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The question of the existence of neutron-electron interaction ($n-e$ -interaction) caused by the inner space electromagnetic structure of the neutron was raised for the first time by Fermi /1,2/. If regions with non-zero charge density exist inside the neutron, then any charged particle getting "inside" the neutron is exposed to the action of electromagnetic forces. In neutron physics $n-e$ interaction is usually described by the constant equivalent potential V_0 related with the scattering amplitude a_{ne} by the expression:

$$a_{ne} = \frac{2}{3} \cdot \frac{MR^3}{\hbar^2} \cdot V_0 \,, \qquad (1)$$

where $R = \frac{e^2}{mc^2} = 2.8 \times 10^{-13}$ cm is the electron classical radius, M is the neutron mass. V_0 is of purely arbitrary character, since for this problem the electron classical radius does not play a fundamental role. V_0 is related with the neutron electric formfactor G_{EN} :

$$\left(\frac{\partial G_{EN}}{\partial q^2}\right)_{q^2=0} = \frac{V_0}{3e^2}\left(\frac{e^2}{mc^2}\right)^3 \,, \qquad (2)$$

where q^2 is the four-dimensional momentum transfer squared and also with the average weighted electric radius of the neutron $\langle r_e^2 \rangle^{1/2}$ and with its anomalous magnetic moment μ_0 :

$$V_0 = 3e\left(\frac{mc^2}{e^2}\right)^3 \left[\frac{e}{6}\langle r_e^2 \rangle + \frac{\hbar^2}{4M^2c^2}\mu_0\right] = V_{0\epsilon} + V_{0\mu}. \qquad (3)$$

Calculations show that $V_{0\mu} = -4080$ eV ($a_{ne} = -1.46 \times 10^{-16}$ cm). The question consists in the following: how much is the $\langle r_e^2 \rangle$ of the neutron? Though this question was raised more than 20 years ago, up to now there is no definite answer to it. Let us note that if the neutron had the same $\langle r_e^2 \rangle$ as that of the proton then $V_{0\epsilon}$ would have been:

$$V_{0\epsilon} \approx 16000 \text{ eV}.$$

Experiment gives nothing of the kind. Table 1 presents the results of the most precise measurements.

Table 1

Authors	Year	Method	V_0, eV	References
Hughes, Harvey Goldberg	1952 1953	Reflection from O_2-Bi mirror	-3860 ± 370	/3,4/
Melkonian, Rustad, Havens	1959	Bi total cross section	-4340 ± 140	/5/
Krohn, Ringo	1966	Scattering on Xe, Kr, Ar, Ne	-3720 ± 90	/6/
Koester et al.	1969	Reflection from Bi mirror, Bi total cross section	-4100 ± 100	/7/

As is seen from the table, the results of the measurements agree with each other with an accuracy of only $\approx 10\%$. Measurements with an accuracy of $\approx 3\%$ performed by different techniques give the results leading to the values of $\langle r_e^2 \rangle$ which differ even in sign.

2. Study of the Mixture Enriched in the ^{186}W Isotope

The main disadvantage of the majority of the methods used so far is a very small value ($<1\%$) of the effect observed in comparison with strong neutron-nucleus interaction. Therefore there always exists a danger that the final result is affected by some ignored nuclear effect. Thus, in case of the measurements with bismuth /5,7/ a change of the bismuth nuclear cross section between 0 and 10 eV only by 1/1000 causes the change of the measured amplitude of ($n-e$) interaction by 10%. In the measurements of the half percent effect with an accuracy of better than 3% on noble gases /6/ one should also be sure of the absence of the influence of any effects (for example, the influence of p-resonances, admixtures of light gases, etc.) which give false asymmetry.

In paper /8/ it was noted that due to the interference of the potential and resonance scattering ^{186}W must have an anomalously small nuclear scattering amplitude in the thermal neutron energy region and was suggested to use this isotope for the determination of a_{ne} by studying neutron diffraction on the mixture enriched with this isotope.

Since metallic tungsten is a paramagnetic, magnetic scattering should not contribute to the diffraction peaks.

Taking into account (ne) interaction, the coherent amplitude for the mixture enriched with the ^{186}W isotope is

$$b_{coh} = R - \frac{\alpha \Gamma_n}{2 k_0 E_0} \left(1 + \frac{E}{E_0}\right) + a_{ne} z f \left(\frac{\sin \theta}{\lambda}\right), \qquad (4)$$

where Γ_n is the neutron width of the first resonance of ^{186}W, E_0 is the energy of the first resonance, k_0 is the wave number, E is the energy of neutrons, a is the content of ^{186}W in the tungsten isotopic mixture, $f(\frac{\sin\theta}{\lambda})$ is the atomic structure factor, 2θ is the scattering angle.

The second term in formula (4) takes into account the contribution of the first resonance of ^{186}W ($E_0 = 18.84$ eV), R takes into account the potential scattering of ^{186}W, the contribution of impurities and also the negligible contribution of the other resonances.

The anomalously small value of the coherent scattering amplitude of the mixture containing 90.7% of ^{186}W was confirmed experimentally in paper /9/. When processing the results of these measurements, $n-e$ interaction, whose contribution to the total amplitude was $\approx 20\%$, was taken into account. The sign of the total amplitude turned out to be negative. The experiments with powdered tungsten (with natural and studied isotopic mixtures) staged separately permitted the value of the amplitude

$$b_{coh,1} = (-0.499 \pm 0.011)\,F \qquad (\lambda = 1.145\ \text{Å},\ Zf = 61.3) \qquad (5)$$

to be determined by comparison of the intensities of the diffraction peaks (110).

This result was confirmed by the precision measurements /10/ performed by the Christiansen-filter method. The total coherent scattering amplitude was determined from the condition that the refractive indices of a powder and a liquid are equal when small angle scattering of the neutrons passing through the filter is almost completely absent. For the mixture of tungsten isotopes containing 90.7% of ^{186}W x) the coherent neutron scattering amplitude with the average wavelength of about 15 Å turned out to be $(-0.466 \pm 0.006)\,F$ and changed to the conditions of (5) the value was

x) The mixture contained 90.7% of ^{186}W, 5.0% of ^{184}W; 1,9% of ^{183}W; 2.4% of ^{182}W (according to the passport of the USSR State Fund of isotopes).

$$b_{coh,F} = (-0.475 \pm 0.006)\,F. \qquad (6)$$

It should be noted that by changing the content of ^{186}W in the mixture one can vary b_{coh} (see formula (4)); at the corresponding concentration of ^{186}W b_{coh} may turn to zero. In Fig. 1 the dependence of b^2_{coh} on a is presented. The left branch of the curve corresponds to the values of $b_{coh} > 0$, the right one to $b_{coh} < 0$.

3. Measurement of (n – e) Scattering at a Stationary Reactor

To perform measurements from a tungsten single crystal containing 90.7% of ^{186}W, a sphere of 0.52 cm diameter was prepared. The measurements were carried out at a crystal monochromator of the stationary reactor emitting neutrons with the wavelength of 1.145 $\mathring{A}$. Preliminary results of these measurements were reported at the Summer School on Neutron Physics at Alushta (May 1969) /11/.

The integrated intensity of the Bragg reflection of monochromatic neutrons from a single crystal is:

$$N_{nk\ell} = K\{[a + Z f_{hk\ell}\, a_{hk\ell}]^2 + (1 - f_{hk\ell})^2 \gamma^2 \operatorname{ctg}^2\theta_{hk\ell}\}A_{hk\ell}\frac{\exp(-2W_{hk\ell})}{\sin 2\theta_{hk\ell}} \qquad (7)$$

where K is the coefficient constant for all measured reflections, a is the nuclear scattering amplitude, $A_{hk\ell}$ is the absorption factor, $\exp(-2W)$ is the Debye–Waller factor taking into account thermal oscillations of atoms in the lattice, $W = B(\frac{\sin\theta}{\lambda})^2$ where B = const for all measured reflections, $\theta_{hk\ell}$ is the Bragg angle, the term containing $\gamma^2 \operatorname{ctg}^2\theta_{hk\ell}$, where $\gamma = \frac{1}{2}\mu\,(\frac{\hbar}{MC})(\frac{ze^2}{\hbar c})$ takes into account the Schwinger scattering.

Using the $\theta - 2\theta$ method, the integrated intensities of eight reflections: (110), (200), (220), (310), (400), (330), (420), (510) were determined experimentally. The absorption factor $A_{hk\ell} = \frac{1}{v}\int \exp(-\mu t)\, dv$ where v is the sample volume, μ - is the attenuation coefficient taking into account absorption, incoherent and coherent scattering, t is the path of the neutron in the sample, was calculated on a computer; the results of the calculations coincided with the available data /12/. The values of the Debye-Waller factor were also found by calculations /13/ from the data on specific heat and the tungsten phonon spectrum. As a result, $B = 0.162$ Å^2 was obtained which corresponds to the Debye temperature $\theta_D = 343^\circ$ K.

The quantity

$$\left\{\frac{N_{hk\ell}\,\mathrm{Sin}^2\theta_{hk\ell}\,\exp(2W_{hk\ell})}{K\,A_{hk\ell}} - (1-f_{hk\ell})^2\gamma^2\,\mathrm{ctg}^2\theta_{hk\ell}\right\}^{1/2} = a + Zf_{hk\ell}\,a_{ne} \quad (8)$$

must be linearly dependent on Zf. Fig. 2 presents the values of this quantity averaged over all 12 series of measurements. K was determined using (5). The dashed line corresponds to the value $a_{ne} = -1.4 \times 10^{-16}$ cm. Attempts were made to find a cause of the deviation of the experimental points from the linear dependence on Zf:

a) Experiments on the determination of the divergence of the neutron beam reflected from a crystal and its variation from reflection to reflection were performed. The divergence of the beam turned out to be much smaller than the collimator divergence of the detector and the dependence on the Bragg angle was negligible.

b) In order to find out the influence of magnetic scattering, an attempt was made to discover ordered magnetic moments in tungsten atoms. Such experiments were performed earlier and they consisted in searches for the (100) reflection from powdered samples of natural tungsten /14/. From these measurements it

follows that $\mu_W < 0.3\ \mu_B$, where μ_B is the Bohr magneton. From the analogous measurements performed at room temperature with a single crystal of mixture enriched in tungsten-186 (90.7%), we obtained that

$$\mu_W \tilde{<} 0.004\ \mu_B$$

c) The influence of extinction is assessed. The accurate account of extinction is practically impossible and measurements with single crystals are reliable if extinction can be neglected. The condition for this is /15/:

$$\frac{1}{\eta} \cdot \frac{Q\, t_0}{\sin\theta} < 0.25\,, \qquad (9)$$

where η is the crystal mosaic spread, t_0 is the crystal thickness, $Q = \frac{\lambda^2 N^2 F^2}{\sin 2\theta}$ $F = \Sigma b_{coh} \exp\{2\pi i (\frac{xh}{a_0} + \frac{yk}{b_0} + \frac{z\ell}{c_0})\}\, e^{-W}$ is the structure factor. Because of the small scattering cross section of ^{186}W and the fact that $\eta \approx (30 \div 40)'$, condition (9) is by far fulfilled for the single crystal in use. ($Q < 3.10^{-5}$ 1/cm).

d) The influence of thermal diffuse neutron scattering (TDS) is assessed. In case of the cubic crystal, the total intensity from a single crystal can be written as /16/:

$$N = N_0 (1 + \alpha)\,, \qquad (10)$$

where N_0 is the true Bragg intensity and αN_0 is the contribution to the observed intensity from TDS. The magnitude of α is dependent on the Bragg angle θ, wavelength λ, temperature and elastic parameters of the crystal.

The calculation of α was performed by the approximate method /16/ on a computer. It turned out that for tungsten $\alpha < 0.015$.

Among other possible reasons for the deviation of the experimental points from the linear dependence, the following should be noted:

1. Systematic errors in the determination of the background of high (hkl) reflection are possible. If for the (110), (200) reflections the ratio of the signal to the background (peak amplitude) was 60 : 1; 30 : 1, then with an increase of (hkl) this ratio dropped and for (510) it was 1 : 1. The parameters of the available monochromator which were far from being optimal for the measurements in question (the glancing angle of the monochromator was only 11°) were one of the reasons. A systematic error of 10-15% in the measurement of the background is sufficient to account for the mentioned deviations.

2. The available data on the Debye temperature of tungsten are rather contradictory. Different measurements and calculations lead to $\theta_D = 290 \div 400^\circ K$ /17/. The deviations from the linear dependence almost disappear if when processing the experimental data one takes $\theta_D = 270^\circ K$ (the corresponding value $B = 0.26\ \text{Å}^2$).

3. When processing the experimental results, the calculated values of the atomic structure factor of tungsten Zf /18/ were used. The question remains to be seen whether any distortions in the distribution of the electrons of the atom entering the crystal lattice are possible and how this affects f . Apparently, such effects will be stronger at large (hkl) (large momentum transfers). Therefore experiments on the direct determination of f of tungsten are desirable.

4. It is possible that the experimental results are effected by some subtle effects due to the neutron magnetic scattering. Such possibilities are now under consideration.

4. Measurements on the IBR Fast Pulsed Reactor*)

Further studies were performed on the IBR reactor /JINR/. The time-of-flight method permitted several reflections corresponding to the wavelengths λ , $\frac{\lambda}{2}$, $\frac{\lambda}{3}$ and so on to be obtained at a time a fixed angle of the detector. The measurements were performed with the single crystal sphere used earlier (enrichment with ^{186}W of 90.7%) with the negative scattering amplitude $b_{coh,1}$(6) and also with the new one whose amplitude was $b_{coh,2}=c\,b_{coh,1}+(1-c)b_{nat}$ (11). c is the concentration of the substance of the first sphere in the new mixture and b_{nat} is the scattering amplitude of the natural mixture of tungsten isotopes; c was taken such that $b_{coh,2}>0$.

For both spheres, the intensities of five reflections: (110), (220), (330), (440), (550) were determined . The ratio of the intensities from the first sphere (N_1) and from the second one (N_2) for the (hkl) reflection is

$$\left(\frac{N_1}{N_2}\right)_{hk\ell} = C_1 \frac{b^2_{coh,1}}{b^2_{coh,2}} \cdot \frac{A_1}{A_2}, \qquad (12)$$

where C_1 is the constant which remains the same for all reflections, A_1 and A_2 are the absorption factors of the first and the second spheres determined from calculations. The constant C_1 , comprizing the ratio of the weights of the spheres can, in principle, also be calculated, however, taking into account possible deviations in the adjustment of the spheres and also possible variations in the reactor power, we did not do this and assumed that it is unknown.

The measurements with two spheres have obvious advantages over the measurements with one sphere. In particular, the Debye-

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*) The measurements were performed by A.M. Balagurov, L.M. Vasilenko, T.A. Machekhina, G.S. Samosvat and the author.

Waller factor does not enter expression (12) and the correction due to TDS which is difficult to take into account is also absent.

However, the use of the time-of-flight method leads to a number of disadvantages: one should take into account the dependence of the nuclear scattering amplitude on the wavelength, the absorption factors A_1 and A_2 differ very much from reflection to reflection, etc. Using (11) and (4) one can obtain

$$b_{coh,1} = R - \frac{\alpha \Gamma_n}{2 k_0 E_0}\left(1 + \frac{\lambda_0^2}{\lambda^2}\right) + Z f a_{ne} = a_1 + Z f a_{ne} \qquad (13)$$

$$b_{coh,2} = c(a_1 + Z f a_{ne}) + (1-c)\{b_{nat} + \frac{\beta \Gamma_n \lambda_0^2}{2 k_0 E_\sigma}\left(\frac{1}{\lambda'^2} - \frac{1}{\lambda^2}\right) - a_{ne} z (f' - f)\}. \qquad (14)$$

The second and the third terms in figure brackets of expression (14) take into account the dependence of the coherent scattering amplitude of the natural mixture of tungsten isotopes on the wavelength λ *). $b_{nat} = (4.77 \pm 0.05)$F /19/ was measured by the Christiansen-filter method at $\lambda' = 15$ Å and $(zf)' = 74$; β is the concentration of ^{186}W in the natural mixture of tungsten isotopes; $c = 0.86$.

The expression for R in terms of a_{ne} can be found using (6). Thus, in five equations of the type of (12) there are two unknown quantities: a_{ne} and C_1. The processing of the intensity ratio (12) by the least squares method gives $a_{ne} = (-1.32 \pm 0.11)\ 10^{-16}$ cm (15). (the corresponding value $V_0 = -3700 \pm 300$ eV). Fig. 3 shows the dependence of

$$\left(\frac{N_1}{N_2}\right)_{hk\ell} \cdot \left(\frac{A_2}{A_1}\right)_{hk\ell}$$

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*) The influence of the first resonance of ^{186}W and the part of the amplitude due to n–e scattering is taken into account. The influence of other known resonances can be neglected.

on zf . The solid curves are drawn for different values of a_{ne} . The error given in (15) is purely statistical. It does not include uncertainties in the values of Γ_n , b_{nat} and $b_{coh,1}$. The total influence of these uncertainties does not exceed 2-3% and at this stage of measurements can be ignored [xx]. To improve the statistical accuracy of the measurements, attempts were made to process the ratio of the intensities $(\frac{N_1}{N_{nat}})_{hk\ell}$ and $(\frac{N_2}{N_{nat}})_{hk\ell}$ where N_{nat} is the intensity of the (hkl) reflection from a single crystal plate of natural tungsten. With this aims, the intensities of the reflections from a single crystal plate of natural tungsten 0.1 mm thick were measured. However, these attempts were not a success because of the influence of extinction on the intensities of the reflections $(N_{nat})_{(110)}$ and $(N_{nat})_{(220)}$.

Fig. 4 presents the dependence of nuclear scattering amplitudes for the first and the second single crystal spheres of tungsten-186 on neutron energy E obtained by processing the measurements with a thin plate of natural tungsten. The solid lines are calculated. The experimental points corresponding to the (110) and (220) reflections do not lie on these lines because of the influence of extinction.

5. Some Perspectives of the Study of (n-e) Scattering Using a Single Crystal of Tungsten-186

The value of a_{ne} (15) was obtained with an accuracy of ~10% after 500 hours of measurements and it is hardly reasonable to continue them in order to reduce the statistical error. It is much more effective to perform measurements on a stationary reactor using a crystal monochromator which has more optimal

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[xx] Formula (13) takes into account the contribution only of the first resonance of ^{186}W . The influence of the other resonances (in particular, a negative energy resonance, if it exists) is practically reduced to the change of the value of Γ_n . As calculations show, a change of Γ_n by 7% causes a change of a_{ne} by 4%.

parameters than the monochromator used in our preliminary investigations (see § 2). In addition to higher intensity of the neutron flux, the constant value of the nuclear scattering amplitude for all (hkl) reflections and very weak (hkl) dependence on the absorption factor are the main advantages of this kind of measurements. As calculations show, the statistical accuracy of the order of 1% in a_{ne} can be achieved approximately during 500 hours of measurements on the reactor of 10 Mw power.

The use of polarized neutrons may also be very perspective. In this case, the intensity of Bragg reflections from a tungsten-186 single crystal is

$$N_{hk\ell} \sim (a_1 + z f a_{ne})^2 + (1-f)^2 \gamma^2 \operatorname{ctg}^2 \theta_{hk\ell} + \left(\frac{k \sigma_{tot}}{4\pi}\right)^2 + 2\gamma \operatorname{ctg}\theta_{hk\ell} \frac{k \sigma_{tot}}{4\pi} (\vec{P}\vec{n}),$$

where $\vec{P}$ is the neutron polarization vector, $\vec{n}$ is the single scattering vector. By measuring the ratio $R = \frac{N_+}{N_-}$, where N_+ and N_- correspond to the directions of the neutron spin "up" and "down", one can obtain the information on a_{ne}. As was shown by calculations performed for the tungsten-186 single crystal used in our measurements, R is of the order of 1.10 ÷ 1.12 for $\lambda \approx 0.5 \div 0.6$ Å, and the statistical accuracy of the order of 1% can be obtained with the available fluxes of polarized neutrons from nuclear reactors.

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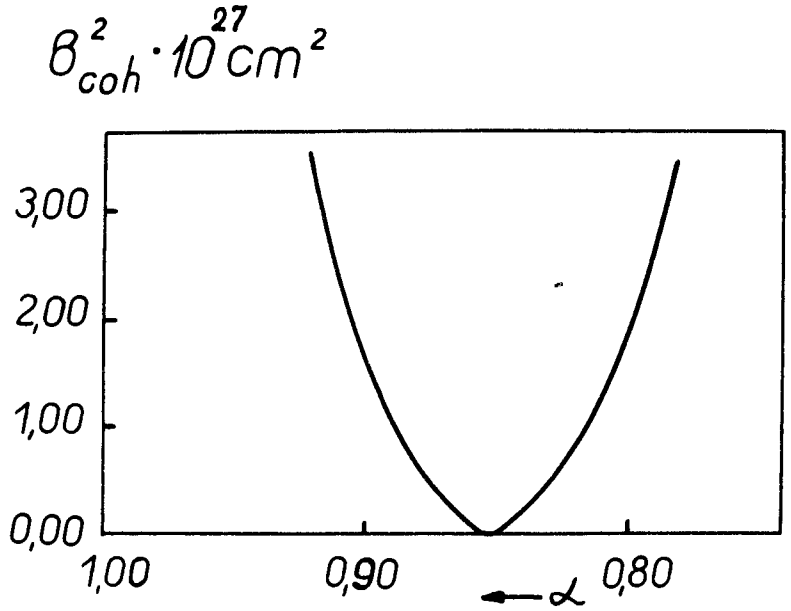

Fig. 1. The cross section of the coherent scattering of tungsten enriched with the ^{186}W isotope versus concentration α. The relation between concentrations of the other isotopes is close to the corresponding relation in the natural mixture.

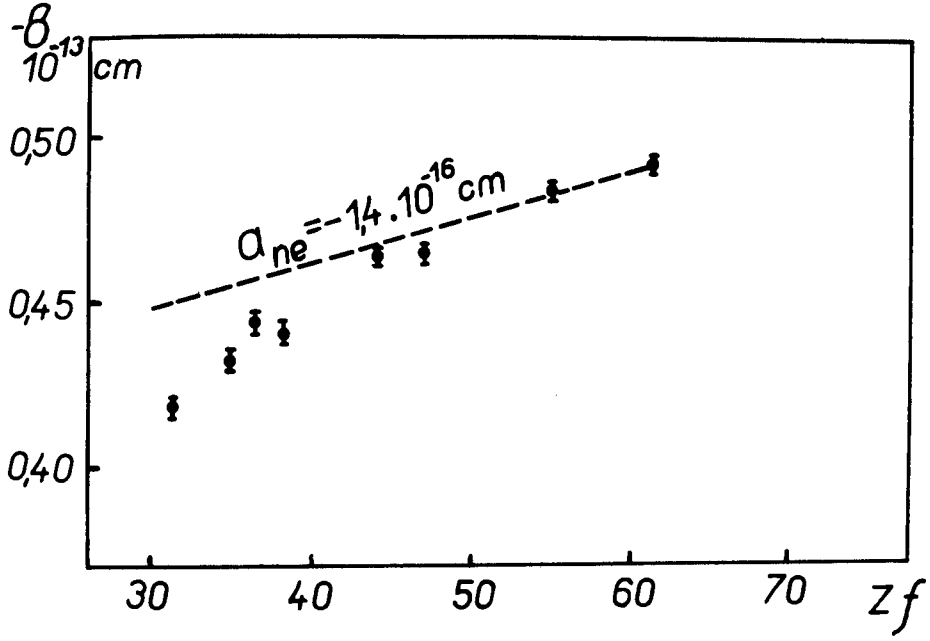

Fig. 2. The dependence of $b = a + z f a_{ne}$ on zf. The dashed line is calculated and corresponds to the value $a_{ne} = -1,4 \times 10^{-16}$ cm.

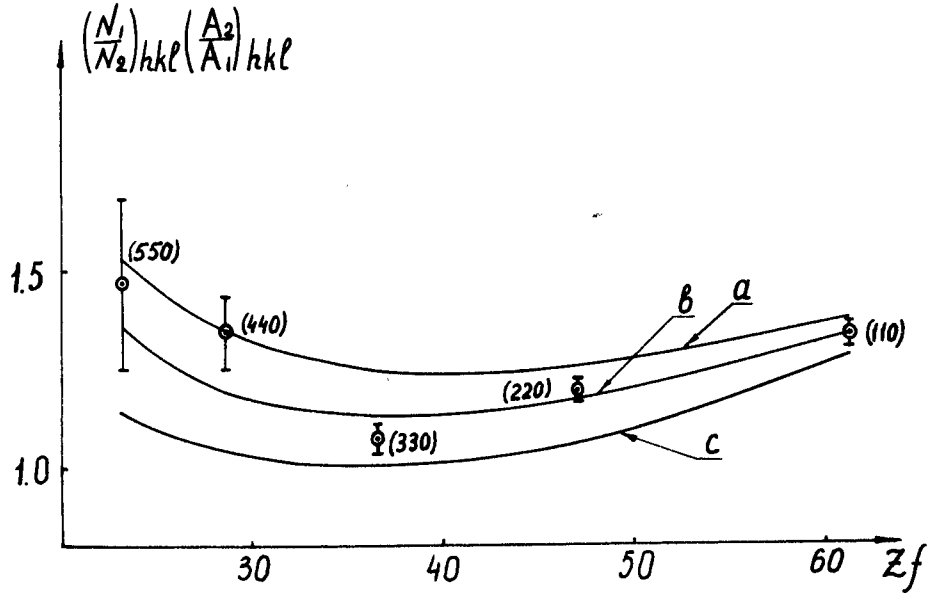

Fig. 3. The dependence of $(N_1/N_2)_{hk\ell}\cdot(\frac{A_2}{A_1})_{hk\ell}$ on zf. The solid curves are calculated for different values of a_{ne} at fixed C_1. a) $a_{ne} = -1.1 \times 10^{-16}$ cm; b) $a_{ne} = -1.32 \times 10^{-16}$ cm; c) $a_{ne} = -1.6 \times 10^{-16}$ cm.

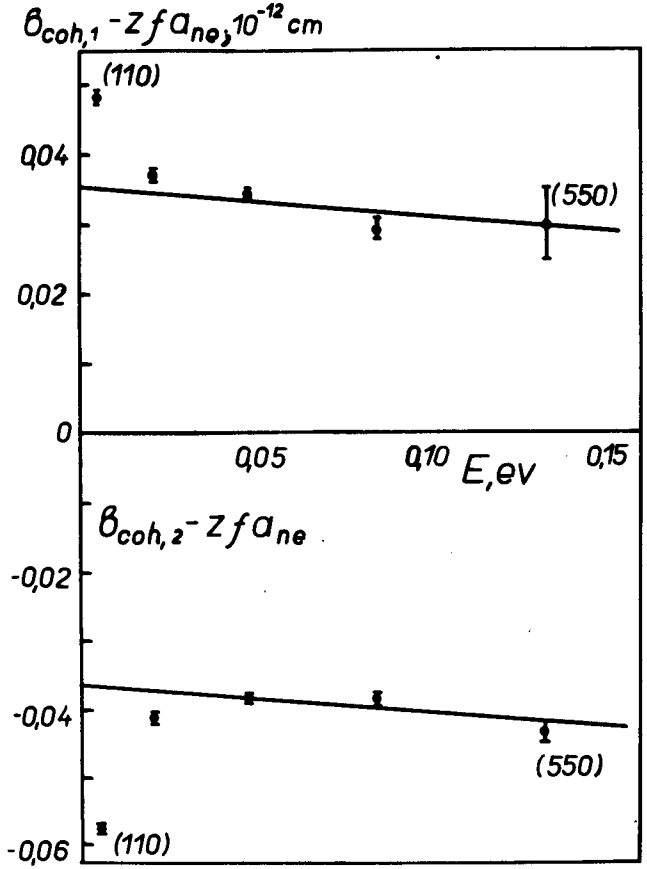

Fig. 4. The dependence of $b_{coh,1} - zf a_{ne}$ and $b_{coh,2} - zf a_{ne}$ on E. The straight lines are calculated by the formula $b_{coh} - zf a_{ne} = R - \frac{a l_n}{2k_0 E_0}(1 + E/E_0)$. The values of $b_{coh,1}(0)$ and $b_{coh,2}(0)$ are found by the extrapolation of the experimental data to the energy equal to zero.