JOINT INSTITUTE FOR NUCLEAR RESEARCH

Laboratory of Nuclear Problems

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Abstract:

The differential 580 MeV neutron-proton elastic scattering cross-sections for the angles 11°, 23° and 35° (centre - of - mass-system) have been measured. Sharp rise of the cross-sections with the decrease of a scattering angle has been found out. The obtained results point out the approximately equal probability of the "forward" and "backward" scattering.

In the present paper we proceeded with the investigations on neutron scattering with the mean energy 580 MeV by protons(1). These investigations were performed to find out the peculatities in the character of elastic (n - p) collisions at neutron energy considerably exceeding the energetic threshold of meson production. This paper is devoted to the measurement of the differential cross sections of small angle (n - p) scattering ($\vartheta \leq 35$ in the centre of mass system). A generally accepted method for measuring the differential elastic (n - p) scattering cross-sections by means of a recoil proton detecting is not convenient due to small energy of the recoil proton in the mentioned angle region. Because of it the described measurements were made applying the method which is different from that used in (1). However, the main conditions of the experiment (the energetic threshold, angular resolution and the solid angle of the detector) in the this experiment and paper (1) are identical*:

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* At the present time V.P. Dzhelepov et al are finishing the measurements of the differential cross sections of small angle (n-p) elastic scattering using the method of ring-shaped scatterer when at the best angular resolution the detector takes the considerably greater solid angle.

1. The set up of the experiment

The determination of the relative cross-sections of (n-p)-scattering has been made by measuring the number of neutrons emerging at the given angle from the hydrogen target placed into a neutron beam. The high energy neutrons have been obtained by charge exchage 680 MeV proton scattering on the berillium target which was placed inside the chamber of the synchrocyclotron at the Laboratory of Nuclear Problems. (The Joint Institute for Nuclear Research).

The~~n~~ neutron energetic spectrum has the maximum at 600 MeV and the half-width-130 MeV[2]. The mean neutron effective energy turns out to be equal to 580 MeV taking into account the neutron detector threshold (450 MeV). The neutron beam flux in the place of the disposition of a scatterer was $2 \cdot 10^4$ neutrons/sec cm^2.

The first experiments have been performed with the polyethylene and graphite scatterers. In the main experiments liquid hydrogen in the cylindrical glass dewar was used as a scatterer. The dewar was three litres in volume, 10 cm in diameter and 34 cm in height. It was placed into a duralaluminium protecting casing, the windows of which were sticked up by an aluminium foil 20 m thick in the place of the beam passage. Such a design of the target provided the performance of the experiment with the liquid hydrogen for seven hours. The effect of (n - p) elastic scattering was determined by the differences of the effects from polyethylene and carbon in the first case and by the differences of the effects from the dewar filled with liquid hydrogen and an empty one in the second case, respectively. The effect from the air filling the dewar after the evaporation of hydrogen was neglected in view of its smallness ($<$ 3%). The neutron detector used for scattered neutron detection consisted of five scintillation counters and a "converter" - the polyethylene cylinder

5,6 g/cm^2 thick and 6 cm in diameter which was placed between the first two counters (Fig. 1). Being incident on the "converter" the scattered neutrons underwent the charge exchange scattering. The recoil protons emerging from the "converter" were detected by four (2,3,4,5) last counters. The first counter served to exclude the charged particles flying from the target. It was connected in anticoincidence with the rest counters. In order to reduce loads in the ant coincidence circuit counter No 1 was originally connected in concidence with counter No 2 and only after it the pulses from the coincidence circuits were applied to anticoincidence circuit (Fig. 1). Fig. 1 the therphenyl solution $(C_6H_5)_2C_6H_4$ in phenylcyclogexan $C_6H_5CH(CH_2)_5$ with the concentration 3 g/liter, filling the plexiglas containers with the dimensions:

1) 12 cm x 12 cm x 1 cm; 2) 5 cm x 5 cm x 1 cm; 3) 5 cm x 5 cm x 1cm; 4) 12 cm x 12 cm x 1 cm; 5) 12 cm x 12 cm x 1 cm served as a scintillator. The energetic threshold of the neutron detector was set by a copper absorber placed between counters No 3. and No 4. When colculating the thickness of the absorbers for the scattering angles $\vartheta = 15^\circ, 10^\circ, 5^\circ$ (lab. system.) it was assumed on the basis of the results obtained from [2,3], that the mean energy loss at neutron "change-exchange" in light matter is about 15% of the initial energy and remains constant in the wide energy interval (170 MeV - 680 MeV). The estimations show that the mean effective energy of scattered neutrons for the angles 15°, 10°, 5° (lab. syst.). changes slightly (in our case - 40 MeV) that makes it possible to consider the efficiency of the neutron detector in the given region of angles to be constant. The angular resolution of the detector was 2°.

In order to determine the differential cross-section of elastic (n - p) scattering a scatterer was placed into the neutron bdam; the neutron detector was set relative to the axis of the beam at the given angle. The difference of the counting rates from the given scatterer with the "converter" placed between the first and second counters and without it was measured. The relative differential cross-sections were obtained according to the formula:

$$(N_{H_2}^{K} - N_{H_2}^{0}) - (N_g^{K} - N_g^{0}) = n\sigma_{np}(\phi) \qquad (1)$$

where $N_{H_2}^{K}, N_{H_2}^{0}, N_g^{K}, N_g^{0}$ - are the counting rates with a "converter" placed between the first and the second counters and without it from the dewar filled with hydrogen and an empty one, respectively; $\sigma_{np}(\phi)$ is the differential cross-section at the given angle ϕ (lab. system) n is the coefficient of the proportionality dependent on the detector's geometry and the intensity of the neutron beam (under the conditions of the experiment remains constant).

Thus, the measurement of neutrons scattered on a given angle made it possible to determine the differential (n - p) scattering cross-sections in relative units for the angles 5°, 10°, 15° (lab. system). The absolute values of the cross-sections have been found by the known |1| scattering cross-section at the angle 15°. The counting rate $N_{H_2}^{0}$ for the angles 15° and 10° was 50% of the counting rate $N_{H_2}^{K}$ and for the angle 5° it was 60%. The accidental coincidence background did not exceed 3%.

It is to be noted also that the small efficientcy of the neutron detector (1 - 2%) imposes strict conditions on the effeciency of anticoincidence circuits. Indeed, the change in the disposition of the "converter" in the measurements with and without it changes considerablγ (in our case approximately by 20 MeV) the detector threshold for the changed particles missed by anticoincidence channel and detected because of it.

The estimation made on the basis of the known neutron spectrum at the given thickness of the "converter" (5,6 g/cm^2 CH$_2$) shows that the relative increment of the number of the counted charged particles $\frac{\Delta N}{N}$ conditioned by the aforementioned change of the detector threshold is equal to: $\frac{\Delta N}{N} = 1/19(1-\varepsilon)$ where ε is the efficiency of the anticoincidence channel.

The efficiency of the anticoincidences was determined in the special experiments performed with an extracted proton beam at 660MeV. It turns out to be equal to (99,9 ± 0.1%). Thus, in our case $\frac{\Delta N}{N} = 0{,}005\%$ and the error in the determination of the number of detected nautrons due to the inefficiency of anticoincidence channel did not exceed 1%. It was neglected because of its smallness.

The Results of Measurements

The differential scattering cross sections measured for the angles 11°, 23° (centre of-mass-system) are equal to $\sigma_{np}(11^\circ) = (7{,}5 \pm 1) \cdot 10^{-27}$ cm^2/sterad and $\sigma_{np}(23^\circ) = (5 \pm 0{,}8) \cdot 10^{-27}$ sm^2/sterad. The mentioned errors are the standard statistical deviations. As well as in (1) the error of the total cross section of the elastic (n–p)-scattering (12%), to which the differential scattering cross-sections were normalized has not been included in those mentioned above.

The differential cross-sections of the neutron-proton $\sigma_p(\vartheta)$ elastic scattering at 580 MeV in the angular interval 11°–180° (centre of mass-system) are given in Fig. 2. The data obtained at 90 MeV(4) and 400 MeV(5) are also given here for comparison (Fig. 2).

The dependence $\sigma_{np}(\vartheta)$ in the small angle region ($\vartheta \leq 35^{o}$) obtained at 580 MeV points out the rapid increase of the differential cross-section with the scattering angle decrease. The comparison of the data presented in Fig. 2 shows that the character of scattering in this angle region changes considerably with the neutron energy increase from 400 MeV up to 580 MeV. The approximate constancy of the scattering cross-section at the angles $\vartheta < 35^{o}$ which was observed at 400 MeV is violated. And the symmetry in the forward (angles $\vartheta \sim 0^{o}$) and backward" scatterings (angles $\vartheta \sim 180^{o}$) which takes place at 90 MeV is restituted to a considerable extent. The ration of the scattering cross-sections for the angles 10° and 170° $\frac{\sigma_{np}(170^{o})}{\sigma_{np}(10^{o})}$ is equal to 1,2; 4 and 0,8 for the energies 90 MeV, 400 ~~and~~ MeV and 580 MeV, respectively. Thus, the ratio between the "usual" and "charge exchange" scattering approximates at 580 MeV, as appears, to the ratio existing at 90 MeV where the curve $\sigma_{np}(\vartheta)$ is symmetrical relative to the angle $\vartheta = 90^{o}$ (centre of - mass-system)) and both types of scattering five an approximately equal contribution to the total cross-section of the interaction. These changes in the character of the neutron-proton elastic scattering in the angle region $\vartheta \leq 35^{o}$ are due, apparently, to the rise of the probability of π -meson production processes in (n - p) collisions with nucleon energy increase from 400 up to 580 MeV |6|.

It is interesting to note that the use of the differential cross-sections for the angles close to 0° with the energy increase from 400 up to 580 MeV is predicted by the consequence of the optical theorem |7|.

$$\sigma_{np}(0) \geq \frac{k^{2}\sigma_{t}^{2}}{16\pi^{2}} \qquad (2)$$

Where $\sigma_{np}(0)$ is the differential elastic (n - p) scattering cross-section for 0° (centre of mass-system); K is the wave number of an incident neutron; σ_t of the total cross-section of the (n - p) interaction.

The minimum possible value $\sigma_{np}(0)$ at 580 MeV equals approximately $6\cdot10^{-27}$ cm^2 according to inequality (2) while the experimental value $\sigma_{np}(0)$ for 400 MeV does not exceed $4\cdot10^{-27}$ cm^2 (F9g.2) at reasonable extrapolation. Thus, at 300-400 MeV the differential elastic neutron-proton scattering cross section at the angle 0° (centre - of mass-system) passes through the minimum and with the rise of the colliding nucleon energy must increase.

Earlier in (1) using the least square method the dependence ~~was~~ $\sigma_{np}(\vartheta)$ was approximated by the series of spherical harmonics $P_L(\cos\vartheta)$ up to the polynomial at the degree $L = 12$.

The dependence $\sigma_{np}(\vartheta)$ for $\vartheta < 35^\circ$ obtained in the given paper changed considerable the character of the approximating expression, which in our case has the form

$$\sigma_{np}(\vartheta) = \bar{\lambda}^2\big[(1{,}38 \pm 0{,}07) - (0{,}7 \pm 0{,}08)\cdot P_1(\cos\vartheta) + (1{,}92 \pm 0{,}08)\cdot P_2(\cos\vartheta) -$$

$$-(0{,}12 \pm 0{,}09)\cdot P_3(\cos\vartheta) + (0{,}92 \pm 0{,}1)\cdot P_4(\cos\vartheta) - (0{,}03 \pm 0{,}1)\cdot P_5(\cos\vartheta) +$$

$$+(0{,}58 \pm 0{,}11)\cdot P_6(\cos\vartheta) - (0{,}15 \pm 0{,}12)\cdot P_7(\cos\vartheta) + (0{,}33 \pm 0{,}14)\cdot P_8(\cos\vartheta) -$$

$$-(0{,}23 \pm 0{,}15)\cdot P_9(\cos\vartheta) + (0{,}11 \pm 0{,}15)\cdot P_{10}(\cos\vartheta) - (0{,}04 \pm 0{,}15)\cdot P_{11}(\cos\vartheta) -$$

$$-(0{,}14 \pm 0{,}11)\cdot P_{12}(\cos\vartheta)\big]$$

where $\bar{\lambda}$ is the nucleon wave length in the centre of mass-system.

The found approximately equal probability of scattering at the angles $\vartheta \sim 0^\circ$ and 180° has led to the fact that in expression (3) the polynomials of add degrees $L > 1$ are present with small coefficients. The deflection from the symmetry relative to $\vartheta = 90^\circ$ is mainly characterized in the obtained expression by the term with $P(\cos\vartheta)$. The contribution of the scattering cross section from the interference of the wave corresponding to the scattering in the states of the (n - p) system with the total isotopic spion T = 0 and T = 1 in the angle region near V 0 and V = 180° is much less at 580 MeV than at 300 - 400 MeV where great assymetry in "forward"($\vartheta \sim 0^\circ$ and "backward" scattering (χ $\vartheta \sim 180^\circ$) is observed.

It is necessary to note, however, that the estimation whether expression (3) is a good appriximation or not does not give quite a satisfactory result. This estimation has been performed using the criterion[8].

$$\sum_i \frac{\left[\sigma_{np}(\vartheta_i) - \sum_L \alpha_L P_L(\cos\vartheta_i)\right]^2}{(\Delta\sigma_i)^2} = m - l, \qquad (4)$$

where $\sigma_{np}(\vartheta_i)$ is the measured differential cross-section in the point ϑ_i; $\sum_L \alpha_L P_L(\cos\vartheta_i)$ is the cross-section calculated from expression (3); $(\Delta\sigma_i)^2$ is the weight of the given measurement; $\Delta\sigma_i$ is the error in the measurement; m is the number of points where the cross-section is measured and 1 is the number of the coefficients in (3). It turns out that the sum of the squares of the calculating curve deflections from the cross sections measured experimentally in the left-hand side of expression (4) is equal to 7,7 whereas m - 1 = 4. The greatest deflections are observed in the angle region near 180° that, as appears, point out the necessity of increasing the number of terms in expansion (3). The magnitudes of errors, however, at the coefficients α_L in expression (3) show that at the existing experimental accuracy there is a lot of doubts that the increase of the number of the terms in expansion (3) is reasonable.

In conclusion it is necessary to note that the comparison of the obtained results with the data on the study of an elastic (p - p) scattering at similar energy (9) confirms the consequences of the isotopic invariance hypothesis.

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Fig. 1.

The scheme of the experiment.

n is the neutron beam;

M is the monitor

P is the scatterer (dewar with liquid hydrogen);

1,2,3,4,5 are the scintillation counters;

K is the converter;

Ф is the filter;

C is the coincidence circuit;

AC is the anticoincidence circuit.

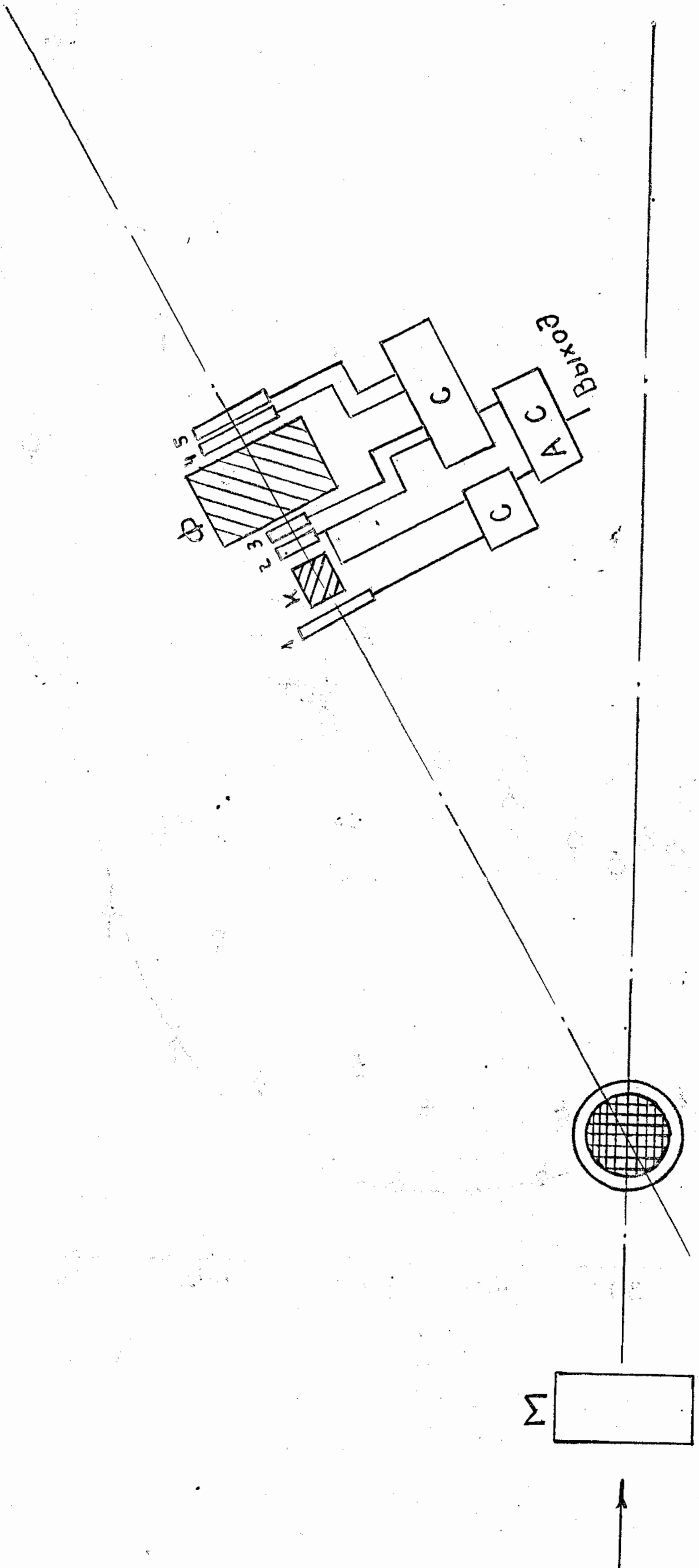
Fig. 2.

The differential elastic (n - p) scattering cross section.

Ф, Ф (5) $E_n = 91$ MeV Υ (4) $E_n = 400$ MeV

△ (1) $E_n = 580$ MeV ⍋ - the given paper

The solid curve is the plot of the approximating expression (3).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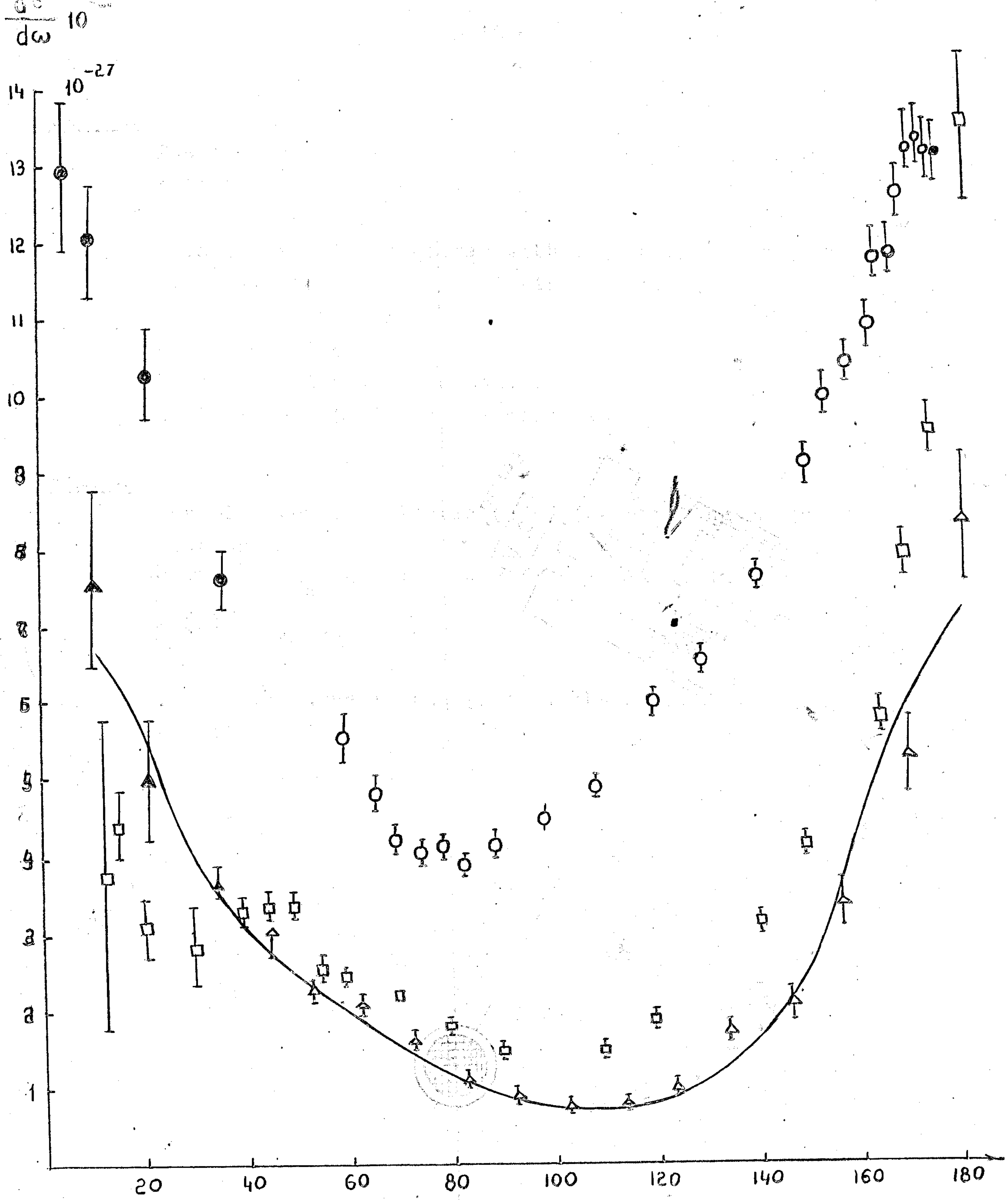
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