-N scattering simultaneously in this framework. There should be some other important mechanism responsible for the spin-orbit potential.

In Ref.[8], we derived a spin-orbit potential from the irreducible two-gluon exchange diagram. There are two terms in the potential: one is color dependent and the other is color independent. The contributions of these two terms cancel each other in the single baryon system, but add in the $^3P_2$ state of the nucleon-nucleon system. A qualitative analysis[3)] shows that the spin-orbit potential from the irreducible two-gluon exchange diagram is helpful to solve the discrepancy mentioned above. In this work, we consider the spin-orbit interactions between two quarks not only from the one-gluon exchange, confinement potential, and σ exchange of chiral field, but also from the irreducible two-gluon exchange mechanism. Consequently both the calculated spin-orbit energy splittings of the baryon spectrum and the $^3P_2$ phase shifts of N-N scattering are in good agreement with the experimental data.

2 Theoretical framework

In this work, we start from the modified quark potential model[7)] in which the coupling between the chiral field and quark spinor was considered because of the chiral symmetry requirement. This is a short and medium range low-momentum nonperturbative effect which comes from the gluon field fluctuations of instanton type. From this low-energy QCD lagrangian, one can get the chiral pion and sigma exchange between two quarks. Although this chiral coupling is very important in explaining the medium and long range behaviors of the baryon-baryon interaction, but it is still not enough to obtain a description of the single baryon properties and the baryon-baryon dynamics, the one-gluon exchange and a confinement potential should also be employed. The total Hamiltonian of the two baryon system can be written as:

$$H = \sum_{i=1}^{6} \frac{P_i^2}{2m_q} - T_G + \sum_{i<j}(V_{ij}^C + V_{ij}^T + V_{ij}^{LS}). \qquad (1)$$

In this expression, V_{ij}^C represents the central potential between two quarks, and is composed of the confinement potential, one-gluon exchange potential and the potential from the chiral field:

$$V_{ij}^{C} = V_{C}^{OGE}(ij) + V_{C}^{conf}(ij) + V_{C}^{ch}(ij), \tag{2}$$

V_{ij}^{T} denotes the tensor potential which consists of V_{T}^{OGE} and V_{T}^{ch},

$$V_{ij}^{T} = V_{T}^{OGE}(ij) + V_{T}^{ch}(ij). \tag{3}$$

The detailed expressions of Eqs.(2) and (3) were given in Ref.[7]. The spin-orbit interaction V_{ij}^{LS}, in this model can be expressed in the following form:

$$V_{ij}^{LS} = V_{LS}^{OGE}(ij) + V_{LS}^{conf}(ij) + V_{LS}^{ch}(ij), \tag{4}$$

with

$$V_{LS}^{OGE}(ij) = -\frac{3}{16}\frac{\alpha_s}{m_q^2 r^3}(\lambda_i \cdot \lambda_j)\vec{L}\cdot(\vec{\sigma}_i + \vec{\sigma}_j), \tag{4a}$$

$$V_{LS}^{conf}(ij) = \frac{a_c}{2m_q^2}(\lambda_i \cdot \lambda_j)\vec{L}\cdot(\vec{\sigma}_i + \vec{\sigma}_j), \tag{4b}$$

and

$$\begin{aligned} V_{LS}^{ch}(ij) = & -\frac{g_{ch}^2}{4\pi}\frac{\Lambda^2}{\Lambda^2 - m_\sigma^2}\frac{m_\sigma^3}{4m_q^2} \\ & \cdot \{(\frac{1}{m_\sigma^2 r^2} + \frac{1}{m_\sigma^3 r^3})e^{-m_\sigma r} - \frac{\Lambda^3}{m_\sigma^3}(\frac{1}{\Lambda^2 r^2} + \frac{1}{\Lambda^3 r^3})e^{-\Lambda r}\} \\ & \cdot \vec{L}\cdot(\vec{\sigma}_i + \vec{\sigma}_j). \end{aligned} \tag{4c}$$

Where α_s is the coupling constant of the one-gluon exchange. m_q denotes the quark mass, a_c stands for the strength of the quadratic confinement potential, m_σ and Λ_σ are the mass and cut-mass of the σ meson respectively, and $\frac{g_{ch}^2}{4\pi}$ represents the chiral coupling constant.

As mentioned above, V_{LS}^{conf} has the opposite sign to V_{LS}^{OGE}, and V_{LS}^{ch} is relatively weak, so that the spin-orbit interaction between two quarks in Eq.(4) is not strong enough to produce a reasonable spin-orbit force of the N-N potential. In Refs. [6] and [7], they increase the strength of V_{LS}^{OGE} by a factor of 6-8 and leave out V_{LS}^{conf} to make the calculated $^3P_2$ phase shifts consistent with the experimental data. However in the single baryon spectrum calculation one finds that this spin-orbit interaction would produce an energy splitting $\Delta E_{th} = E(1P_{1/2}) - E(1P_{3/2})$ of about -700MeV, whose absolute value is too large to meet the measured value $\Delta E_{exp} = 15$MeV. This is because that V_{LS}^{OGE} is too strong while no cancellation from V_{LS}^{conf} presents.

In Refs. [8] and [9], we have indicated that the spin-orbit term from the irreducible two-gluon exchange mechanism (see Fig.1) is helpful for solving the spin-orbit problem. Fig.1 is a diagram folded by two transition potential $V_{q\to qq\bar{q}}$ and $V_{qq\bar{q}\to q}$. It is an important diagram which can produce the effective meson exchange effect. The transition potential in the coordinate space in Refs. [10] and [11] is given by

$$\begin{aligned} V_{q\to qq\bar{q}} &= i\frac{1}{4}\alpha_s(\lambda_1\cdot\lambda_2)[-\frac{1}{4}(\frac{1}{m_1} + \frac{1}{m_2})\frac{1}{r^3}\vec{r}\cdot\vec{\sigma_2} \\ &+ i\frac{1}{2m_1 r}\vec{k_1}\cdot\vec{\sigma_2} + \frac{1}{4m_1 r^3}i(\vec{\sigma_1}\times\vec{\sigma_2})\cdot\vec{r}], \end{aligned} \tag{5}$$

with $\vec{r} = \vec{r_1} - \vec{r_2}$, ("1" denotes the sea quark, and "2" the valence quark). By making the closure approximation to the energy propagator of the intermediate state, we can easily obtain the effective potential between two quarks of Fig.1. The spin-orbit potential of the irreducible two-gluon exchange can be expressed as:

$$V_{LS}^{TGE.Fig.1} = -(\frac{32}{9} + \frac{14}{3}(\lambda_i \cdot \lambda_j))\frac{3}{128}\frac{\alpha_s^2}{m_q^3 r^4}\vec{L}\cdot(\vec{\sigma}_i + \vec{\sigma}_j). \quad (6)$$

In Eq.(6) there are two different components, one is color dependent, the other is color independent. Since the adoption of the closure approximation in deriving Eq.(6) and the existences of some other two-gluon exchange processes which also contribute to the color independent term, it is difficult to obtain the strengths of both terms in V_{LS}^{TGE} seriously. Actually, some multi-gluon exchange processes should also be included. Therefore, as a semi-phenomenological approach, we introduce an adjustable parameter a_{LS} to adjust the strength of the color independent term in Eq.(6), and thus we have:

$$V_{LS}^{TGE} = -(a_{LS}\frac{32}{9} + \frac{14}{3}(\lambda_i \cdot \lambda_j))\frac{3}{128}\frac{\alpha_s^2}{m_q^3 r^4}\vec{L}\cdot(\vec{\sigma}_i + \vec{\sigma}_j). \quad (7)$$

In our calculation, the parameter a_{LS} is firstly determined by fitting the baryon energy splitting $\Delta E = E(1P_{1/2}) - E(1P_{3/2})$, then the phase shifts of N-N scattering for different partial waves are studied. The results show that both the spin-orbit energy splitting in the baryon spectrum and the phase shifts of N-N scattering can be well explained.

3 Results and Discussion

As usual, the nucleon size parameter b is taken to be 0.45fm, and the constituent quark mass m_q is chosen to be 313MeV. The coupling constant of the chiral field is related to the coupling constant of $NN\pi$[7],

$$\frac{g_{ch}^2}{4\pi} = (\frac{3}{5})^2\frac{g_{\pi NN}^2}{4\pi}\frac{m_q^2}{M_N^2} = 0.592. \quad (8)$$

and the mass of the sigma meson can be estimated by the following relation[12]:

$$m_\sigma^2 = (2m_q)^2 + m_\pi^2 = 650 \sim 700MeV. \quad (9)$$

The one-gluon exchange coupling constant α_s is determined by fitting the mass difference $M_\Delta - M_N$, and the confinement strength a_c can be obtained by satisfying the stability condition of nucleon. The strength of the color independent term in V_{LS}^{TGE}, a_{LS}, is merely an adjustable parameter. All the parameters used in the calculation are listed in Table 1.

We calculate the spin-orbit energy splittings of some low-lying states in the baryon spectrum, and then the $^3S_1$, ^3P_J, ^3D_J, $^3F_2$, $^3F_3$ and $^3G_3$ partial wave phase shifts of N-N scattering by solving the Resonating Group Method variation equation. The results of the single baryon spin-orbit energy splittings are listed in Table 2, while the phase shifts of N-N scattering are shown in Figs. 2, 3, 4, 5 and 6. For comparison, we also calculate these quantities in the case of without V_{LS}^{TGE}. In Table 2 and Figs. 2~6, the calculated results are shown for three different cases. In case A, the irreducible two-gluon exchange spin-orbit potential V_{LS}^{TGE} is included, $V_{LS}^{(A)} = V_{LS}^{OGE} + V_{LS}^{conf} + V_{LS}^{ch} + V_{LS}^{TGE}$, with $a_{LS} = 7.15$. In case B, V_{LS}^{TGE} is not included, $V_{LS}^{(B)} = V_{LS}^{OGE} + V_{LS}^{conf} + V_{LS}^{ch}$. And in case C, V_{LS}^{OGE} is considered only, and the strength of V_{LS}^{OGE} is multiplied by a factor of 4.7, i.e. $V_{LS}^{(C)} = 4.7\ V_{LS}^{OGE}$. From these results, one can see that the contribution from V_{LS}^{TGE} is very important in explaining the experiments. When V_{LS}^{TGE} does not present (see case B), the calculated $^3P_2$ phase shifts are negative in sign, which is opposite to the experimental data. If we take V_{LS}^{OGE} only and increase the strength of V_{LS}^{OGE}, (case C),[1] then the $^3P_2$ phase shifts can be improved, but the baryon spin-orbit energy splittings become entirely unreasonable. As long as V_{LS}^{TGE} is employed in the calculation, one can find that it is not difficult to explain the

[1]In this case the treatment is similar to that in Refs. [4], [6] and [7], in which the strength of V_{LS}^{OGE} was increased by a factor of 8 and 6, respectively.

single baryon spin-orbit energy splittings and the $^3P_2$ phase shifts of N-N scattering satisfactorily by adjusting the strength of the color independent term in V_{LS}^{TGE}. The physical reason is that in the baryon spectrum calculation, the contribution from the color independent term in V_{LS}^{TGE} has an opposite sign to those from V_{LS}^{OGE} and the color dependent term in V_{LS}^{TGE}, but the contributions from all these terms have the same sign in the P wave N-N scattering. Thus, the effect from the irreducible two-gluon exchange mechanism reduces the single baryon spin-orbit energy splittings and increases the attraction in the P wave N-N interaction. Thus the calculated phase shifts of $^3P_2$ can be raised to fit the experimental data. From Figs. 4a and 4b, one can see that the $^3D_3$ and $^3D_2$ phase shifts are also improved. This is because that in $^3D_3$ and $^3D_2$, the contribution from color independent term in V_{LS}^{TGE} is repulsive and dominant, but the contributions from V_{LS}^{OGE} and the color dependent term in V_{LS}^{TGE} are attractive. For other partial waves, the effect of the spin-orbit interaction is not so important. Thus, the calculated phase shifts of different partial waves are all in good agreement with the experimental data.

In summary, it is noteworthy that although in the derivation of V_{LS}^{TGE} a semi-phenomenological approach is used and an adjustable parameter a_{LS} is introduced, yet the results show that the spin-orbit energy splitting ΔE_{1P} in the baryon spectrum and the different partial wave phase shifts of N-N scattering can be explained reasonably when the V_{LS}^{TGE} is included. This means that in the quark-quark spin-orbit interaction, the color independent term due to the high-order diagrams is very important in explaining both baryon spectrum and N-N phase shifts.

Table 1. Parameters

b(fm)	0.55
m_q(MeV)	313
m_π (fm^{-1})	0.7
m_σ(fm^{-1})	3.294
Λ (fm^{-1})	4.2
$\frac{g_{ch}^2}{4\pi}$	0.592
α_s	0.790
a_c (MeV/fm^2)	30.1
a_{LS}	7.15

Table 2. Spin-Orbit Energy Splittings in Baryon Spectrum

state			$\Delta E = E_{J=L-S} - E_{J=L+S}$			
				Theor. (MeV)		
T	S	$\Psi_{NL(\sigma)}$	Exp[13]	A	B	C
$\frac{1}{2}$	$\frac{1}{2}$	1P(MX)	15.0 MeV	14.7	-87.4	-698.0
$\frac{1}{2}$	$\frac{1}{2}$	2P(A)		14.7	-87.4	-698.0
$\frac{1}{2}$	$\frac{1}{2}$	2D(S)		18.5	-15.8	-465.5
$\frac{1}{2}$	$\frac{1}{2}$	2D(MX)		21.5	-81.2	-814.8
$\frac{1}{2}$	$\frac{3}{2}$	1P(MX)		39.2	-234.4	-1561.3
$\frac{1}{2}$	$\frac{3}{2}$	2D(MX)		64.5	-243.5	-2444.3
$\frac{3}{2}$	$\frac{1}{2}$	2P(MX)		0	0	0
$\frac{3}{2}$	$\frac{1}{2}$	2D(MX)		18.5	[illegible]	-465.5
$\frac{3}{2}$	$\frac{1}{2}$	2D(S)		50.4	-47.3	-1396.5

(S, MX and A represent that the orbital wave functions are in symmetry, mixed symmetry and antisymmetry respectively).

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Figure Captions:

Fig.1. Irreducible diagram of two-gluon exchange.

Fig.2. $^3S_1$ phase shifts of N-N scattering.

Experimental data are taken from Ref.[14].

Curve A is for the case of $V_{LS}^{(A)} = V_{LS}^{OGE} + V_{LS}^{conf} + V_{LS}^{ch} + V_{LS}^{TGE}$ with $a_{LS} = 7.15$

Curve B is for the case of $V_{LS}^{(B)} = V_{LS}^{OGE} + V_{LS}^{conf} + V_{LS}^{ch}$.

Curve C is for the case of $V_{LS}^{(C)} = 4.7 V_{LS}^{OGE}$.

Fig.3a. The same as Fig.2 for $^3P_0$ phase shifts of N-N scattering.

Fig.3b. The same as Fig.2 for $^3P_1$ phase shifts of N-N scattering.

Fig.3c. The same as Fig.2 for $^3P_2$ phase shifts of N-N scattering.

Fig.4a. The same as Fig.2 for $^3D_1$ phase shifts of N-N scattering.

Fig.4b. The same as Fig.2 for $^3D_2$ phase shifts of N-N scattering.

Fig.4c. The same as Fig.2 for $^3D_3$ phase shifts of N-N scattering.

Fig.5a. The same as Fig.2 for $^3F_2$ phase shifts of N-N scattering.

Fig.5b. The same as Fig.2 for $^3F_3$ phase shifts of N-N scattering.

Fig.6. The same as Fig.2 for $^3G_3$ phase shifts of N-N scattering.

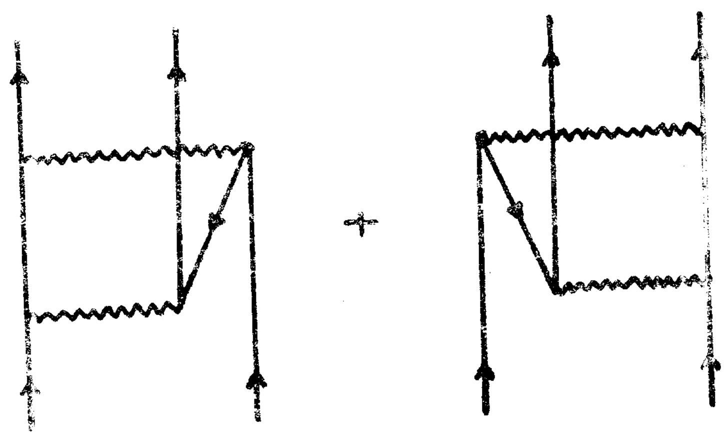


Fig. 1

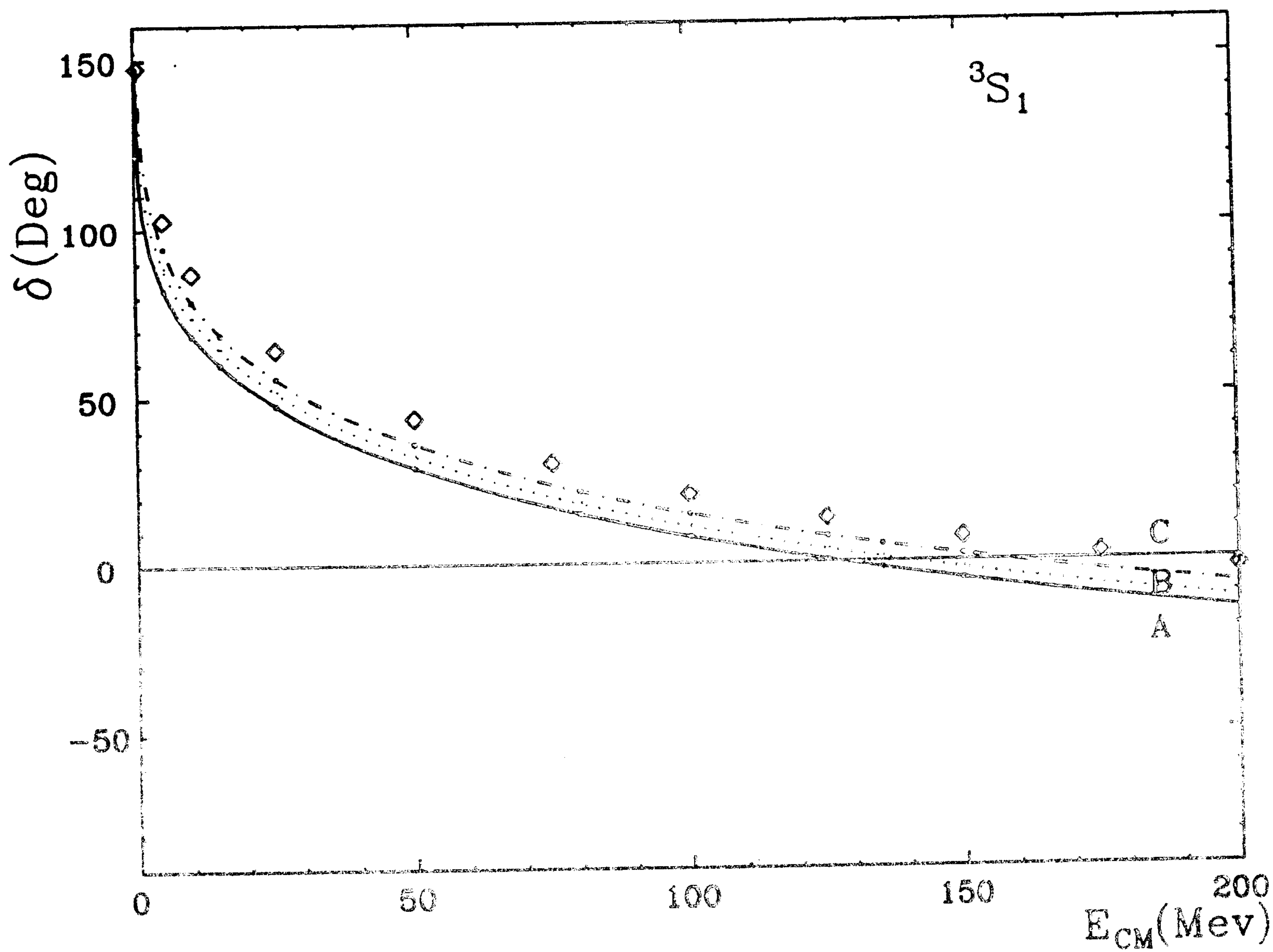


Fig 2.

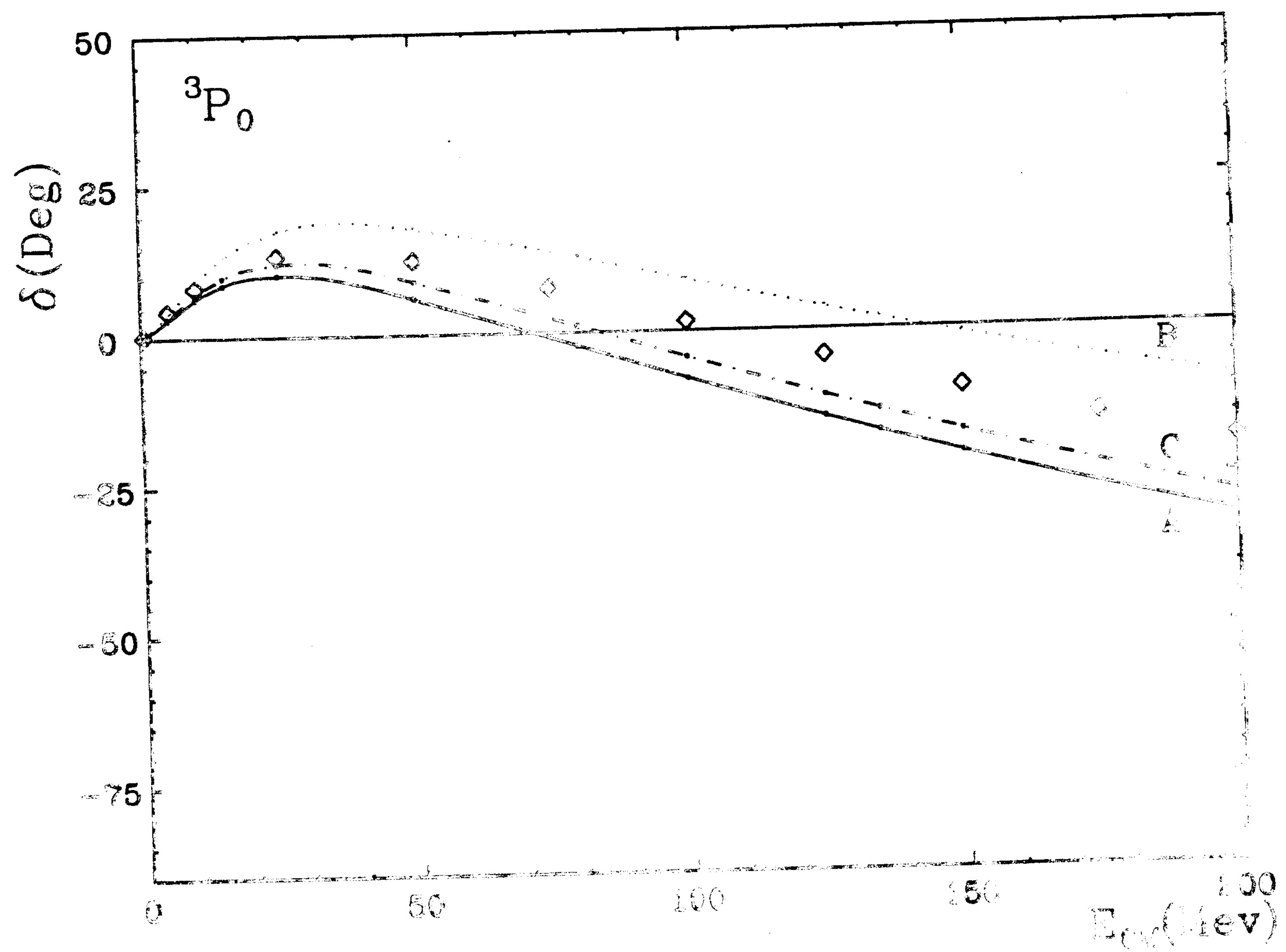


Fig. 3a.

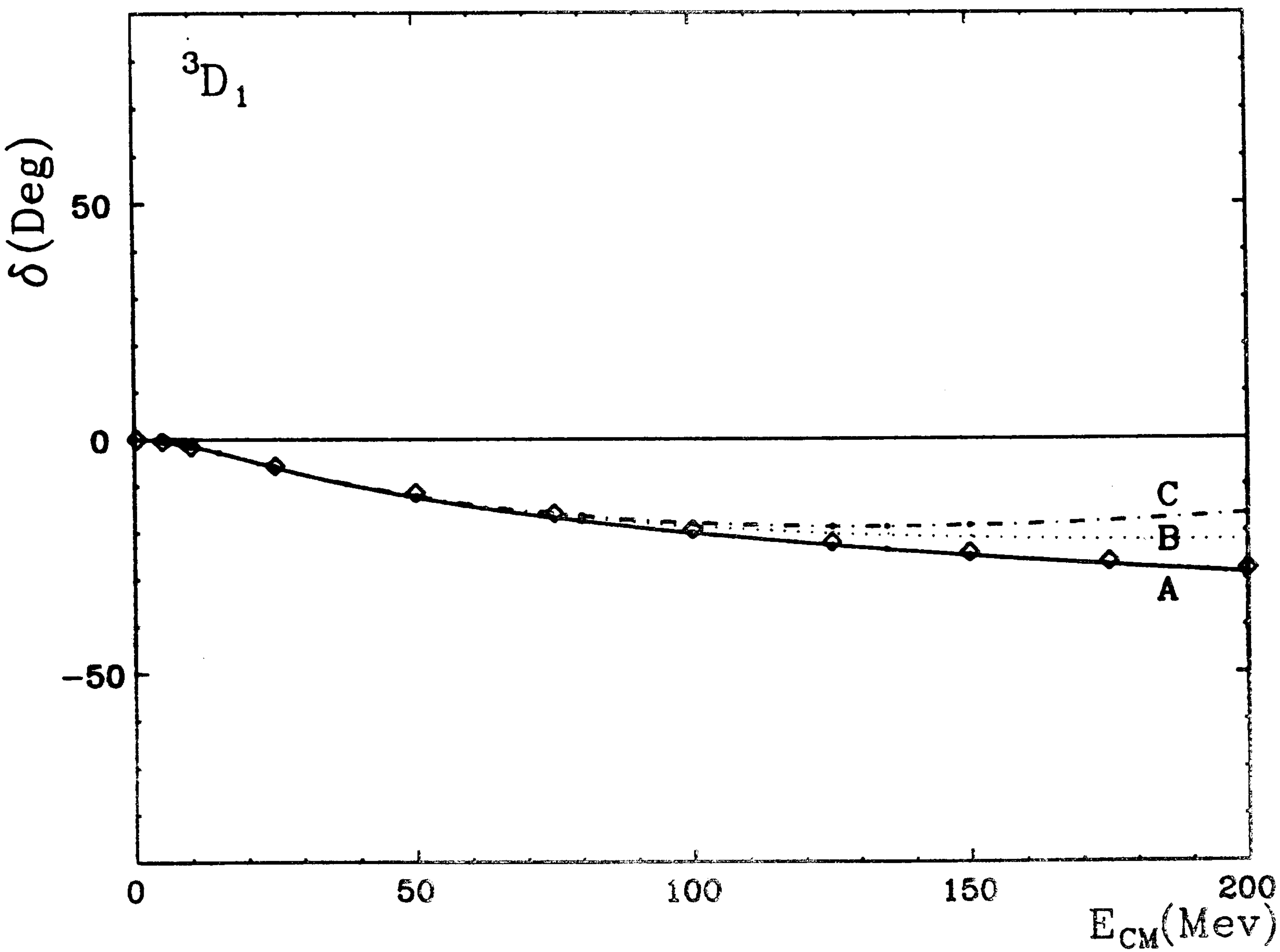


Fig 4a.

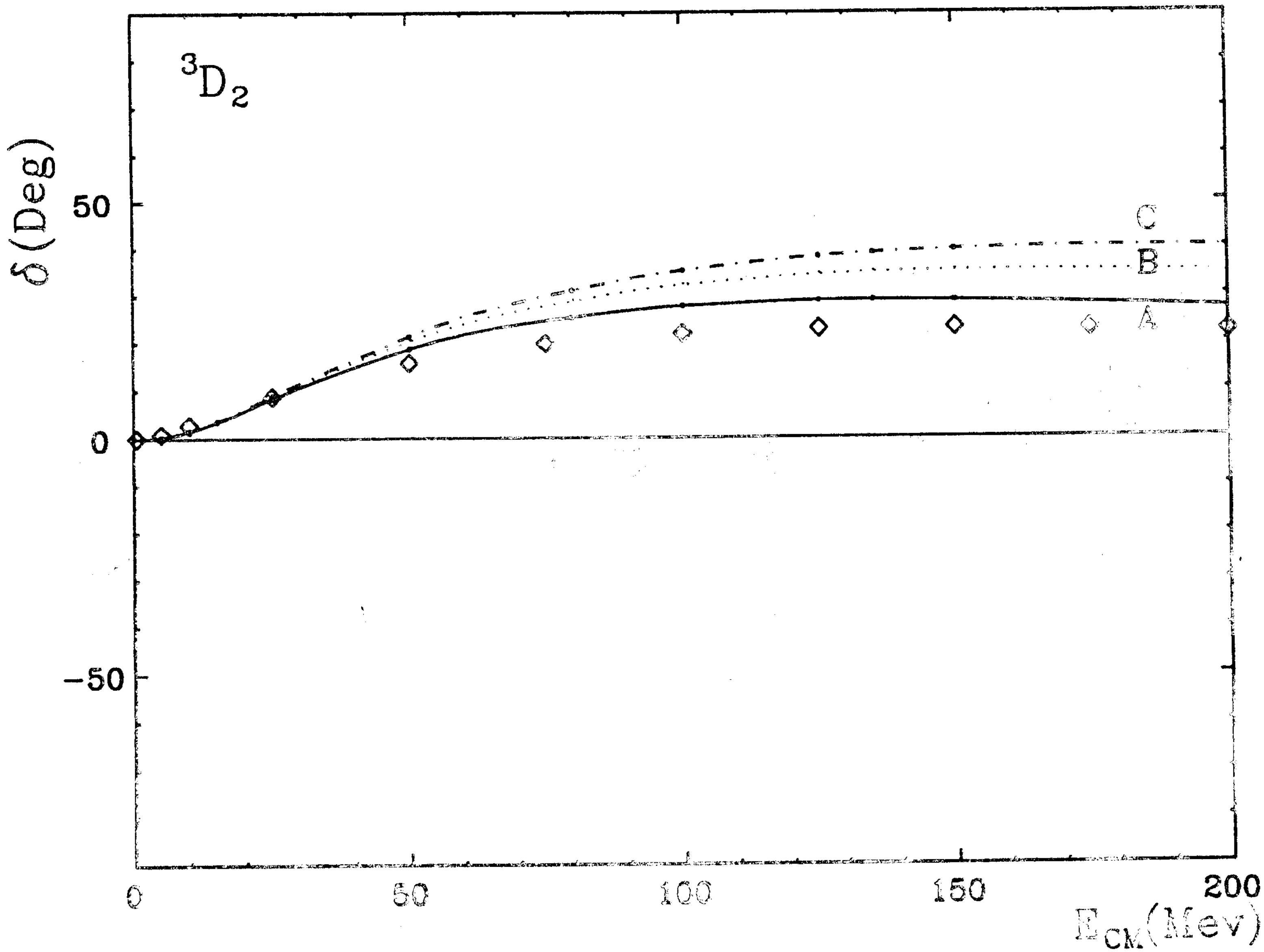


Fig 4b.

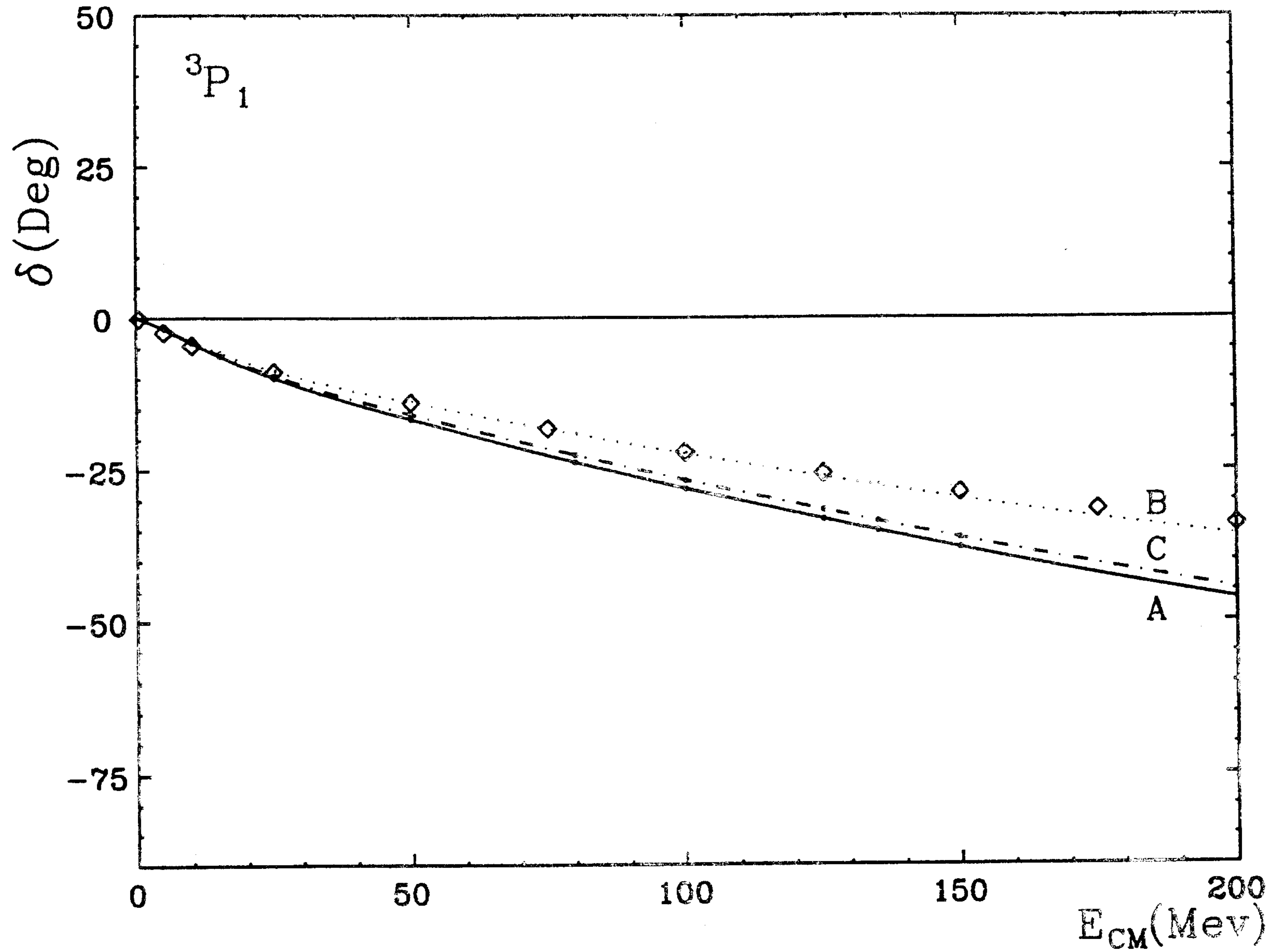
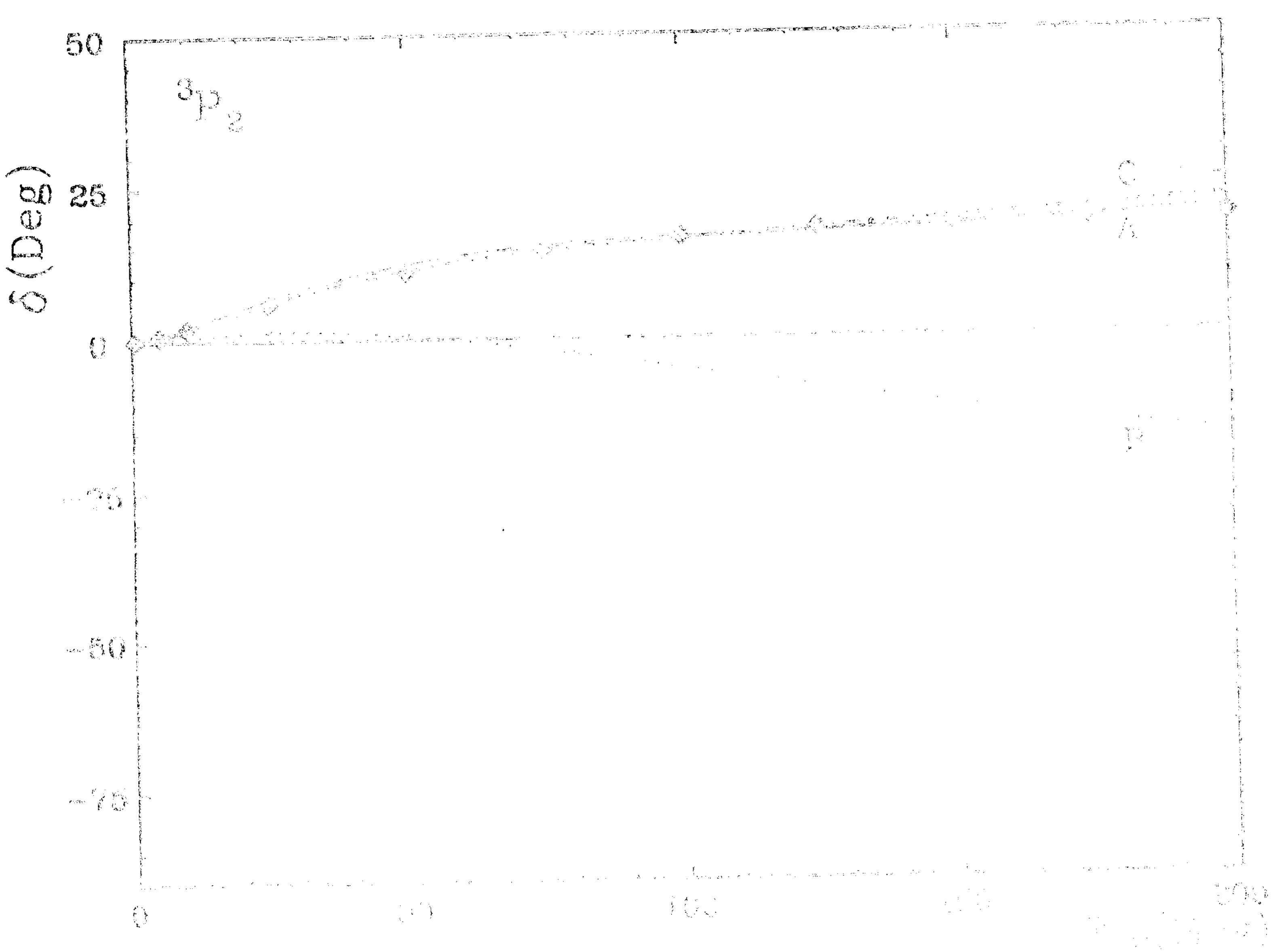


Fig 3b.


δ (Deg)
50
25
0
−50
−75
$^3P_2$
0

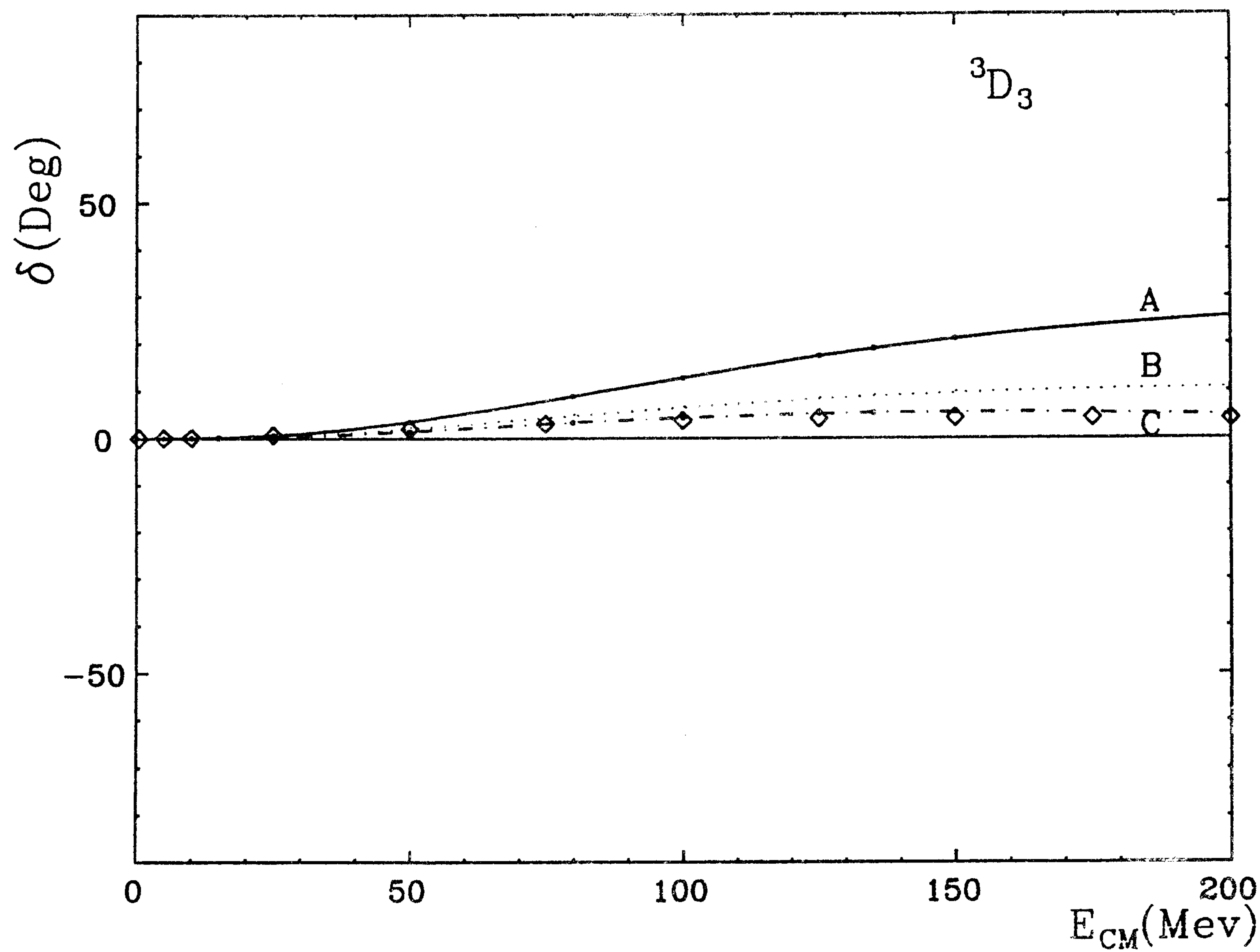


Fig 4c

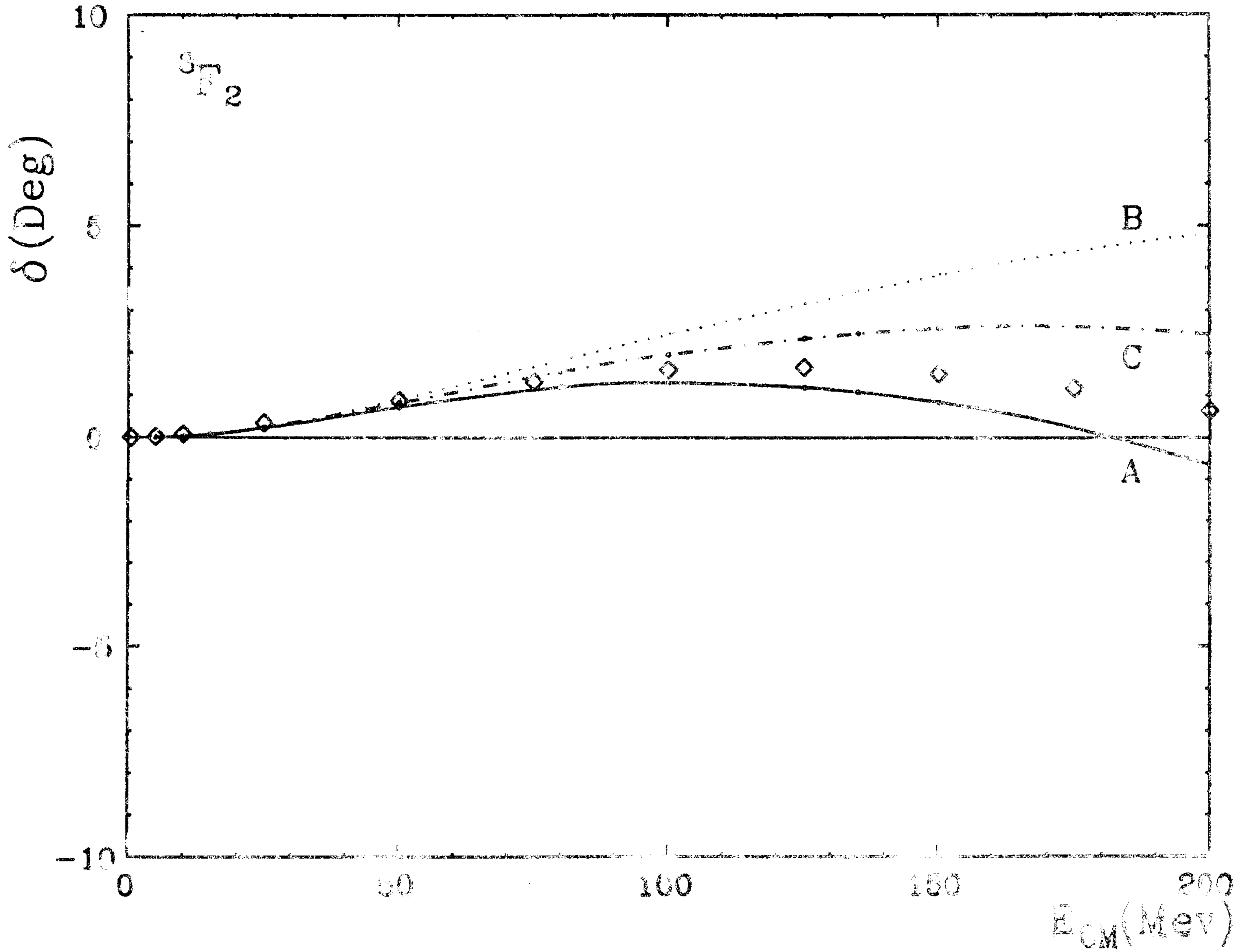


Fig 5a

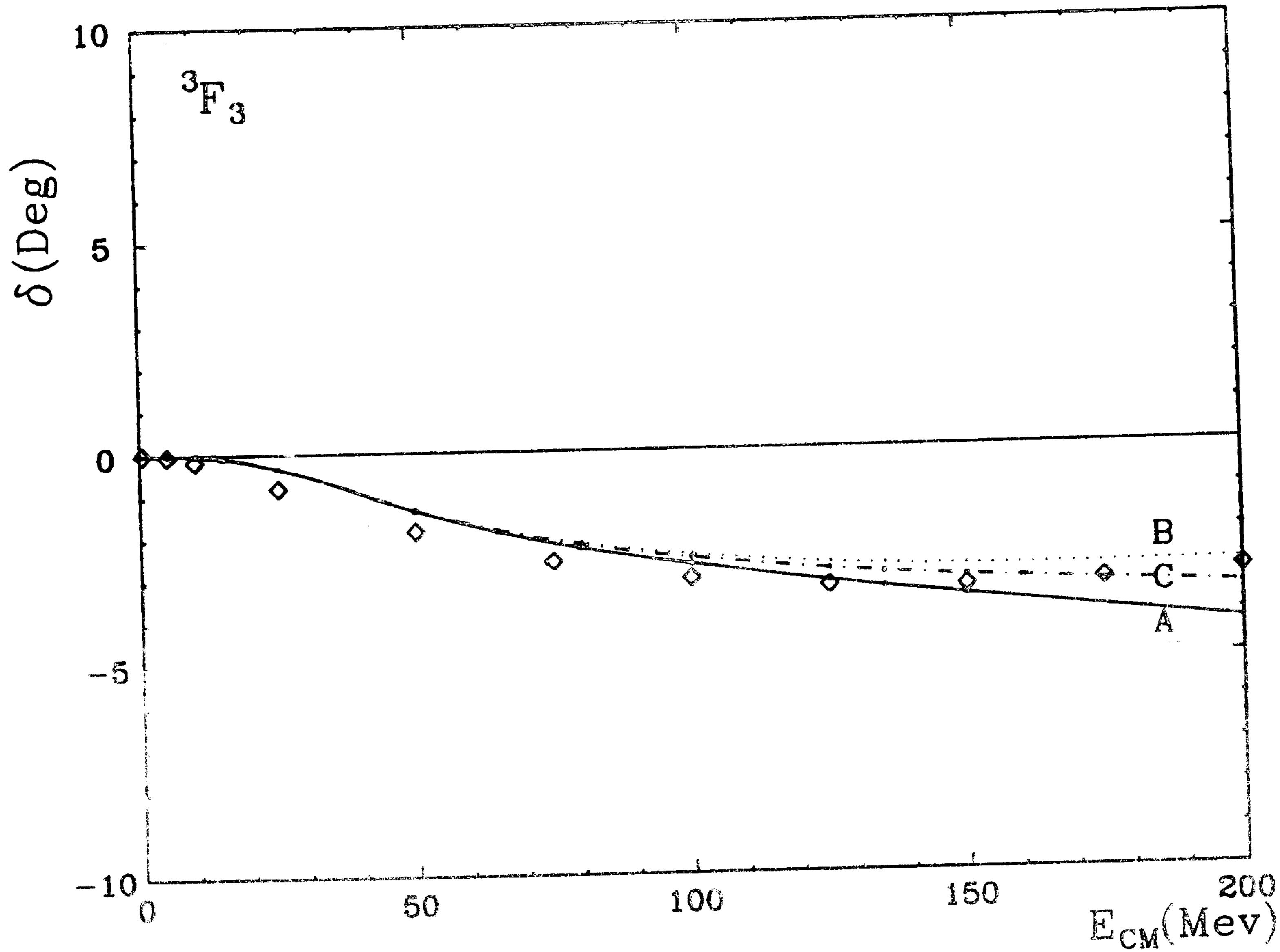


Fig 5b.

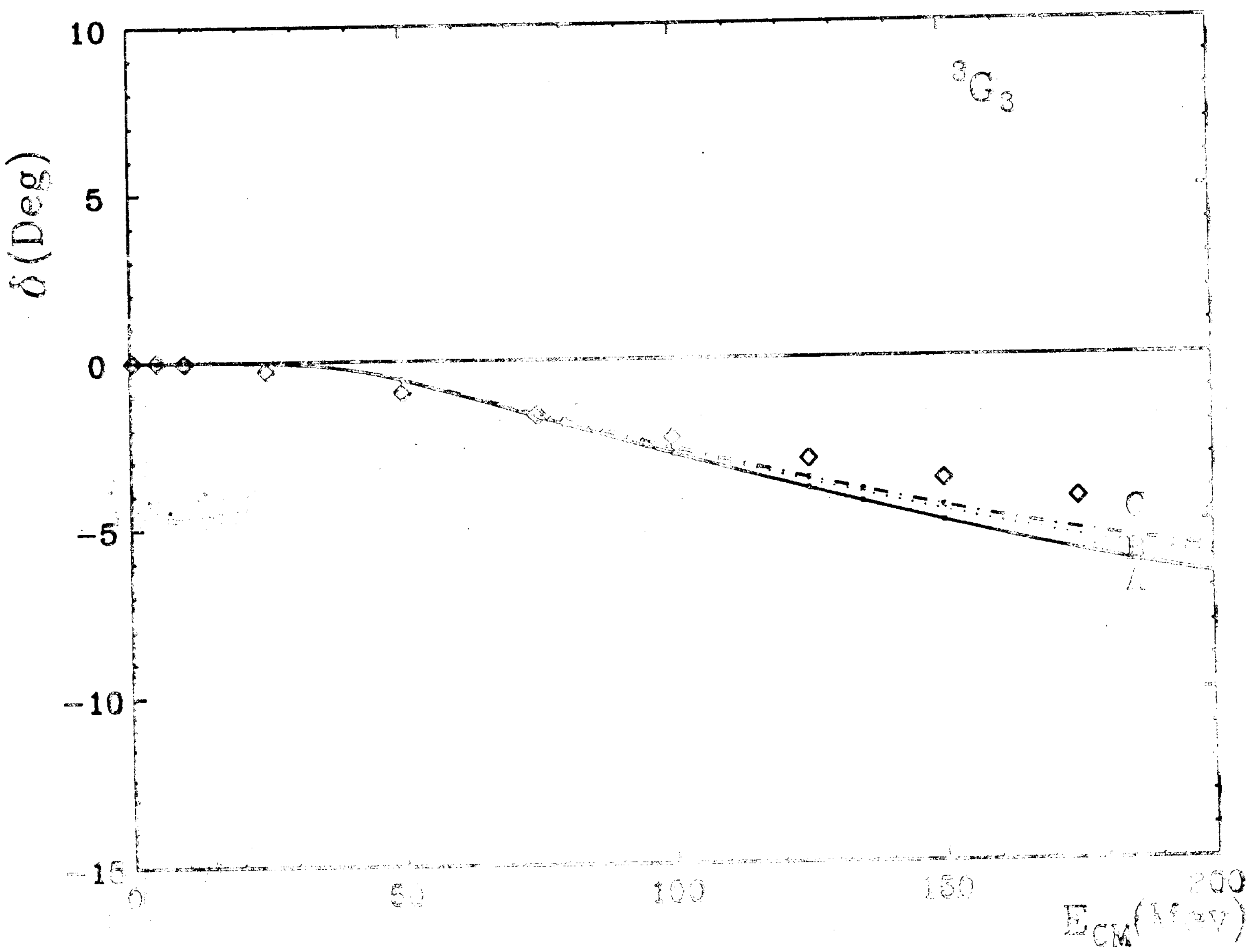


Fig 6