On the Proton-Proton Scattering in the Energy Range 25～70 MeV

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ON THE PROTON-PROTON SCATTERING IN THE ENERGY RANGE 25~70 MeV

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ABSTRACT

Proton-proton scattering data in the energy range 25~70 MeV were analyzed on the several sets of data combination. The correlation between the phase shifts and the observables has been investigated in order to make clear the present situation of the proton-proton scattering experiments in this energy region. Especially we pay our attention to the behaviour of the $^3P_0$ phase shift and the inconsistency among the experimental data.

1. Introduction

The nucleon-nucleon interaction in the outer region[1] ($r \gtrsim 1.5\,\mu^{-1}$; which is called the static region, where μ^{-1} is the pion compton wave length.) is realized well on the one pion exchange mechanism. But in the inner region ($1.5\mu^{-1} \gtrsim r \gtrsim 0.7\mu^{-1}$) which is called the dynamical region, nucleon-nucleon interactions should be learned on the multi-pion or boson exchange mechanism.

At low energies (below 20 MeV), triplet P wave phase shifts show the typical tensor type splitting owing to the OPEC-tail. In the energy region 20~100 MeV, the interaction in the inner region are revealed and triplet P-wave phase shifts are determined mainly by the competition of the one pion exchange contribution and the multi-pion exchange contribution. But the contribution from the innermost region are not so large. So the behavior of $3P$-wave phase shifts in this energy region are very important to make clear the nucleon-nucleon interaction mechanism in the inner region. Especially the behavior of $\delta(^3P_0)$ is very sensitive to this competition.

From the above consideration proton-proton scattering near 50 MeV region have been systematically investigated by the nuclear force study group in our country.[2)~10)] The measurements of spin correlation parameters C_{KP} and C_{NN} at 50 MeV were performed at INS,[2)] and in parallel to these experiments, the polarization, D, R and A parameters have been measured at 50 MeV by Rutherford Laboratory group.[11)~13)] The phase shift analysis with A data gave $\delta(^3P_0)$ as $11°\sim12°$ which was consistent with the prediction of H.J. potential, though analysis without A data gave $\delta(^3P_0)$ as $14°\sim17°$. The significance of this inconsistency was discussed by Tamagaki, Watari and Nisimura in their review articles.[10)]

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Since 1967 A_{XX} and A_{YY} data (these are related to C_{KP} and C_{NN} in the following equation; $A_{XX}=1/2\,(C_{NN}-2\sin(\theta)\times C_{KP}-1)$, and $A_{YY}=C_{NN}$) in this energy region have been obtained. (i.e., at 26.5 MeV at Saclay,[14] at 47.5 MeV at INS,[7] at 37.2 MeV and 26.5 MeV at Grenoble[15] and at 46.9 MeV and 26.5 MeV at Grenoble.[16] These data also requirde relatively large value of $\delta(^3P_0)$, though there seems to be apparent inconsistency between the A_{XX} value at 47.5 MeV and the A_{XX} value at 46.9 MeV.

If $\delta(^3P_0)$ is larger than 15° at $T=50$ MeV, the energy dependence of $\delta(^3P_0)$ up to 310 MeV hardly be fitted by an energy independent potential. On the other hand the results of Kantor amplitude analysis by Furuichi[9] suggest a large value of $\delta(^3P_0)$ near 50 MeV. One Boson Exchange Model prediction are more favorable to the large value of $\delta(^3P_0)$.[19)~22)] From these situations, more extensive measurements in the intermediate energy region are desired.

In order to clarify the present experimental situation and to test the sensitivity of observables to the splitting of the triplet P-wave phase shifts, we have carried out the phase shift analyses with the different sets of the data combination in this energy region.

2. Results of the numerical test

For the purpose of the present analyses, energy dependences of data in a small energy range are not significant and are disregarded.

The experimental data refered in this paper are summarized in Table 1.

Table I. The experimental data used in our analysis

Energy (MeV)	Number and type of data	Angular range (c.m.) (deg.)	Comment	
25.6	$23\sigma(\theta)$	10~90	Minesota	see Ref. 23)
27.4	$1P(\theta)$	45	Harwell	see Ref. 24)
26.5	$1A_{XX}$, $1A_{YY}$	90	Saclay	see Ref. 14)
26.5	$1A_{XX}$, $1A_{YY}$	90	Grenoble	see Ref. 15)
26.5	$1A_{XX}$, $1A_{YY}$	90	Grenoble	see Ref. 16)
27.6	$3A(\theta)$, $3R(\theta)$	23~55	Rutherford	see Ref. 12)
39.4	27σ	8~90	Minesota	see Ref. 25)
36.8	$1P(\theta)$	60	Harwell	see Ref. 24)
38.3	$1P(\theta)$	45	Harwell	see Ref. 24)
37.2	$1A_{XX}$, $1A_{YY}$	90	Grenoble	see Ref. 15)
52.3	$29\sigma(\theta)$	14~90	INS	see Ref. 3)
47.5	$5A(\theta)$	23~87	Rutherford	see Ref. 11)
47.8	$5A(\theta)$, $5R(\theta)$	23~87	Rutherford	see Ref. 12)
51.7	$1P(\theta)$	60	Harwell	see Ref. 24)
50.0	$1D(\theta)$	70	Rutherford	see Ref. 13)
52.0	$1C_{NN}$, $1C_{KP}$	90	INS	see Ref. 2)
46.9	$1A_{XX}$, $1A_{YY}$	90	Grenoble	see Ref. 16)
47.5	$1A_{XX}$, $1A_{YY}$	90	INS	see Ref. 7)
68.3	$26\sigma(\theta)$	10~101	Minesota	see Ref. 26)
66.0	$11P(\theta)$	20~71	Harvard	see Ref. 27)
73.5	1C	90	Harwell	see Ref. 28)

Table II

Analy. No.	$\sigma(\theta)$	P	C_{KP}	C_{NN}	A_{XX}	D	R	A	χ^2/N	$^1S_0$	$^1D_2$	$^3P_0$	$^3P_1$	$^3P_2$	ε_2	Comment
1	29	1	1	1		1	5	5	0.88	38.17	1.65	13.13	−8.24	5.92	−1.71	
2	29	1	1	1		1	5	5	1.15	38.32	1.68	12.31	−8.27	6.10	−1.71	a
3	29	1	1	1		1	5	5	1.00	38.65	1.62	12.84	−7.97	5.82	−1.71	b
4	29	1	1	1		1	5	5	0.97	39.18	1.56	12.60	−7.66	5.70	−1.68	c
5	29	1	1	1		1	5	5	1.02	37.93	1.90	13.89	−8.80	6.11	−1.82	d
6	29	1	1	1		1	5	5	1.06	39.17	1.74	12.53	−7.57	5.67	−1.77	e
7	29	1	1	1		1			0.90	37.70	1.66	13.74	−8.44	5.92	−1.70	
	29	1	1	1		1	5	5	0.91	39.04	1.57	12.57	−7.77	5.76	−1.67	f
9	29	1	1	1		1	5	5	0.94	38.09	1.65	13.23	−8.28	5.92	−1.71	g
10	29	1	1	1		1	5	5	0.84	38.27	1.64	13.02	−8.19	5.92	−1.70	h
11	29	1	1	6		1	5	5	0.90	37.69	1.67	13.37	−8.51	6.04	−1.70	i
12	29	1	1	6		1	5	5	0.76	36.41	1.77	14.07	−9.13	6.30	−1.73	i
13	29	1		1	1	1	5	5	0.84	38.27	1.64	13.02	−8.19	5.92	−1.70	k
14	29	1		1	6	1	5	5	0.82	38.30	1.70	13.47	−8.06	5.77	−1.80	j
15	29	1		1	6	1	5	5	1.82	36.55	1.84	16.32	−8.47	5.55	−1.91	j
16	29	1				1	5	5	0.81	38.33	1.64	12.86	−8.18	5.94	−1.70	
17	29	1		1	1	1	5	5	0.82	37.30	1.76	13.72	−8.66	6.05	−1.78	h,k
18	29	1		1	1	1	5	5	1.76	37.21	1.78	15.33	−8.32	5.01	−1.87	h,l
19	29	1		1	1	1			1.41	38.26	1.70	13.84	−7.98	5.67	−1.81	h,k
20	29	1		1	1	1			1.61	37.62	1.83	15.68	−7.84	5.39	−1.94	h,l
21	29			1	1				0.78	37.02	1.68	14.29	−8.74	6.01	−1.62	h,k
22	29			1	1				0.78	36.90	1.65	17.54	−7.94	5.02	−1.78	h,l

a. A data at 47.5 MeV
b. Each value of A and R multiplied by 1.05
c. Each value of A and R multiplied by 0.95
d. Each value of A and R multiplied by 1.1
e. Each value of A and R multiplied by 0.9
f. Input value of D is taken as the upper limit of the error bar of its experimental value.
g. Input value of D is taken as the lower limit of the error bar of its experimental value.
h. C_{NN} is an interpolated value between C_{NN} data at 47.5 MeV and at 73.5 MeV.
i. Form of angle dependence of C_{NN} are estimated by the predicted values of the results of analysis 1 as shown in Fig. 1c).
j. Form of angle dependence of A_{XX} are estimated by the predicted values of the results of analysis 1 as shown in Fig. 1d).
k. A_{XX} data at 46.9 MeV in Grenoble.
l. A_{XX} data at 47.5 MeV in INS.

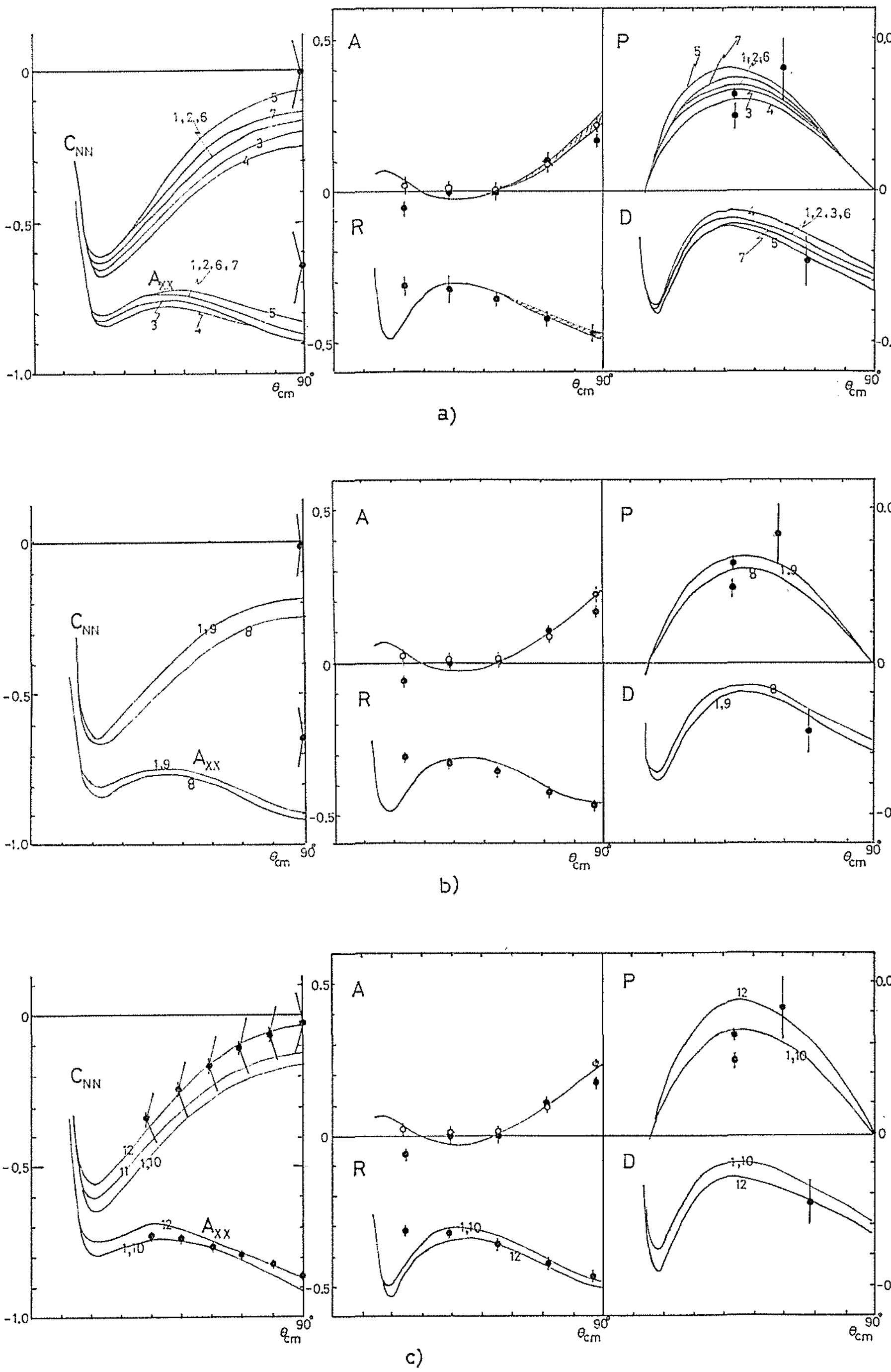
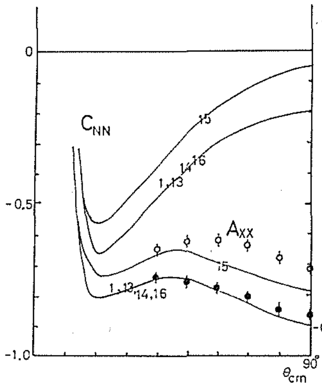
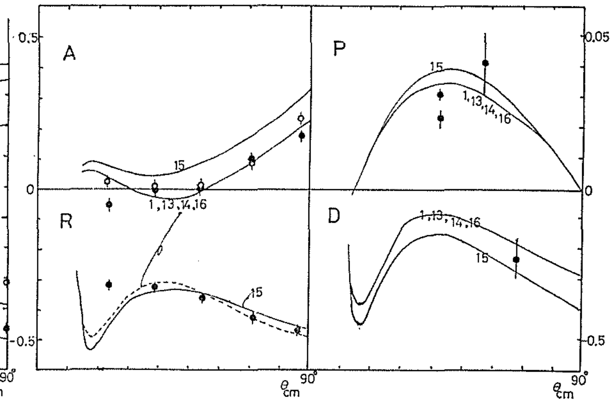
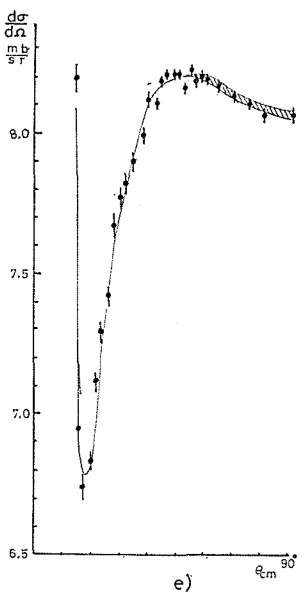


Fig. 1





d)



e)

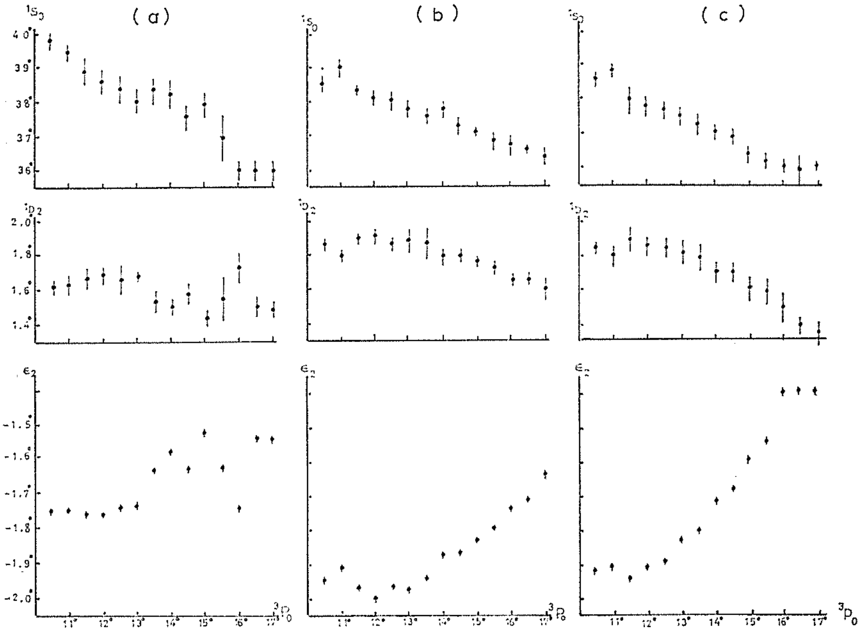
Fig. 1 a)~e). The predicted velues of some observables at 50 MeV with the data. Annexed numbers to lines correspond to analysis number. The A data by open circle are 47.8 MeV data and solid circle are 47.5 MeV data. The form of angle dependence of C_{NN} in Fig. 1 c) and of A_{XX} in Fig. 1 d) are determined by the result of analysis 1.

2-1 At T=52 MeV

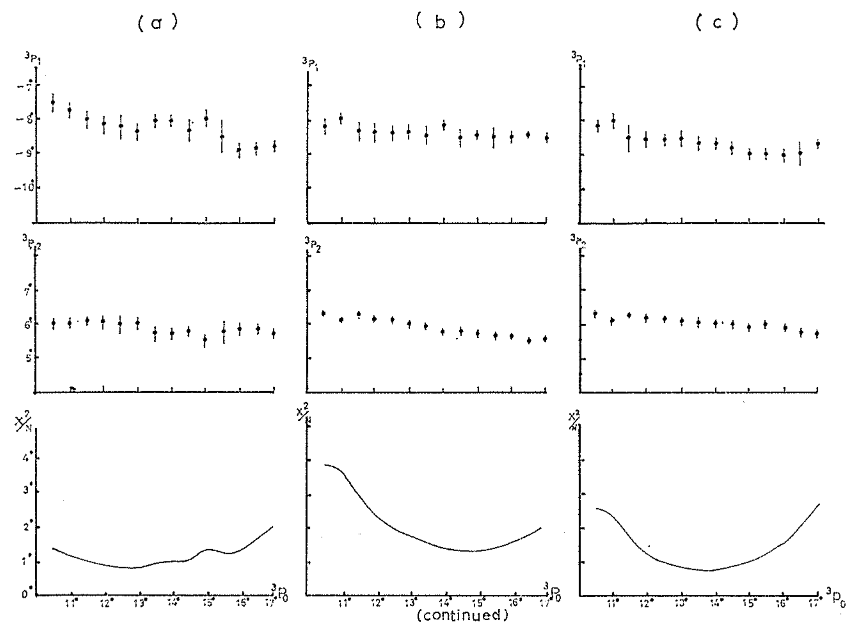
The sets of the data combination and the values of phase shifts from the present analysis are summarized in Table II and Figs. 1 a)~e).

In comparison of analysis (1) with analysis (2), A data at 47.5 MeV give larger χ^2/N than A data at 47.8 MeV. Moreover the predicted values of A parameter from analysis (2) in which data at 47.5 MeV are adopted as the input data of A parameter are very close to the experimental values at 47.8 MeV as shown in Fig. 1 a). So in the rest of analyses A data at 47.8 MeV are adopted as the input data of A parameter.

When input values of A and R parameters are changed in the vicinity of its experimental values, $\delta(^3P_0)$ does not move remarkably until we take the normalization factor as large as 1.1. But the predicted values of C_{NN}, A_{XX}, D and P are very sensitive to the A and R parameters as shown in Fig. 1 a). The results of analyses (8) and (9) indicate that a large value of D demand smaller $\delta(^3P_0)$.

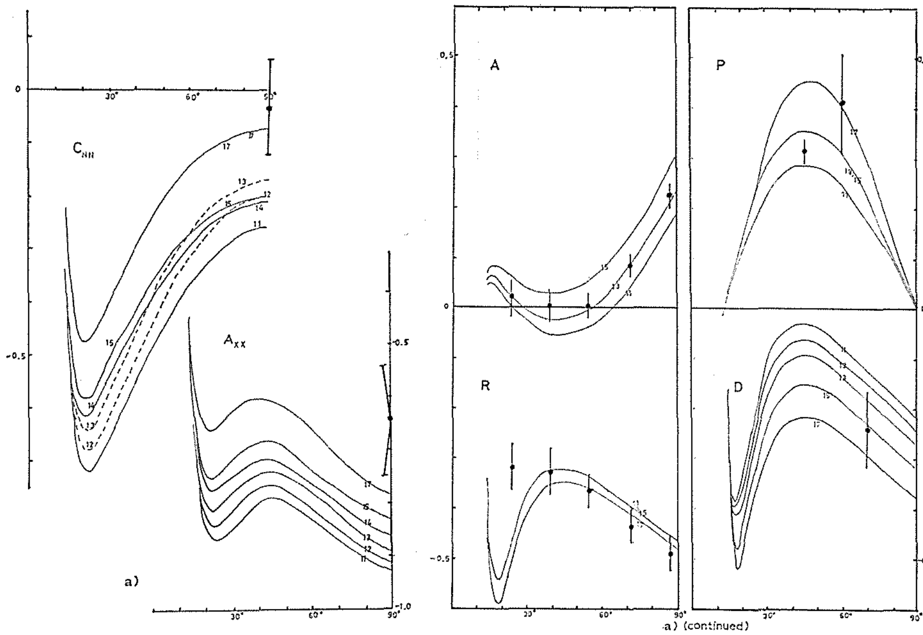


a



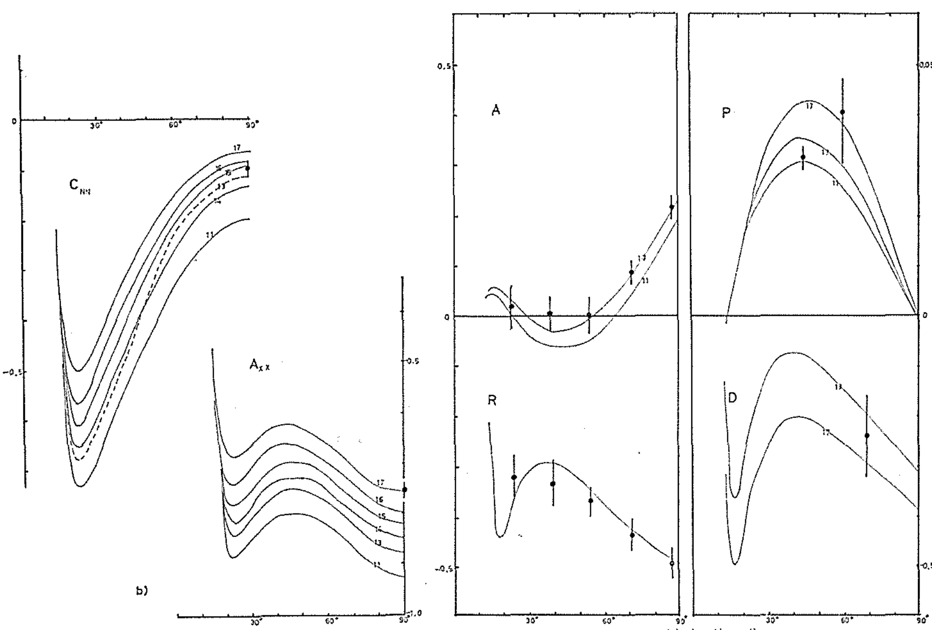
b

Fig. 2. The phase shifts and χ^2/N versus to $\delta(^3P_0)$ for three cases of the data selection. Selection of the data are described in the text.



C_{NN}
A_{XX}
A
P
R
D
a)
a) (continued)
0
-0.5
0.5
0.05
-1.0
30°
60°
90°

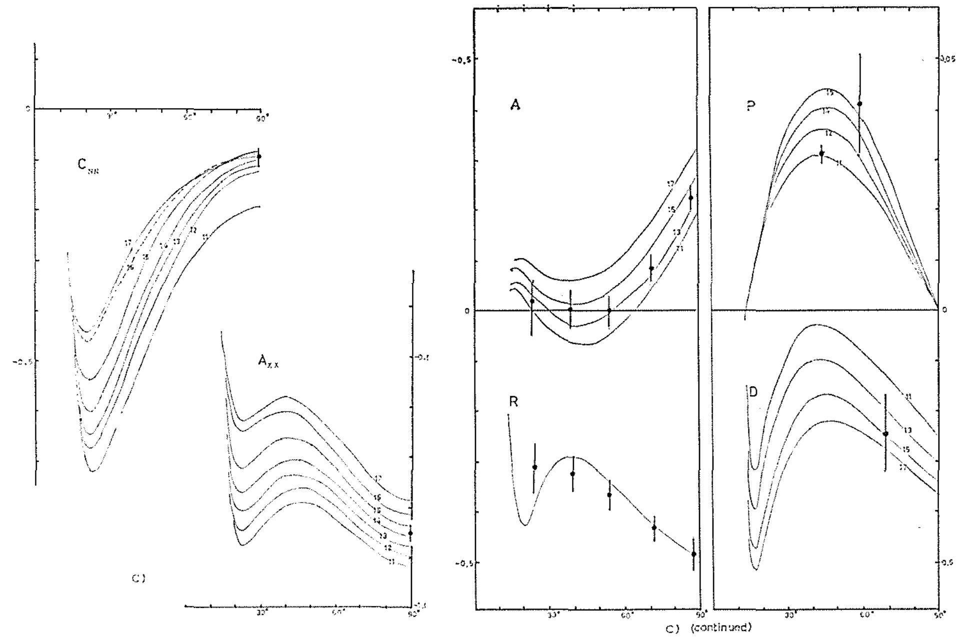
a



C_{NN}
A_{XX}
A
P
R
D
b)
b) (continued)
0
-0.5
0.5
0.05
-1.0
30°
60°
90°

b

Fig. 3



c

Fig. 3. The predicted values of some observables corresponding to Fig. 2. Annexed number corresponds to $\delta(^3P_0)$.

Analyses 10~16 show that forms of angle dependence of C_{NN} and A_{XX} are influential informations about $\delta(^3P_0)$. The results of analyses 17~22 show that, the A_{XX} data at INS give larger $\delta(^3P_0)$ than the Grenoble data and value of $\delta(^3P_0)$ is pulled down by the A and R data.

Then we analyze with fixed $\delta(^3P_0)$ in following three cases.

a) $C_{NN}=-0.034+0.095$ $\quad C_{KP}=0.13+0.11$

b) $C_{NN}=-0.1+0.02$ $\quad A_{XX}=-0.75+0.02$

c) $C_{NN}=-0.1+0.02$ $\quad A_{XX}=-0.85+0.015$

The results are shown in Fig. 2 as a function of $\delta(^3P_0)$ from 10.5° to 17°. In the case a) there are two minimum points of χ^2/N. One is at $\delta(^3P_0)=12.5°$ and the other is at $\delta(^3P_0)=15.5°$. In the case b) and the case c) there are minimum point of χ^2/N at $\delta(^3P_0)=15°$ and 13.5° respectively. INS data demand rather large $\delta(^3P_0)$ than Grenoble data. The value of χ^2/N in case c) is smaller than that in case b), but in present stage, we can not say, which data is suitable or not, from χ^2/N values. The predicted values of observables by this analysis are shown in Fig. 3. These results seemed to give effective information for a phase shift analysis.

2–2 At 25.0 MeV, 39.4 MeV and 68.3 MeV

The results are summarized in Table 3 and in Figs. 4~6. At 25.6 MeV, larger value of C_{NN} and A_{XX} require large $\delta(^3P_0)$. A and R data prefere a rather small $\delta(^3P_0)$, which is consistent with the energy dependent phase shift analysis

Table III

	Analy. No.	$\sigma(\theta)$	P	C_{NN}	A_{NN}	R	A	χ^2/N	$^1S_0$	$_1D^2$	$^3P_0$	$^3P_1$	$^3P_2$	Comment
25.6 MeV														
	1	23	1	1	1	3	3	0.97	48.73	0.74	8.39	−5.24	2.65	a
	2	23	1	1	1	3	3	1.18	48.56	0.74	9.03	−5.31	2.58	b
	3	23	1	1	1	3	3	1.13	48.46	0.75	8.92	−5.39	2.63	c
	4	23	1			3	3	0.83	49.30	0.73	7.68	−4.69	2.46	
	5	23	1	1	1			0.51	48.50	0.74	9.07	−5.29	2.53	a
	6	23	1	1				0.50	48.48	0.74	9.41	−5.22	2.42	a
	7	23	1		1			0.50	49.01	0.72	8.83	−4.71	2.26	a
39.4 MeV														
	1	27		1	1			1.37	43.47	1.29	11.23	−6.13	4.18	
	2	27	2	1	1			1.30	43.49	1.28	11.25	−6.10	4.16	
	3	27	2	1	1			1.28	43.51	1.28	11.50	−5.95	4.03	d
	4	27	2	1	1			1.21	43.57	1.32	9.95	−6.27	4.48	d
68.3 MeV														
	1	26	11	1				0.60	32.84	2.62	9.10	−10.66	8.76	−2.03
	2	26	11					0.63	32.55	2.58	11.13	−10.71	8.41	−2.11

a. C_{NN} and A_{XX} data at Saclay in 1970.
b. C_{NN} and A_{YY} data at Grenoble in 1970.
c. C_{NN} and A_{XX} data at Grenoble in 1971.
d. For input value of A_{XX}, see the Text.

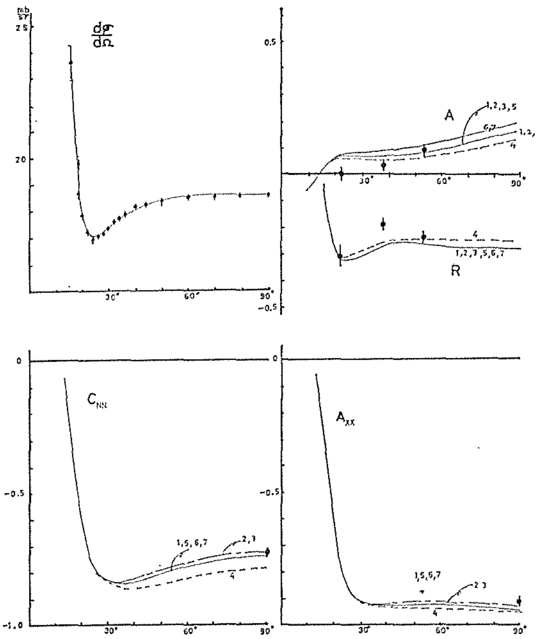


Fig. 4. The prediction of some observables at 25 MeV.

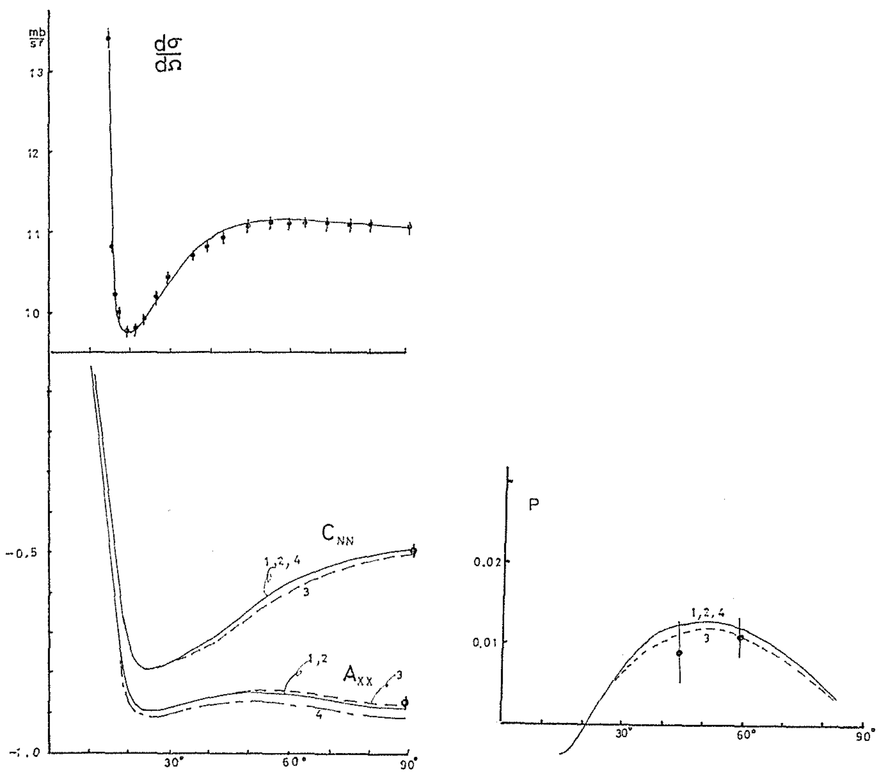


Fig. 5. The prediction of some observables at 39 MeV.

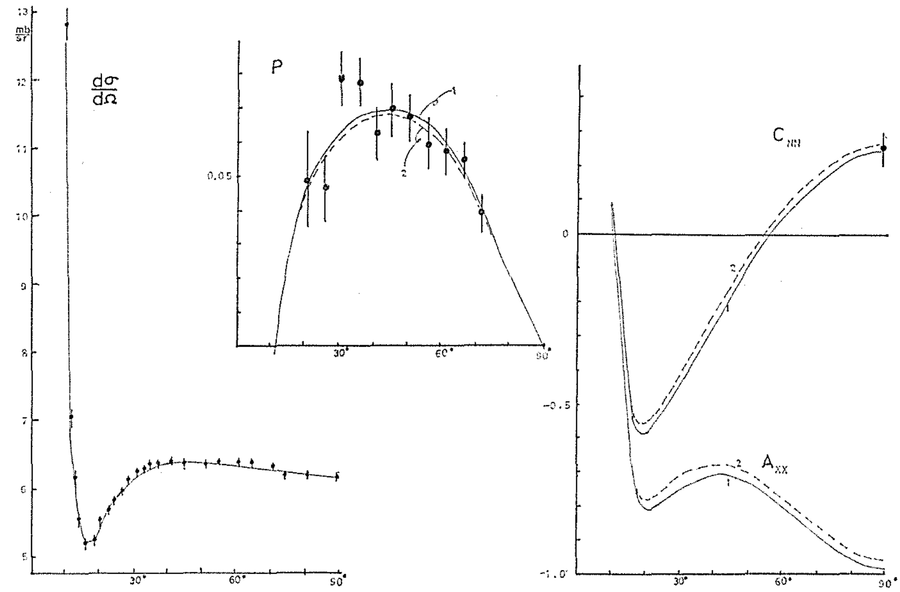


Fig. 6. The prediction of some observables at 68 MeV.

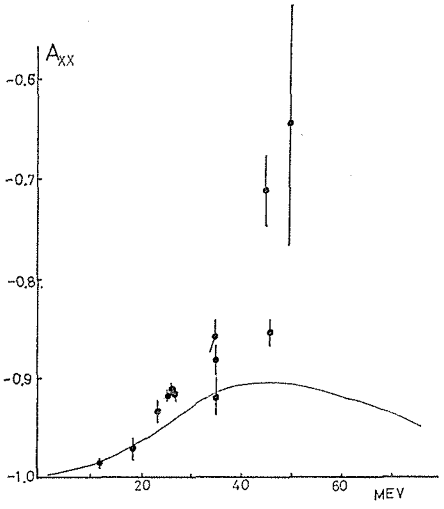


Fig. 7. Energy dependence of A_{xx}. Closed circles indicate experimental data and open circles are the pseudo data given by the author. Solid line is the prediction of MAWX.

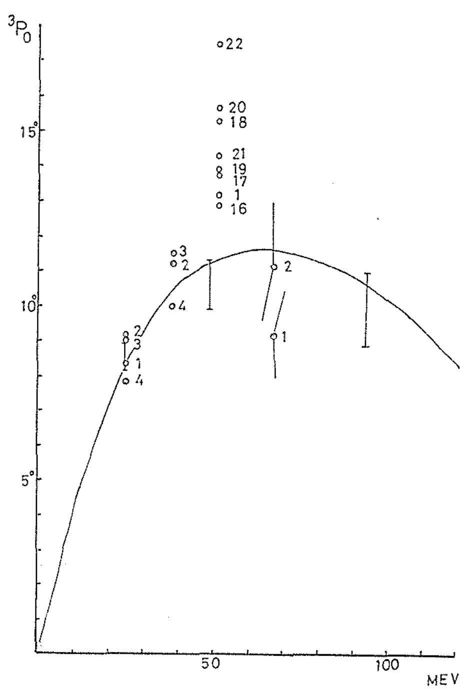


Fig. 8. The value of $\delta(^3P_0)$ are plotted. Annexed number correspond to analysis number. Solid line is MAWX and solid bars are the energy independent analysis by MAWX.

by Livermore group (MAWX)[18] A_{XX} data prefere a larger $\delta(^3P_0)$. At 39.4 MeV, analyses with P and without P give same results because of the poor statistics of P data at this energy. In analysis 3, input va ue of A_{XX} is postulated as a value which is seemed upper limit considering the energy dependence of A_{XX} and in analysis 4 it is postulated as a value of the prediction from MAWX. (See Fig. 7) At 68.3 MeV, the result with C_{NN} gave smaller $\delta(^3P_0)$ than the result without C_{NN}. But both require a same predicted value of observables on account of the large error of $\delta(^3P_0)$.

In Fig. 8 the values of $\delta(^3P_0)$ given from present analyses are shown with the energy dependent and independent phase shift analysis by Livermore group.

3. Conclusion and discussion

Determination of A_{XX} parameter in the vicinity of 50 MeV is very important because of its sensitivity to $\delta(^3P_0)$. Now we have a few data in this region and all these data demand rather large value of $\delta(^3P_0)$ compared with MAWX. But there seems to be appearent inconsistency between these data. The appearent inconsistency is a puzzle because of very good consistency in A_{YY} data which are measured simultaneously with A_{XX} data. So the systematical measurments of spin correlations parameter in these energy region are desired. Especially angular dependence of A_{XX} and C_{NN} will give very effective informations. And also more accurate angular dependence of polarization in these energy region make contributions to perform a phase shift analysis. D parameter, which we have only one point in these energy region, is also effective parameter if it is measured accurately and systematically.

Measurements of D, A and R parameters request double scattering experiments, though measurements of A_{XX} and A_{YY} can be performed by a single scattering process using polarized beam and polarized target. So the measurements of A_{XX} and A_{YY} are desirable in order to fix the phase shifts and to make clear the mechanism of proton-proton sacttering in the intermediate energy region.

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