ficients in the temperature interval from 200 to 300° C, i.e., the vicinity of the phase transition point.

As can be seen from the figures the elasticity coefficients of an $NaNO_3$ crystal change in different manners at the phase transition point: the constant s_{33} exhibits a jump, while in the case of the coefficients s_{11}, s_{44}, and s_{12} only the derivatives with respect to the temperature show a true jump. As Dzialoshinskii and Lifshitz[7] showed, this fact is in agreement with the theory of one phase transition of the second kind.

°C	$(s \cdot 10^{11})$ cm²/dyne			
	s_{11}	s_{33}	s_{44}	s_{12}
20	0.32	0.42	1.18	—0.05
100	0.34	0.45	1.34	—0.04
150	0.36	0.47	1.45	-0.03_5
200	0.39	0.50	1.65	—0.02
230	0.41_5	0.54	1.86	0.00
250	0.44_5	0.57	2.07	$+0.01_5$
260	0.46_5	0.60	2.20	$+0.02_5$
270	0.50	0.64	2.48	+0.05
275.5	0.54_5	0.70	2.78	$+0.09_5$
280	0.55_5	0.65_5	2.82	+0.10
290	0.57	0.66_5	2.88	$+0.10_5$
300	0.59	0.68_5	2.95	+0.11

[1] L. D. Landau and E. M. Lifshitz, Статистическая физика (Statistical Physics) Moscow, 1951.

[2] F. C. Kracek, J. Amer.Chem.Soc. 53, 2609 (1931); Kracek, Posnjak, and Hendricks, J. Amer. Chem. Soc. 53, 3339 (1931).

[3] Handbook of Chemistry and Physics, 34 ed., 1952-1953.

[4] R. F. S. Hearmon, Revs. Mod. Phys. 18, 409 (1946).

[5] J. Stefan, Wiener Berichte 57, 697 (1868).

[6] M. I. Kornfel'd, J. Exptl. Theoret. Phys. (U.S.S.R.) 13, 116 (1943); M. I. Kornfel'd and E. M. Zhurkhovitskii, J. Tech. Phys. (U.S.S.R.) 25, 1998 (1955).

[7] I. E. Dzialoshinskii and E. M. Lifshitz, this issue, 233.

Translated by E. J. Rosen
5

SOVIET PHYSICS JETP VOLUME 6, NUMBER 1 JANUARY, 1958

POLARIZATION IN (p—p) SCATTERING AT 635 MEV

M. G. MESCHERIAKOV, S. B. NURUSHEV, and G. D. STOLETOV

Joint Institute for Nuclear Research

Submitted to JETP editor April 16, 1957

J. Exptl. Theoret. Phys. (U.S.S.R.) 33, 37-45 (July, 1957)

The angular distribution of polarization arising in (p—p) scattering was studied in the range $11.6 \leq \theta \leq 90.3°$ (cms) by means of single and paired telescopes of scintillation counters. A proton beam of 635 Mev energy and polarization of 0.58 ± 0.03 was employed. An analysis of the results of measurement of the differential cross-sections $\sigma_0(\theta)$ for elastic scattering of 657 Mev unpolarized protons, was performed on basis of the optical model of (p—p) scattering with the aim of establishing the nature of interference between the Coulomb and nuclear scattering amplitudes. The polarization data can be satisfactorily approximated by a function of the form (9). The presence of the term $\sin\theta \cos\theta \, P_4(\cos\theta)$ in this formula indicates that triplet F-states play an important role in the scattering. It is found that at 635 Mev the polarization in quasi-elastic (p—p)-scattering by beryllium comprises about 85% of the polarization of protons scattered by hydrogen.

I. INTRODUCTION

It is well known that the empirical facts examined by nuclear shell theory as well as the observations on the polarization of fast nucleons resulting from elastic scattering by nuclei are in general agreement with predictions based on the assumption that nuclear forces have a non-central character connected in some way with a spin-orbit interaction. The source of such interactions between nuclei, in the final analysis, must be a tensor force between pairs of nucleons. As a result of such forces, nucleon-nucleon interaction in the triplet state gives rise to a polarization of the secondary nucleons. This was first observed by Oxley et al.[1]

The use of high energy polarized nucleons in nucleon-nucleon scattering experiments gives information on the two-nucleon interaction in various spin states. The number of independent experiments needed to analyze uniquely the data from these experiments depends, in the last analysis, on the structure of the scattering matrix. According to Wolfenstein[2] the general form of this matrix in (p—p) scattering is:

$$M = BS + C(\sigma_1 + \sigma_2)\,\mathrm{n} + {}^1\!/_2 G\,[(\sigma_1\mathrm{k})(\sigma_2\mathrm{k}) + (\sigma_1\mathrm{p})(\sigma_2\mathrm{p})]\,T + {}^1\!/_2 H\,[(\sigma_1\mathrm{k})(\sigma_2\mathrm{k}) - (\sigma_1\mathrm{p})(\sigma_2\mathrm{p})]\,T + N(\sigma_1\mathrm{n})(\sigma_2\mathrm{n})\,T, \quad (1)$$

where σ_1 and σ_2 are the Pauli spin operators for the incoming and struck protons, S and T are the singlet and triplet projection operators, n, k, and p are unit vectors directed along $k_i \times k_f$, $k_f - k_i$ and $k_i + k_f$, respectively; here k_i and k_f are the initial and final momenta in the center of mass system (c.m.s.). Thus the scattering of protons by protons is described by five complex amplitudes, B, C, G, H, and N, which depend on the energy and on the angle of scattering θ. Of these, B, $C/\sin\theta$, and H are even functions and G and N are odd functions of $\cos\theta$.

Independent experiments on single, double, and triple scattering of protons are needed to establish the amplitudes of the scattering matrix [Eq. (1)].[2,3] The first step in this direction is the measurement of the differential cross-section of scattering for an unpolarized beam impinging on an unpolarized hydrogen target, $\sigma_0(\theta)$; the next step is a measurement of the polarization $P(\theta)$ in the scattering of an initially polarized beam by an unpolarized hydrogen target. Triple scattering in one plane and triple scattering under conditions where the planes of the successive scatterings are perpendicular to each other determine the magnitude of the parameters $D(\theta)$ and $R(\theta)$. These represent the changes in magnitude and direction of the polarization vector upon second scattering. $\sigma_0(\theta)$, $P(\theta)$, $D(\theta)$, and $R(\theta)$ can be expressed as functions of the amplitudes of the scattering matrix in the following way:

$$\sigma_0(\theta) = {}^1\!/_4|B|^2 + 2|C|^2 + {}^1\!/_4|G-N|^2 + {}^1\!/_2|N|^2 + {}^1\!/_2|H|^2, \quad (2)$$

$$\sigma_0(\theta)\cdot P(\theta) = 2\,\mathrm{Re}\,(C^*N), \quad (2a)$$

$$\sigma_0(\theta)\,[1 - D(\theta)] = {}^1\!/_4|G - N - B|^2 + |H|^2 \quad (2b)$$

which become in the non-relativistic approximation

$$\sigma_0(\theta)\,R(\theta) = {}^1\!/_2\,\mathrm{Re}\,[(G-N)^*(N+H) + B^*(N-H)]\cos\frac{\theta}{2} + \mathrm{Im}\,[C^*(G-N+B)]\sin\frac{\theta}{2}. \quad (2c)$$

Further experiments can be directed either toward the observation of triple scattering under conditions where a magnetic field is introduced between the first and second scattering perpendicular to the momentum of the singly scattered proton and the vector n, as was done by Segre's group,[3] or toward measurement of the components of the correlation tensor of polarization P_{ik}.[4–6]

In principle, the execution of five of the described experiments determines uniquely the scattering matrix at energies less than or close to the threshold of π-meson production.[6] However, at higher energies, where inelastic processes begin to play a significant role, the determination of the elements of the scattering matrix and the unique determination of the phases from experimental data becomes very difficult. The study of polarization effects in inelastic collisions can give significant additional evidence on the character of the (p—p) interaction.[7]

The work described below, a part of the program of studying elastic and inelastic (p—p) collisions on the six meter synchrocyclotron of the Joint Institute for Nuclear Research, was undertaken with the purpose of getting evidence on the angular distribution of the polarization in (p—p) scattering at 635 Mev. The results of measurements of the differential scattering cross-section of unpolarized protons by protons in the same energy region have been reported earlier.[8–10]

2. EXPERIMENTAL PROCEDURE

The object of the experiment was the measurement of the asymmetry of the scattering of a polarized proton beam by protons. This asymmetry is defined by the relationship $\epsilon = \frac{L-R}{L+R}$, where L and R are the normalized counts of protons scattered to the left and to the right (seen by an observer looking along the beam) at the same angle relative to the beam and in the plane of the original scattering producing the polarization. The technique of obtaining a polarized proton beam at the six meter synchrocyclotron and the determination of the energy of the protons in such beams has been described in our previous paper.[11] In this work we used the beam B (in the nomenclature indicated in Fig. 1 of Ref. 11) containing polarized protons with an energy of 635 ± 15 Mev. This beam had an intensity of about 10^5 protons/cm^2 sec at the position of the second scatterer. The beam intensity was monitored by an ionization chamber filled with argon using an integrating dc amplifier. The degree of polarization of the beam was 0.58 ± 0.03, as determined by experiments involving double scattering of the protons by beryllium.

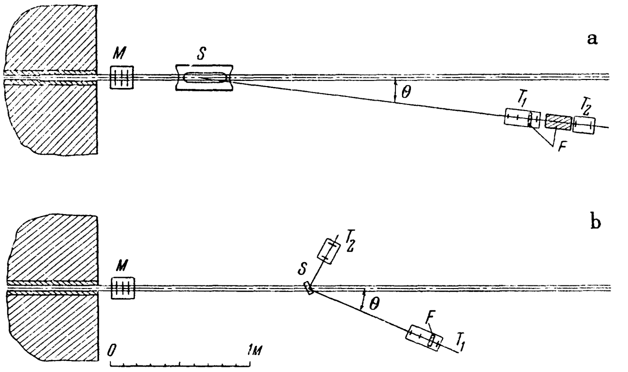

FIG. 1. Experimental setup. M — Monitor, S — Scatterer, T_1, T_2 — telescopes, F — copper absorber.

In the measurements of the asymmetry in the angular region 5° ≤ Θ ≤ 12° in the laboratory system, the scatterer consisted of a thin metallic container filled with liquid hydrogen and placed in vacuum. This is shown in Fig. 1a. The thickness of the hydrogen was 2.1 g/cm^2. The measurements were carried out with the chamber first filled with liquid hydrogen and then empty. The protons came through a 2 cm diameter opening in the shield. The scattered protons were detected by two telescopes T_1 and T_2 standing in back of each other, connected in coincidence, and consisting of scintillation counters which could be locked into the coincidence circuit separately in various combinations. This detector subtended a solid angle of 1.3×10^{-4} sterad for the scattered protons. Since in this angular region the range of the protons from elastic p—p scattering is greater than the range of the π-mesons from the reactions $p + p \to d + \pi^+$, the elastically scattered protons could be separated from the π-mesons by a 21 cm copper absorber placed between the counters. Taking into account the increased path in the copper due to multiple scattering the threshold for registering the protons was about 560 Mev. One of the deficiencies of this method of distinguishing scattered protons from π-mesons is the large loss in counting rate due to nuclear absorption and scattering of the protons in the absorber.

In the angular region 12° ≤ Θ ≤ 41°, the elastic p—p scattering was measured, as is shown in Fig. 1b, by using a pair of telescopes placed in positions corresponding to the kinematics of the elastic p—p scattering to the right and to the left of the beam. In this case a 3 cm diameter opening in the shield was used. The solid angles subtended by telescopes T_1 and T_2 were 1×10^{-3} and 4.3×10^{-2} sterad respectively. The yield of protons from the elastic p—p scattering was determined by the difference in counting rates of polyethylene and graphite scatterers. These contained the same number of carbon atoms per unit surface area. A control experiment, in which the counting rate was measured when the telescopes were placed in positions not corresponding to the kinematics of the elastic p—p scattering, showed that the contribution of inelastic p—p scatterings was less than 1% of the counting rate.

The same scintillation counters and electronics were used as in our previous work.[11] The number of accidental events was determined, for all angles at which ϵ was measured, by introducing delays for the signals from the counters; ordinarily these accidental events contributed not more than 1% to the counting rate. Before the start of each series of measurements it was established that the counters were operating on the plateaus of the photomultiplier voltages.

The position of the central trajectory of the beam was determined photographically and also by measuring the counting rates of telescopes placed at angles small enough to detect the protons that had suffered multiple scattering. The center of the beam was used to center the scintillators, the angle-measuring circle, and the zero point of the scale on this circle. Special attention was paid to balancing the apparatus in the measurements at small angles. Several checks showed that the shift in the zero point of the angle-measuring device relative to the central trajectory to the beam was less than 0.03°. The error in the asymmetry as influenced by the errors in the measurements of angles and inaccuracies in defining the center of the beam could amount to 5% at Θ = 5° but fell to 0.5% at Θ = 41°. The angular resolution, $\pm \Delta\theta$, was established from the corresponding geometrical factors, the beam size, and the multiple scattering of the protons in the scatterers.

The averaged final results of four series of measurements of the asymmetry, together with the standard measurement errors as well as data on the angular resolution, are presented in Table I. It should be mentioned that the main source of errors in these measurements was the statistical error of the measurements; the errors in the determination of the angles, the errors connected with the measurement of the beam intensity over the profile of the beam, and the errors arising from the shape of the scatterers and dimensions of the scintillators were relatively less important.

TABLE I. Values of the Asymmetry and Polarization in (p—p) Scattering at 635 Mev

$\Theta°$	$\theta°$	$\pm\Delta\theta°$	$\varepsilon \pm \Delta\varepsilon\%$	$P_H \pm \Delta P_H\ \%$	Nature of the Second Scatterer
5	11.6	1.1	-1.3 ± 5.6	-2.2 ± 9.5	H_2
7	16.2	1.2	11.4 ± 2.6	19.7 ± 4.6	»
9	20.8	1.4	16.0 ± 2.1	27.6 ± 3.9	»
12	27.6	1.6	22.3 ± 2.6	38.4 ± 4.9	»
12	27.6	1.6	23.3 ± 1.5	40.2 ± 3.3	CH_2-C
15	34.4	1.6	23.2 ± 1.3	40.0 ± 3.0	»
18	41.2	2.5	24.6 ± 1.1	42.4 ± 2.9	»
21	47.9	2.5	21.9 ± 1.1	37.8 ± 2.7	»
24	54.5	2.5	20.7 ± 0.8	35.7 ± 2.3	»
27	61.0	2.5	17.8 ± 0.8	30.7 ± 2.1	»
30	67.5	2.6	16.2 ± 1.3	27.9 ± 2.7	»
33	73.8	2.6	11.3 ± 1.5	19.5 ± 2.8	»
36	80.1	2.6	9.7 ± 1.4	16.7 ± 2.6	»
39	86.3	2.6	4.9 ± 2.3	8.4 ± 4.0	»
41	90.3	2.6	-0.9 ± 1.4	-1.6 ± 2.5	»

3. ANGULAR DISTRIBUTION OF THE POLARIZATION IN (p—p) SCATTERING

The polarization arising from the p—p scattering in our experiment was calculated from the relation $\epsilon = P P_H$, where P is the polarization of the beam being used, taken as equal to 0.58 ± 0.03. The values of P_H obtained are presented, together with the standard errors, in Table I and in Fig. 2 as a function of the scattering angle in the c.m.s.

The angular distribution of the polarization, P_H has the following features:

(a) The polarization goes through zero at a scattering angle of 90° as it should in view of the identity of the of the colliding particles;

(b) The maximum value of the polarization is 0.42 ± 0.03 at $\theta = 41°$;

(c) At smaller angles the polarization falls rapidly and reaches -0.02 ± 0.09 at $\theta = 11.6°$. In view of the possibility of systematic errors and the large errors associated with the measurements at small angles, one cannot vouch for the validity of this change in sign of the polarization.

Earlier studies of the angular distribution of the polarization in p—p scattering have been carried out in the energy regions 130 — 439 Mev.[12 — 17*] Figure 2 shows, for comparison, the results obtained at 170, 315, and 415 Mev. It is seen that increasing the energy from 415 to 635 Mev does not lead to any further increase in polarization outside of experimental errors.

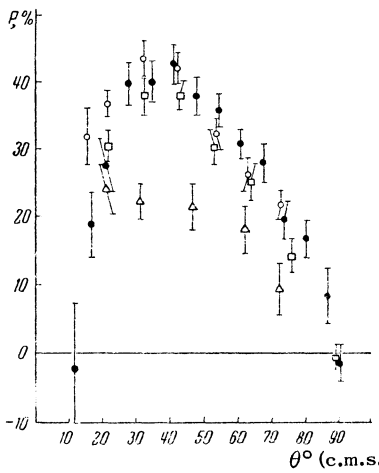

FIG. 2. Dependence of the polarization $P_H(\theta)$ in elastic p—p scattering on the angle of scattering: ● — present work, ○ — 415 Mev,[15] □ — 315 Mev,[12] △ — 170 Mev.[16]

The fact that the angular distribution of the polarization in p—p scattering does not change significantly as the energy is increased by 200 Mev appears to be a very significant point concerning the p—p interaction, especially if it is kept in mind that in the same energy interval the angular distribution of the p—p scattering changes from an isotropic one to a distribution concentrated at small angles.

4. ELASTIC SCATTERING OF UNPOLARIZED PROTONS BY PROTONS AT 657 MEV

The differential cross-section $\sigma_0(\theta)$ of the elastic p—p scattering consists of three terms

$$\sigma_0(\theta) = \sigma_N(\theta) + \sigma_C(\quad) + \sigma_{int}(\theta), \tag{3}$$

corresponding to the cross-section for nuclear scattering, for Coulomb scattering, and for interference between the two, respectively. In the same way one can write for $\sigma_0(\theta)$ P (θ):

$$\sigma_0(\theta)\,P(\theta) = \sigma_N P_N + \sigma_C P_C + (\sigma P)_{int}. \tag{4}$$

In order to examine the question of the angular dependence of $\sigma_0(\theta)$ $P(\theta)$, it is necessary to know the lower limit of the angular range in which only nuclear processes play an important role. In the present

*We are indebted to Prof. A. Roberts (Univ. of Rochester) for sending to our laboratory a manuscript in which are described results of experiments on polarization in p—p scattering at 130, 170, and 210 Mev.

study, use was made of data on the differential cross-section of scattering of unpolarized protons by protons obtained in our laboratory at 657 Mev. These data are presented in Table II and Fig. 3, together with their statistical errors. The total elastic p—p scattering cross-section at 657 Mev is $(24.7 \pm 1.0) \times 10^{-27}$ cm^2.[10]

In the case of isotropic nuclear (p—p) scattering in the c.m.s., evidence concerning the character of the interference of the amplitudes of the Coulomb and nuclear scattering is obtained from a comparison of observations at small angles of p—p scattering with the sum of the Coulomb and isotropic nuclear scattering. In this way it has been established that at 170 and 260 Mev,[18] and likewise at 330 Mev,[19] the interference between Coulomb and nuclear scattering has a destructive character. For protons having an energy of 330 Mev, Coulomb scattering produces effects at angles of scattering less than 20°.

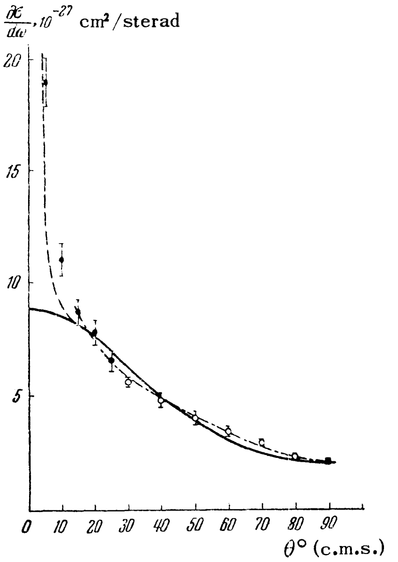

FIG. 3. Dependence of the cross-section for elastic p—p scattering at 657 Mev on the angle of scattering from the following sources: ● — Ref. 10, ○ — Ref. 8, ■ — average of results from (8) and (9); the solid curve corresponds to formula (5); the dashed curve gives the sum $\sigma_N(\theta) + \sigma_C(\theta)$; the dot-dashed curve has been drawn through the points visually.

In view of the strong anisotropy of the p—p scattering at 657 Mev, we had to extrapolate the measurements of $\sigma_N(\theta)$ to sufficiently small angles in the forward direction in order to evaluate the Coulomb effects. This extrapolation was made using the optical model of p—p scattering,[20 — 22] according to which:

$$\sigma_N(\theta) \sim |J_1(kR\sin\theta)/kR\sin\theta|^2, \tag{5}$$

where J_1 is the Bessel function of the first order, $R = (\sigma_t/2\pi)^{1/2}$, $k = (ME/2\hbar^2)^{1/2}$, and M and E are the mass of the proton and its energy in the laboratory system. At 657 Mev the total cross-section σ_t is about 41×10^{27} cm^2,[23] so that $kR = 2.28$. The determination of the proportionality constant in Eq. (5) was carried out by a least squares fit to the experimental data in the range $20 \le \theta \le 90°$. The solid curve of Fig. 3 shows the angular distribution given by Eq. (5). The extent to which the calculated curve represents the experimental data in the angular region considered is shown by the fact that the Gaussian mean square relative deviation of the calculated points from the experimental ones comes out to be ~ 0.05. The dashed curve in Fig. 3 gives the sum of the nuclear scattering, given by Eq. (5), and the cross-section for purely Coulomb scattering, $\sigma_C(\theta)$. The latter was calculated by Mott's formula:

$$\sigma_C(\theta) = \left(\frac{\eta}{2k}\right)^2\left[\sin^{-4}\frac{\theta}{2} + \cos^{-4}\frac{\theta}{2} - \sin^{-2}\frac{\theta}{2}\cos^{-2}\frac{\theta}{2}\cos\left(2\eta\ln\tan\frac{\theta}{2}\right)\right], \tag{6}$$

where, following Breit,[24]

$$\eta = \left(\frac{e^2}{\hbar c}\right)\left(1 + \frac{E}{Mc^2}\right)\left[\frac{E}{Mc^2}\left(2 + \frac{E}{Mc^2}\right)\right]^{-1/2}. \tag{7}$$

From Fig. 3 it is seen that the total cross-section obtained in this way $\sigma_N(\theta) + \sigma_C(\theta)$ is somewhat less than the corresponding experimental values, $\sigma_0(\theta)$, in the interval $5 \le \theta \le 15°$. This would mean, if the method used to determine the nuclear p—p scattering in the region of small angles is valid,* that the interference term in Eq. (3) is positive at 657 Mev. The accuracy of this procedure for determining $\sigma_{int}(\theta)$ is not large, and for this reasion it is impossible to exclude the possibility that $\sigma_{int}(\theta) = 0$. To the extent that the real part of the amplitude of the Coulomb scattering is repulsive and significantly greater than the imaginary part, then if $\sigma_{int}(\theta) > 0$, the real part of the amplitude of the nuclear scattering in the forward direction must also be repulsive. The imaginary part of the amplitude of the forward nuclear scattering must be positive and equal to $k\sigma_t/4\pi$.

5. ANGULAR DEPENDENCE OF $\sigma_0(\theta)P(\theta)$

From the analysis of the angular dependence of the asymmetric part of the p—p scattering cross-section, $\sigma_0(\theta)P(\theta)$, it is possible to get some evidence concerning the highest orbital angular momentum

*Recently Rarita[25] has brought forth arguments against the use of the optical model of p—p scattering at an energy of about one Bev.

contributing to the scattering. We start from the statement of Wolfenstein[26] that if the scattering is determined by interactions in states of angular momentum up to L_{max}, then

$$\sigma_0(\theta)P(\theta)=\sin\theta\cos\theta\sum_{n=0}^{N}a_{2n}\cos^{2n}\theta, \tag{8}$$

where $N = L_{max} - 1$ for odd L, and $N = L_{max} - 2$ for even L. In the calculation of $\sigma_0(\theta)P(\theta)$, the values of $\sigma_0(\theta)$ for angles for which the measurements of had been carried out were taken from a smooth curve drawn visually through the experimental points taking account the probable errors and the angular resoltuion (see Fig. 3). On the assumption that the angular distribution of polarization in p—p scattering does not change if the energy is raised from 635 to 657 Mev, the values of $\sigma_0(\theta)P(\theta)$ obtained in this work can be ascribed to an energy of 657 Mev.

TABLE II. Summary of Data on the Differential p—p Scattering Cross-Section at 657 Mev

Angle of Scattering (c.m.s.)	$\sigma_0(\theta)\times 10^{27}$ cm²/sterad	Literature Source
5°	18.9±1.1	[10]
10°	11.0±0.7	»
15°	8.67±0.53	»
20°	7.75±0.48	»
25°	6.56±0.40	»
30°	5.58±0.15	[8]
40°	4.78±0.26	»
50°	3.99±0.20	»
60°	3.41±0.13	»
70°	2.94±0.12	»
80°	2.20±0.05	»
90°	2.10±0.07	»
90°	2.05±0.07	[9]

Figure 4 shows the dependence of $\sigma_0(\theta)P(\theta)/\sin\theta\cos\theta$ on $\cos^2\theta$ in the interval $16.2° \leq \theta \leq 80.5°$. Shown also are the limits of error which have been calculated taking into account all the errors contributing to the measurements of $\sigma_0(\theta)$ and $P(\theta)$. The data show that the angular distribution of $\sigma_0(\theta)P(\theta)$ definitely differs from $\sin\theta\cos\theta$. This latter is the form expected if the polarization arose from the interference only of triplet P-states.

A least squares fit was made to the values of $\sigma_0(\theta)P(\theta)/\sin\theta\cos\theta$ using even Legendre polynomials. After several attempts with various numbers of polynomials it was found possible to approximate the experimental data by the function:

$$\sigma_0(\theta)P(\theta)=\sin\theta\cos\theta\{(3.20\pm 0{,}08)P_0(\cos\theta)+(3.13\pm 0.29)P_2(\cos\theta)$$
$$+(1.20\pm 0.32)P_4(\cos\theta)-(0.12\pm 0.37)P_6(\cos\theta)\}\cdot 10^{-27}\ \text{cm}^2/\text{sterad}. \tag{9}$$

This expression gives a sufficiently good fit to the experimental data as is evidenced by the magnitude of the value of the sum of the least squares

$$M=\sum_{i=1}^{11}\{\delta[\sigma_0(\theta)P(\theta)]_i/\Delta[\sigma_0(\theta)P(\theta)]_i\}^2$$

(where $\delta[\sigma_0(\theta)P(\theta)]$ is the difference, at an angle θ_i, of the calculated value of $\sigma_0(\theta)P(\theta)$ from the experimental value, and $\Delta[\sigma_0(\theta)P(\theta)]$, is the probable error in the determination of $\sigma_0(\theta)P(\theta)$ from the experimental data for this angle). The value of M is equal to 1.6; the expected value of M, equal to the difference between the number of experimental points and the number of independent parameters in the approximating function, should equal 7. The distribution calculated from Eq. (9) is shown in Fig. 4 as a solid curve.

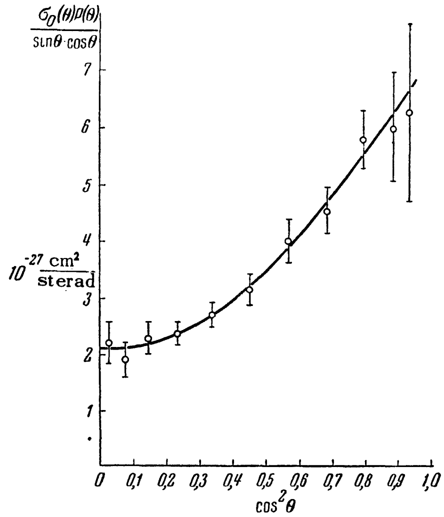

FIG. 4. Dependence of $\sigma_0(\theta)P(\theta)/\sin\theta\cos\theta$ on $\cos^2\theta$. The solid curve shows the function (9).

That the approximating function contains a term $\sin\theta\cos\theta P_4(\cos\theta)$, with a coefficient whose value is several times the probable error, appears to be definitely established. Thus the results of the present measurements indicate the presence of non-vanishing terms up to and including $\sin\theta\cos^5\theta$ in the expansion of $\sigma_0(\theta)P(\theta)$. This means that at the energies in question triplet P- and F-states play a significant role in p—p scattering. The calculations of Breit et al.,[27] carried out taking into account orbital momenta $L < 4$, indicate that a term of the form $\sin\theta\cos^5\theta$ can appear in the expansion of $\sigma_0(\theta)P(\theta)$ only if interactions occur in the $^3F_4$-state.

The fact that partial waves with angular momenta $L = 3$ contributed strongly to a scattering associated with a large polarization is, by itself, evidence that the p—p interaction in the triplet F-states is noncentral to a considerable extent.

6. CONCERNING POLARIZATION IN QUASI-ELASTIC p—p SCATTERING

It has been noted earlier[11] that the polarization of the protons undergoing quasi-elastic scattering from Be at an angle $\theta = 40°$ is only a little less than the polarization in free p—p scattering. The results of the present experiments indicate that a similar situation exists in a large angular region of scattering. A comparison of the data given in Table I and Fig. 7 of Ref. 11 indicates that, in the angular region $27 \leq \theta \leq 90°$, the polarization in the quasi-elastic scattering from beryllium is about 85% of the polarization of protons scattered in hydrogen. This is in contrast to the situation in the energy region of ~ 300 Mev, where, according to Donaldson and Bradner,[28] the quasi-elastic p—p scattering leads to a polarization lower by almost a factor of two than does elastic scattering.

These results indicate definitely that raising the energy from 300 to 600 Mev washes out, to a large extent, the difference between scattering by free protons and by protons bound in nuclei.

7. CONCLUSIONS

Experiments determining the asymmetry in the scattering of polarized protons by hydrogen at 635 Mev have established a polarization, which does not differ significantly in either amount or angular distribution from the polarization p—p scattering in the region 300 — 400 Mev.

If an analysis of the experimental data on p—p scattering at 657 Mev is carried out on the basis of the optical model, it is found that the interference between Coulomb and nuclear scattering is not large, the small amount leading to a raising of the differential p—p scattering cross-section in the regions $5 \leq \theta \leq 15°$.

The angular distribution of the asymmetric part of the p—p scattering cross-section contains the term $\sin\theta\cos^5\theta$ which means that triplet F-states contribute significantly to the scattering in the investigated energy region.

No significant difference in the angular distribution or in the amount of polarization is observed at 635 Mev between quasi-elastic p—p scattering in beryllium and elastic p—p scattering.

The authors express their thanks to R. M. Ryndin and L. M. Soroko for participating in discussions of the results of the present work; to A. S. Kuznetsov for help in the construction of the electronic apparatus; and to L. A. Kuliukin for carrying out a series of calculations.

[1] C. Oxley, W. Cartwright, J. Rouvina, Phys. Rev. **93**, 806 (1954).

[2] L. Wolfenstein, Phys. Rev. **96**, 1654 (1954).

[3] E. Segre, Physica **22**, 1079 (1956). J. Simmons, Phys. Rev. 104, 416 (1956).

[4] H. Stapp, Bull. Am. Phys. Soc. **29**, 8, 19 (1954).

[5] V. Vladimirskii and Ia. Smorodinskii, Dokl. Akad. Nauk SSSR **104**, 713 (1955).

[6] J. Smorodinskii, Proc. CERN Symposium, **2**, 148 (1956); Puzikov, Ryndin, and Smorodinskii, J. Exptl. Theoret. Phys. (U.S.S.R.) **32**, 592 (1957), Soviet Phys. JETP **5**, 489 (1957).

[7] R. Tripp, Phys. Rev. **102**, 862 (1956).

[8] N. Bogachev and I. Vzorov, Dokl. Akad. Nauk SSSR **99**, 931 (1954).

[9] Mescheriakov, Neganov, Soroko, and Vzorov, Dokl. Akad. Nauk SSSR **99**, 959 (1954).

[10] N. Bogachev, Dokl. Akad. Nauk SSSR **108**, 806 (1956), Soviet Phys. "Doklady" **1**, 361 (1956).

[11] Mescheriakov, Nurushev, and Stoletov, J. Exptl. Theoret. Phys. (U.S.S.R.) **31**, 361 (1956), Soviet Phys. JETP **4**, 337 (1957).

[12] Chamberlain, Segre, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **93**, 1430 (1954); Chamberlain, Donaldson, Segre, Tripp, Wiegand, and Ypsilantis, Phys. Rev. **95**, 850 (1954); Chamberlain, Pettengill, Segre, and Wiegand, Phys. Rev. **95**, 1348 (1954).

[13] Marshall, Marshall, and Carvalho, Phys. Rev. **93**, 1431 (1954).

[14] Carvalho, Heiberg, Marshall, and Marshall, Phys. Rev. **94**, 1796 (1954).

[15] Kane, Stallwood, Sutton, Fields, and Fox, Phys. Rev. **95**, 1694 (1954).

[16] D. Fischer and J. Baldwin, Phys. Rev. **100**, 1445 (1955).

[17] Baskir, Hafner, Roberts, and Tinlot. Polarization in proton-proton scattering at 130, 170 and 210 Mev, NYO-7818 (1956).

[18] O. Chamberlain and J. Garrison, Phys. Rev. **95**, 1349 (1954).

[19] D. Fischer and G. Goldhaber, Phys. Rev. **95**, 1350 (1954).

[20] Ia. Smorodinskii, Проблемы современной физики, (Problems of Contemporary Physics) **7**, No. 7 (1954).

[21] R. Serber and W. Rarita, Phys. Rev. **99**, 629 (1955).
[22] A. Batson, L. Riddiford, Proc. Roy. Soc. **A237**, 175 (1956).
[23] Dzhelepov, Moskalev, and Medved, Dokl. Akad. Nauk SSSR **104**, 380 (1955).
[24] G. Breit, Phys. Rev. **99**, 1581 (1955).
[25] W. Rarita, Phys. Rev. **104**, 221 (1956).
[26] L. Wolfenstein, Phys. Rev. **75**, 1664 (1949).
[27] Breit, Ehrman, Saperstein, and Hull, Phys. Rev. **96**, 807 (1954).
[28] R. Donaldson and H. Bradner, Phys. Rev. **99**, 892 (1955).

Translated by A Turkevich
6

SOVIET PHYSICS JETP VOLUME 6, NUMBER 1 JANUARY, 1958

COUPLING BETWEEN INTERMOLECULAR AND INTRAMOLECULAR VIBRATIONS IN A CRYSTAL

N. N. PORFIR'EVA

Leningrad Shipbuilding Institute

Submitted to JETP editor July 23, 1956

J. Exptl. Theoret. Phys. (U.S.S.R.) **33**, 47-52 (July, 1957)

A model of a molecular cyrstal with "semi-rigid" molecules is examined. The conditions for separation of intermolecular and intramolecular vibrations are investigated. By way of example a two-dimensional lattice with C_{4v} symmetry is examined.

BORN'S theory of crystal lattices gives the most general solution of the problem of propagation of elastic waves in a crystal. In the case of complex molecular crystals, however, direct application of the theory leads merely to several very general deductions; hence it is natural to seek approximate models that would make it possible to move forward in utilizing the Born theory of crystal lattices. One such model for molecular cyrstals consists of separating the molecules as a whole from the lattice; in the first approximation the molecules are considered as solids with six degrees of freedom.[1] Solution of the problem formulated in this way made it possible to investigate the propagation of orientational-translational waves in the crystal and to determine the conditions for separation of the translational and orientational oscillations. In the following approximation the molecules are regarded as "semi-rigid" systems, that is, systems for which the magnitude of the intramolecular interactions is much greater than that of the intermolecular ones. In this case the interaction between molecules can be treated as a perturbation.

The solution should result in free-molecule vibrations that are modulated by lattice vibrations. A problem of this kind has been examined by Davydov,[2] but was solved only in the general form and primarily from the standpoint of energy transfer from the intramolecular vibrations to the lattice vibrations, a transfer leading to attenuation of the vibrations and broadening of the absorption bands.

A more detailed solution of this problem permits an investigation of the interaction between intermolecular and intramolecular vibrations.

The present study is devoted to an examination of the coupling between intermolecular and intramolecular vibrations and the conditions for their separation. We solve only the classical problem through the application of group theory.

1. Let us examine a three-dimensional crystal containing N molecules of S atoms each. The unit cell contains ν molecules; n is the ordinal number of the cell and n_ν is the index of the molecule. The