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DISCUSSION

SANDWEISS: Referring to your elastic scattering cross section, of 8.7 mb, did that refer to 3 BeV protons?

VEKSLER: 8.2 BeV.

RECENT WORK ON NUCLEON-NUCLEON SCATTERING AT HARWELL

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I. POLARIZATION IN *n—p* SCATTERING (20-120 MeV) (Huxtable, Langsford, Scanlon, and Thresher)

In comparison with that on the $p-p$ scattering process, the data on $n-p$ scattering in the energy range above 20 MeV is very scarce. We are attempting at Harwell to remedy this in such a manner that, in some respect, the $n-p$ data will be more abundant, even though of less accuracy, than the *pp* data in the energy range up to 100 MeV.

At last year's conference, preliminary data were presented of the $n-p$ differential scattering cross section as a function of energy in the range 37.5-125 MeV. I had hoped that the final values of the cross section would be available to present today, but they are not. However, I offer instead a set of preliminary values for the polarization in $n-p$ scattering in the energy range 22.5-110 MeV, using the same time of flight techniques.

This is illustrated in Fig. 1. The entire internal proton beam of the Harwell synchro-cyclotron is deflected vertically at 143 MeV on to an internal aluminium target which is 60 MeV thick. This produces a single burst of neutrons about 10ns long, corresponding to the RF structure of the circulating proton beam. Neutrons produced at 45° to the incident proton beam are collimated to pass down to a 25 meter flight path, at the end of which they are scattered by liquid hydrogen.

These neutrons are polarized in the production process and this polarization was determined by small angle Schwinger scattering from uranium. A solenoid placed near the beginning of the flight path was used to precess the neutron spins about their direction of motion towards the horizontal direction, and the horizontal component of the polarization of the neutrons was measured by an up-down scattering. There are two points to note. The first is that since measurements are being made at all energies simultaneously, for only one energy will the neutron spin be horizontal and allowance must be made for this in determining the polarization of the neutron beam. The other point is that the neutron producing target is about 3 cm above the magnetic median plane of the cyclotron and consequently there is some longitudinal component of magnetic field while the neutron traverses the cyclotron fringe field. This produces a significant rotation of the neutron spin before it enters the solenoid. Consequently to have " equal but opposite " states of polarization of the beam after passing through the solenoid, it is necessary to pass different currents in the two directions—in practice +1000 amps and −860 amps. It should be noted also that the whole experiment is basically a comparison of the asymmetries observed in scattering from uranium and hydrogen so one does not really need to know these correction factors at all, except in so far as they enter into estimates of small correction terms, such as multiple scattering, which are different for the uranium and hydrogen scatters.

The analyzing power of the uranium scatterer was calculated from values of the uranium total cross section and its small angle differential scattering cross section, which were specifically measured for that purpose.

The measured polarization of the beam is approximately 20-30% from 20 MeV up to 120 MeV. The useful horizontal transverse component of this varies from 75-100% of these values.

The polarization in *n-p* scattering is of course determined by making an up-down asymmetry measurement in scattering from liquid hydrogen, with two counters in a self monitoring arrangement. The ratio

$$\frac{UN}{DN}\cdot\frac{DR}{UR}=\frac{(1+P_1P_2)^2}{(1-P_1P_2)^2}$$

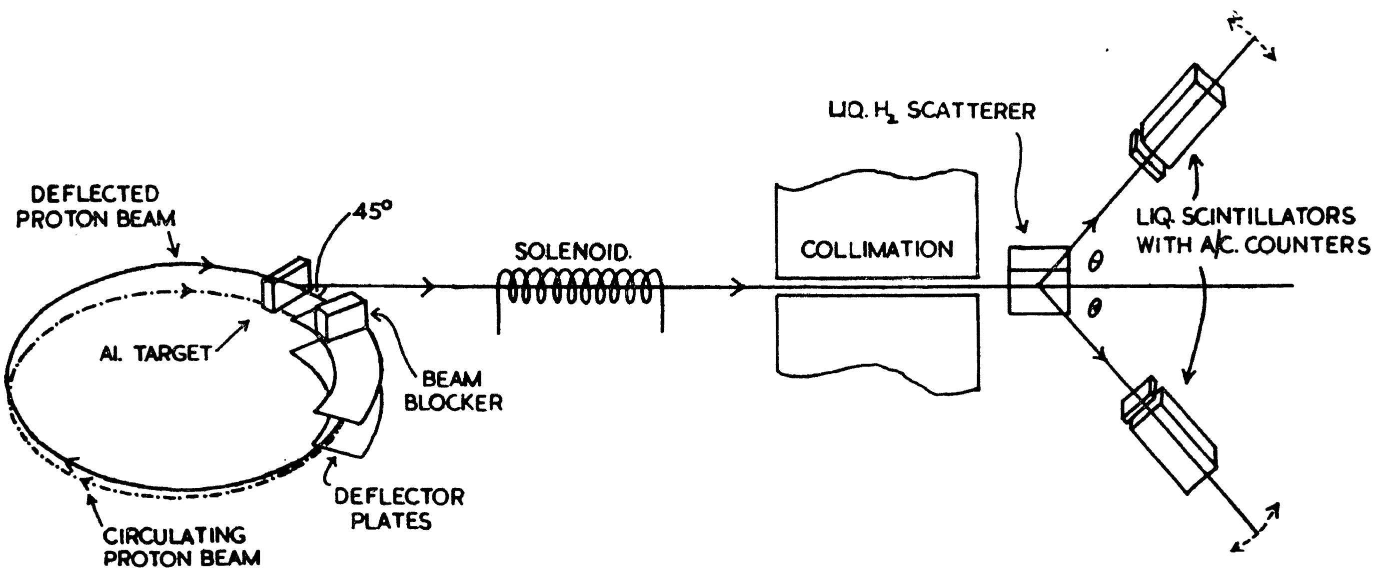

Fig. 1 Schematic representation of the *n−p* polarization experiment.

is determined, where UN represents the counting rate in the up counter with the solenoid current normal, DR the rate in the down counter with the solenoid current reversed, and so on. In this system the efficiencies of the counters do not need to be equal since they cancel out in the ratio.

Measurements have been made for that region of the angular distribution where it is appropriate to measure the scattered neutrons—that is from 20° to 80° c. of m. The neutrons were detected in large tanks of liquid scintillator $4'' \times 8'' \times 18''$ long. The remainder of the angular range from 90-160° c. of m. will be covered by detecting the recoil protons.

The preliminary results are shown in Fig. 2, plotted as polarization at a given laboratory angle against neutron energy. The horizontal bars give the energy resolution for each point. Comparison with previous work at 77 and 95 MeV, Hillman, Stafford, Tornabene and Whitehead is satisfactory, though the energy resolution is much better in the present work.

It is apparent that the polarization falls to very low values at 40 MeV. This is in qualitative agreement with some values estimated by Hamilton from the Gammel Thaler phase shift, as can be seen from Fig. 3.

These data are preliminary on two counts. First, certain multiple scattering effects in the liquid hydrogen target are not included. These have been roughly estimated to call for corrections which do not exceed about one-third of the assigned standard errors,

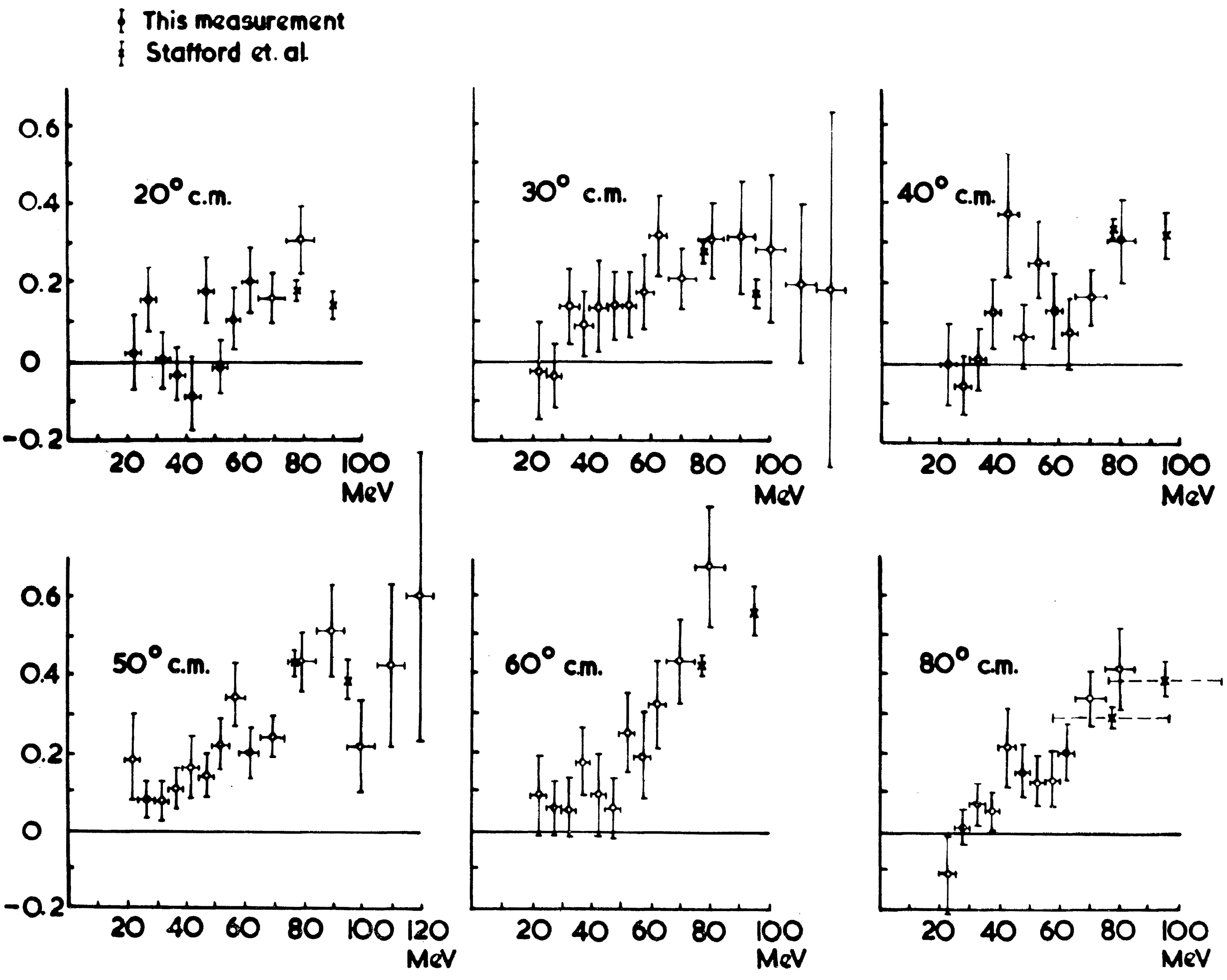

Fig. 2 $n-p$ polarization *vs.* energy, at various angles.

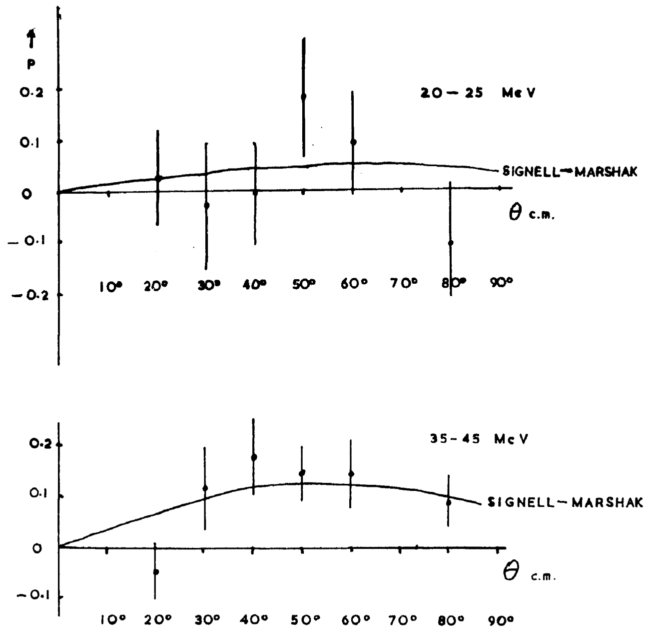

Fig. 3 $n-p$ polarization *vs.* angle, at 23 and 40 MeV.

which are themselves almost entirely statistical. Secondly, the whole of these data are to be taken again with improved electronic techniques. This improvement will enable the highest energy to be raised to 110 MeV, but should not affect the lower energy data, except to improve it statistically.

II. D-PARAMETER IN p—p SCATTERING AT 142 MeV (Taylor)

It will not be news to this assembly that there has been a disagreement between experimental values for *D*, the depolarization parameter, as determined at Harwell and Harvard [1]. The extent of the disagreement is shown in Fig. 4, and it is apparent that at least one of the experiments contains systematic errors several times as large as the assigned errors, which are themselves largely statistical. Further consideration has shown that small corrections should be applied to the Harwell data and that results from a preliminary run should be excluded because of internal inconsistencies. On the average these changes raise the points by about the assigned errors.

However, though each experiment has been examined by the opposition, neither group was satisfied that the whole of the difference could be ascribed to an error in one experiment. Probably the most important difference between the two experiments was in the method of alignment of the counters. Owing to the very low asymmetries to be measured (less than 4%) a small spurious asymmetry, especially in the large angle region, would have a serious effect on the derived values of *D*.

Since the two *D* experiments were performed, measurements have been made at both laboratories [2, 3] to determine *R*, the rotation parameter, using a new technique in which the asymmetry is measured by reversing the proton spins with the use of a solenoid. Provided the focal spot of the beam does not move during the reversal of solenoid current which produces the spin reversal, many spurious asymmetries which bedevil a conventional experiment are eliminated. Using this new and very powerful technique it has been possible to get concordant results in the two laboratories; as shown in Fig. 1 of Wilson, in the next paper.

As Harwell made the first measurement of *D*, it was clearly our responsibility to make the third and this has been carried out by Taylor, using the solenoid technique. Fig. 5 shows a schematic diagram of the apparatus. Thirty counters were set up to form twelve three-counter telescopes, to analyze protons scattered in the horizontal plane at six angles from the liquid hydrogen target. The proton spins were either pointing upwards, with the solenoid off, or pointing downwards, having been rotated either through $\pm 180°$ by passing ± 910 amp through the solenoid.

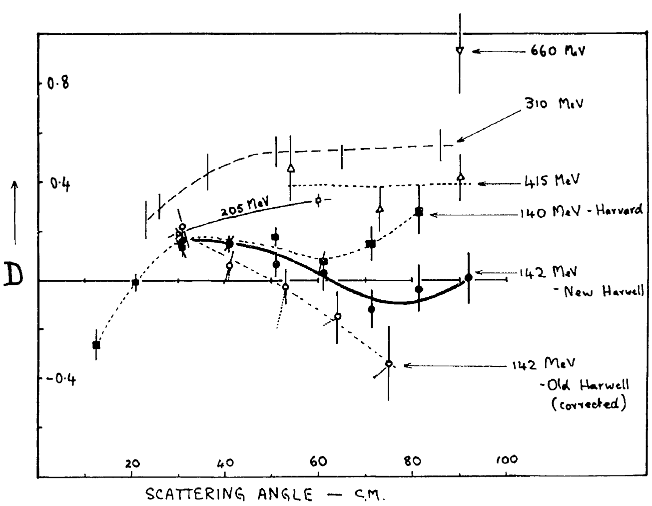

Fig. 4 Depolarization parameter in $p-p$ scattering, as measured at various energies by different groups.

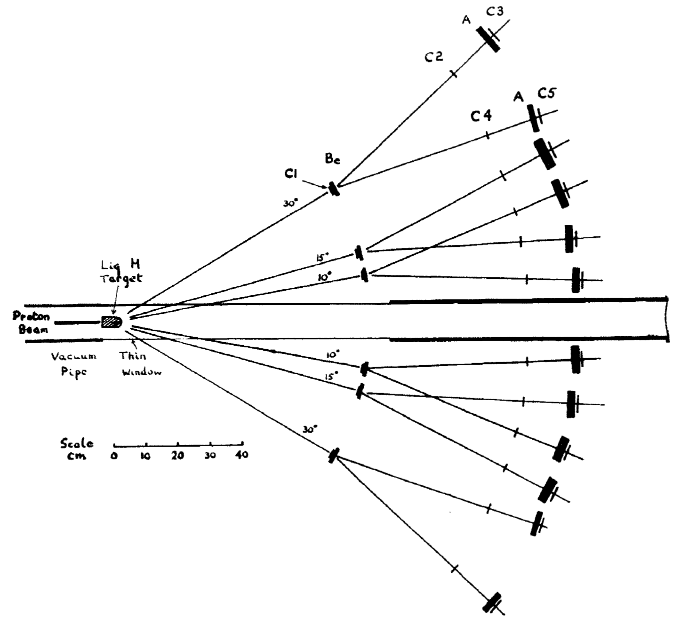

Fig. 5 Scale drawing of the new Harwell D apparatus.

The asymmetry was determined from the following set of relations:

$$\varepsilon_1 = \frac{\left(\frac{LLU}{LLD}\cdot\frac{RRD}{RRU}\right)^{\frac{1}{2}} - 1}{\left(\frac{LLU}{LLD}\cdot\frac{RRD}{RRU}\right)^{\frac{1}{2}} + 1}$$

$$\varepsilon_2 = \frac{\left(\frac{LRU}{LRD}\cdot\frac{RLD}{RLU}\right)^{\frac{1}{2}} - 1}{\left(\frac{LRU}{LRD}\cdot\frac{RLD}{RLU}\right) + 1}$$

$$\varepsilon_1' = \varepsilon_1(1+P_2P_3)\,, \quad \varepsilon_2' = \varepsilon_2(1-P_2P_3)$$

and

$$DP_1P_3 = \tfrac{1}{2}(\varepsilon_1'-\varepsilon_2')\,, \quad P_1P_2 = \tfrac{1}{2}(\varepsilon_1'+\varepsilon_2')$$

where for example LLU is the rate in the counter detecting protons which have been scattered twice to the left, when the beam polarization is upwards. P_1, P_2 and P_3 are the polarization of the incident beam, polarization in scattering from hydrogen and the analyzing power of the final scatterer respectively. In this method of formulation, the efficiencies of the counters cancel out because of the ratios taken, and one also derives a quantity $P_1 P_2$ which can be compared with known values.

The solenoid was adjusted in position so that the movement of the spot on energizing the solenoid was less than 0.05 cm, and the position of the spot with solenoid off was mid-way between the positions with it energized in the two opposite directions. Hence any spurious asymmetry due to spot movement would be simply reversed with the two opposite currents, though the polarization was the same. Therefore, any spurious asymmetries arising from spot movement could *(a)* be determined by comparing the asymmetry determined from 0 amp and +910 amp data with that from the 0 amp and −910 amp data and *(b)* be eliminated by taking the average value. This check showed that the spurious asymmetry from this cause was $\leqslant 0.003$.

Another check was to compare the asymmetry determined solely from the spin up data, with that from both sets of the spin down data.

i. e. $$\frac{LL-LR+RL-RR}{LL+LR+RL+RR}$$

and again the results were in agreement within the statistical errors.

A further check was to put an unpolarized beam through the apparatus and determine the solenoid asymmetry in the usual way. The results at 15°, 20° and 35° were $+0.006\pm0.013$, $+0.011\pm0.012$, and -0.005 ± 0.008 giving a mean value of $+0.0015\pm$ ±0.0060. These checks were a sufficiently convincing experimental demonstration that there was no systematic error larger than the statistical errors, though one believes that the systematic errors are indeed less than that.

The preliminary results are listed in Table I and shown in Fig. 4 together with the older Harwell results with the correction mentioned earlier, and the Harvard values. The new results coincide with the Harvard values at small angles but lie between the older sets of values at larger angles. An error of displacement of the beam with respect to the pivot of 0.02 cm would largely eliminate the discrepancy between the new and old Harwell values. (The new Harwell results supersede the older ones, and are not intended to be averaged with them).

The measured values at other energies were included on this slide because of a remark by Heer [4)] in a recent Physical Review Letter, to the effect that his recent determination of D at 205 MeV was easier to reconcile with the Harvard than the old Harwell value of D. I would only comment that there seems very little basis for this remark even with respect to the old data in view of the erratic energy dependence indicated at 60° c. of m.; and of course there is even less basis with respect to the new data.

Table I. D in $p-p$ scattering at 142 MeV—preliminary values

θ_{lab}	New values of D	Old values of D(*)	Harvard values
15°	0.164 ± 0.071	0.22 ± 0.080	0.137 ± 0.033
20°	0.151 ± 0.034	0.06 ± 0.060	0.156 ± 0.031
25°	0.068 ± 0.053	-0.025 ± 0.075	0.178 ± 0.033
30°	0.030 ± 0.070	-0.150 ± 0.11	0.076 ± 0.031
35°	-0.120 ± 0.080	-0.342 ± 0.15	0.147 ± 0.070
40°	-0.033 ± 0.10		0.286 ± 0.099
45°	0.001 ± 0.11		

(*) Corrected as indicated in the text.

III. PHASE SHIFT ANALYSIS OF p—p DATA (Perring)

Prior to the arrival of the new D data J. K. Perring had been making a phase shift analysis of the $p-p$ data at various energies, and in particular at 140 MeV. His conclusions were

(a) using the old Harwell D data there was only one solution giving a satisfactory χ^2 when all data *(P R D)* down to 9° c. of m. were included.

(b) using all the Harvard data, there was no satisfactory fit in the neighborhood of the Gammel-Thaler values.

These conclusions depend to some extent on what is meant by satisfactory. Perring has taken a purely statistical approach and rejected any solution below the 0.1% probability level.

The fit to the old data gave a value of the phase which was markedly different from the " Gammel-Thaler " values.

He then performed an analysis with the following combined data :

(a) the shape of the cross section curve (but not its absolute value) was taken as the mean of the Harvard and Harwell shapes above 30° c. of m. and the Harwell shape for smaller angles; all data >8½° c. of m. was included.

(b) the absolute values were taken from the Orsay value of 3.70 mb at 90° c. of m. quoted as having an accuracy of 1%.

(c) the polarization and values of R were taken from mean values of the Harwell and Harvard result, which are in good agreement.

(d) the new value of D.

Two analyses were carried out : in the first the absolute cross section was assumed to have only 4½% error, and in the second 1% error. A good fit was obtained in each case, with χ^2 of 36 and 51 respectively, for 33 degrees of freedom. There was very little difference between the solutions, which are given in Table II, the phase shifts being nuclear-bar phase shifts, in degrees.

The value of $^3P_0$ is now quite close to the Gammel-Thaler value and what is probably more significant, now lies satisfactorily between values obtained by analysis of data at 98 MeV and 210 MeV.

Table II. $p-p$ phase shift analysis at 142 MeV (J. K. Perring, provisional)

Data used : mean $d\sigma/d\Omega$, Orsay $(d\sigma/d\Omega)$ at 90°.
mean P, mean R, new Harwell D,

$\chi^2(1) = 36$, $\chi^2(2) = 51$ } for 33 degrees of freedom

	$^1S_0$	$^1D_0$	$^3P_0$	$^3P_1$	$^3P_2$	$\bar{\varepsilon}$	$^3F_2$	$^3F_3$	$^3F_4$
Solution 1	16.0	6.4	7.0	−18.2	14.2	−2.7	−1.0	0.2	0.5
Solution 2	14.4	6.4	5.7	−17.2	13.6	−2.3	−1.0	0.6	0.5
S.E.	0.6	0.1	0.7	0.3	0.2	0.1	0.1	0.3	0.1

The other point of interest is that the F_2 and F_3 phases are both significantly different from the pole values. This is in contrast to the results of his analysis at 98 MeV, where an adequate fit was obtained with pole values for the F waves.

Finally the small disagreement between Harwell and Harvard on the shape of the differential cross section was examined. The Harvard value at 147 MeV show a significant rise of about 0.15 mb in the region of 20-40° cm and the Harwell results at 142 MeV do not. The solution 1 above was used to calculate the cross section at 142 MeV. The cross section was then recalculated at 147 MeV with the phase shifts modified slightly to take account of the energy change. The results show that there should indeed be such a difference in shape, and a rise of 0.1 mb in the appropriate angular region solely due to the difference in energy.

There is, therefore, no reason to assume that one or the other of the measurements is wrong in this angular region.

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DISCUSSION

WILSON : I presume that if Perring has 33 degrees of freedom he must have made some selection in the data. Is that correct?

ROSE : Yes, that is correct. The storage capacity in the Mercury is such that one cannot use all the data that is available.

BREIT : Are these results the same as those in a recent preprint?

ROSE : No, these are some additional results. All the D Data were taken in July and August.

BREIT : I would like to say that the results on D are not very different from our fit that we refer to as YRB1, in spite of the fact that in these calculations there is considerable sensitivity especially to the P_0 phase shift, that is the difference between YRB1 and YLAM is largely due to the P_0 and in the searches this is influenced by effects of P_2 and F_2. So it really is quite a sensitive test of a particular feature from the point of view of fitting.

ROSE : This is born out by Perring's analysis in which his fit to the old data is really little different from the fit to the new data apart from the triplet P phase shift. The F waves were also changed appreciably. They are very small of course.