Structure of the excitation spectrum of liquid ^{4}He

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Results of high-resolution measurements of the inelastic scattering of neutrons from normal and superfluid ^{4}He are presented. A complicated structure of peaks corresponding to phonon-maxon-roton excitations is observed. At $T < T_\lambda$, the scattering can be described by a narrow peak plus a wide component. The relative intensity of the narrow and wide components in the maxon-roton region follows the temperature dependence of density of the Bose condensate. Above T_λ, for the wave vectors $q > 0.65$ Å^{-1}, only the wide component exists. In the long-wave region ($q < 0.65$ Å^{-1}), a considerable transformation of peaks with changing temperature occurs as well, although the two-component structure persists in the normal phase.

I. INTRODUCTION

In 1941, Landau described the properties of superfluid ^{4}He in terms of quasiparticle elementary excitations.[1] A form of the dispersion law of these excitations was established in 1947 by Bogolubov in the theory of weakly nonideal Bose gas[2] and by Landau on the basis of analysis of the experimental data on thermodynamics of liquid ^{4}He.[3] Connection of the structure factor of liquid ^{4}He with the spectrum of elementary excitations was determined by Feynman,[4] and the same result was obtained by Pitaevskii on the basis of quantum-liquid hydrodynamics.[5]

In 1961, Henshaw and Woods[6] measured the dispersion curve for excitations in superfluid ^{4}He by the method of neutron inelastic scattering and found that it coincides with Landau's predictions. Since then, many experimental neutron studies of helium were aimed at correcting the position of the dispersion curve as a function of temperature and pressure and at determining the parameters of neutron-scattering peaks for different values of the wave vector q.[7–11] In Fig. 1, we show the dispersion curves of elementary excitations in superfluid ^{4}He (1) and the position of multiphonon scattering maximum (2).

At present, qualitative picture of the neutron scattering in liquid ^{4}He can be described as follows. Below the λ point, the peak of neutron scattering is sharp and well defined. At T_λ it is somewhat widening, especially in the maxon and roton ranges of the spectrum. In the normal phase the broad peaks of scattering are observed, whose dispersion curve is significantly shifted relative to the corresponding curve in the superfluid phase in the region of maxon and roton. In the phonon region, no drastic changes in the scattering occur when crossing the λ point.

The issue of fundamental physical reasons for the observed temperature dependence of the excitation spectrum in liquid ^{4}He and its transformations in transition from the superfluid to normal phase is still open for discussion. It is worth noting, that in other quantum liquids (He^3, H_2) the neutron scattering is similar to the normal phase of ^{4}He and weakly depends on temperature.[12,13]

Despite the similarity between the dispersion law of the excitation spectrum in ^{4}He measured by inelastic neutron scattering and the Landau energy spectrum, the connection of the observed dispersion curve with the energy spectrum of quasiparticles in liquid helium is quite a complicated problem. The problem may be formulated

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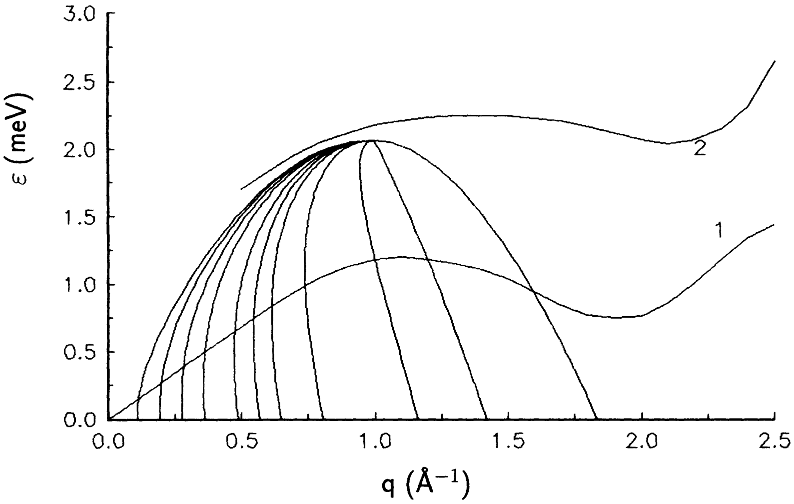

FIG. 1. The phonon-roton dispersion curve in superfluid helium-4 (1) and multiphonon excitations (2). The kinematics laws at various angles scattering at incident neutron energy $E_0=2.08$ meV are shown [see Eq. (4)].

as follows: if a certain many-body system can be described in terms of quasiparticle excitations, the dispersion law of these excitations is, as shown in Ref. 14, defined by poles of the one-particle Green function,

$$G^{-1}(q,\varepsilon(q))=0 \ . \quad (1)$$

In experiments on neutron inelastic scattering, the dynamic structure factor that represents a double Fourier transform of the correlation function of density fluctuations[14] is measured

$$S(r,t;r',t)=\langle n(r,t)n(r',t')\rangle-\langle n(r,t)\rangle\langle(r',t')\rangle \ . \quad (2)$$

In turn, the dynamic structure factor $S(q,\varepsilon)$ can be expressed in terms of the dynamic susceptibility $\chi(q,\varepsilon)$.[14] In general, the peaks of $S(q,\varepsilon)$ should not correspond to the poles of the one-particle Green function (1). In other words, elementary excitations defined by (1) are not connected immediately with density fluctuations and their spectrum cannot be directly determined from neutron experiments. Nevertheless, the spectrum parameters obtained in the neutron measurements in superfluid ^{4}He turned out to be in good agreement with the Landau spectrum. It means that inelastic neutron scattering allows us to restore the dispersion law of quasiparticles in He-II.

Progress in understanding this possibility was achieved due to the development of the microscopic theory of Bose liquids. The corresponding quantum-field methods have been developed by Belyaev,[15] Hogenholtz and Pines,[16] Gavoret and Nozieres,[17] Hohenberg and Martin,[18] Shepfaluzy and Kondor,[19] Griffin and Cheung.[20] Extending the Bogolubov result[2] for a weakly nonideal Bose gas, Govoret and Nozieres have shown that in superfluid helium at $T=0$, the elementary excitations (quasiparticles) defined by the Green function $G(q,\varepsilon)$ and collective sound excitations appearing in the dynamic structure factor $S(q,\varepsilon)$ at small q obey a common dispersion law of the form $\varepsilon(q)=cq$ where c is the velocity of the first sound. Also, an important result of the theory was the proof of the fact that in a superfluid liquid, in view of the presence of Bose condensate, the poles of the one-particle Green function $G(q,\varepsilon)$ and dynamic susceptibility $\chi(q,\varepsilon)$ [and consequently, the dynamic structure factor $S(q,\varepsilon)$] coincide.[19,20] This basic result supports the possibility of studying the quasiparticle spectrum of excitations of ^{4}He by the method of inelastic neutron scattering. The proof is based on the method of dielectric formalism extended for a superfluid liquid.[19,21,22] Owing to the phase transition that breaks the gauge symmetry and leads to a nonzero density of the Bose condensate n_0, the spectrum of quasiparticles appears as density fluctuations and becomes accessible to observe in neutron experiments.

Griffin, Glyde, and Stirling[23–26] have proposed a phenomenological model qualitatively describing the excitation spectrum in liquid ^{4}He. According to the model, the poles of the function $\chi(q,\varepsilon)$ in the normal phase do not coincide with the poles of the Green function, i.e., they are not connected directly with the spectrum of quasiparticles. The physical nature of energy excitations can be connected with collective modes of the type of first and zero sounds, scattering on thermally excited quasiparticles. In the superfluid phase and at a nonzero density of the Bose condensate n_0 there occurs hybridization of the collective oscillations of the density and elementary phonon excitations by means of interaction through the condensate. As a result, the function $\chi(q,\varepsilon)$, apart from poles typical for the normal phase, acquires new poles related to the Green function, and hence, to the spectrum of quasiparticles. The measure of the scattering component associated with quasiparticles is the quantity n_0. The part of the scattering related to excitations inherent to a normal liquid should also be somewhat modified in the helium superfluid state. Analyzing some recent experimental data on neutron studies of liquid ^{4}He, especially at high pressures,[24,27] Glyde and Griffin have interpreted them to be compatible with that concept.

A rather complicated spectrum of excitations in liquid helium predicted in the above papers requires a detailed experimental check in a wide range of wave vectors $q=(0-3.5)$ Å^{-1}. This problem is a part of our long-term plans. We could start realizing this program on a new spectrometer DIN-2PI at the IBR-2 reactor, JINR (Dubna). A part of the results obtained is reported in this paper. In Sec. II we describe the experimental setup and the technical means it provides. In Sec. III, main experimental results are reported. In Sec. IV, the experimental results are compared with the data accumulated by other authors. In Sec. V, we discuss our results in light of recently developed ideas on the nature of excitations in liquid ^{4}He and, in particular, within the Glyde-Griffin concept. Some part of the results of this work was published earlier in Ref. 28.

II. EXPERIMENTAL DETAILS

The experiments on neutron inelastic scattering in liquid ^{4}He were carried out on the DIN-2PI spectrometer (for a detailed description, see Ref. 29) at the IBR-2 reactor (Joint Institute for Nuclear Research, Dubna). For measurements we took a cryostat[30] allowing us to operate with a sample of liquid helium-4 with a 3.6-l volume in the temperature range from 4.2 to 0.4 K, the accuracy in maintaining the temperature being 0.01 K.

We will consider some methodical peculiarities of the measuring system. An important parameter of a spectrometer is the width of the energy resolution. In a time-of-flight method, it depends on the incident neutron energy E_0 and final energy E

$$\Delta E \approx \sqrt{aE_0^3 + bE^3} , \tag{3}$$

where a and b are constants. According to (3), to achieve better resolution, the energy of incident neutrons should be taken as low as possible. Preliminary experiments have shown that the level of intensity from the neutrons scattered from liquid ^{4}He allows us to operate with the initial neutron energy $E_0 \sim 2$ meV. As follows from the results of measurements at the lowest temperature $T \sim 0.4$ K and the initial energy of about 2 meV, the full width at a half maximum of the resolution function did not exceed 50 μeV in the maxon region and 100 μeV in the roton-phonon region. It should be noted that the resolution estimated for the measuring system by the Monte Carlo method turned out to be close to the experimental widths of peaks at $T \sim 0.4$ K.

The advantages of utilizing these low initial energies of neutrons are following. Just above the dispersion curve there exists the multiphonon continuum. The q dependence of a maximum of this part of the scattering is labeled with (2) in Fig. 1. This scattering is rather complicated in structure and is an interesting object of studies itself.[31,32] This problem is beyond the scope of the present paper. Low-energy tails of multiphonon scattering can influence the shape of the one-phonon or one-particle component scattering. This can significantly influence the excitations in the maxon region. As is seen from Fig. 1, the initial energy ~ 2 meV lies below the band of multiparticle excitations in He, and thus, processes of their production are weakened and their low-energy parts contribute little to the intensity of one-particle scattering of neutrons. This is clearly seen in Fig. 2 where two experimental spectra at 3.5 and 2.08 meV are shown. There is a significant decrease in the width of a one-particle peak and in the contribution of multiphonon scattering. The curves are normalized to the area of the one-particle peak.

Thus, the use of initial low-energy neutrons allowed us to increase the accuracy of measurements, to suppress multiparticle scattering, and to observe and analyze the details of neutron spectra $(1-5)\times 10^2$ times smaller than the intensity of the one-particle peak. In these experiments, peaks were observed associated with scattering of neutrons in superfluid helium corresponding to positive energy transfer.

As compared to the experimental equipment of other authors, we worked with rather large volume of liquid ^{4}He with the cross section of neutron beam being adequate. In principle, this could increase the influence of the multiple scattering and distort the genuine shape of a peak. To verify these effects, we have performed particular experiments with a cadmium inserted into the container splitting the whole volume into a set of thin layers (2 cm wide). Comparison of the results of experiments with and without that insert has not revealed noticeable discrepancies in the shape of scattering peaks. In experiments with very low initial energies, apart from the decrease in the total scattering cross section (at $E_0 = 2.08$ meV, $\sigma_{tot} \sim 0.2$ b and the transmission of the sample is of

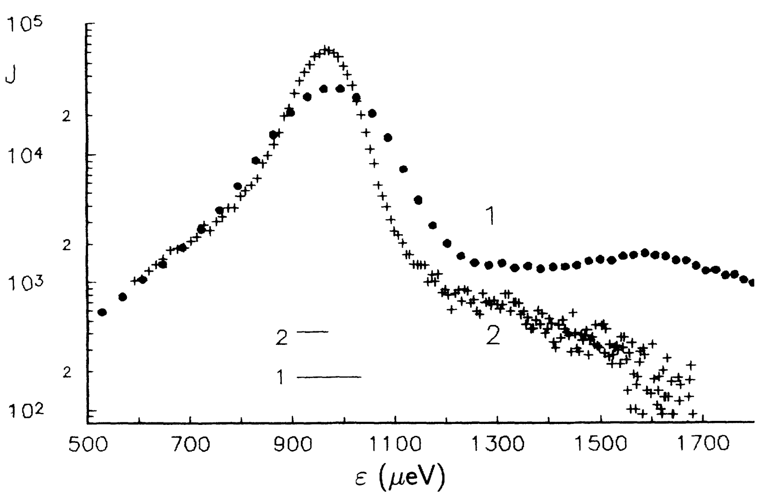

FIG. 2. Comparison of the experimental neutron-scattering spectra of liquid ^{4}He at $q \sim 1.6$ Å^{-1} for different initial energies. (1) $T = 1.5$ K and $E_0 = 3.5$ meV; (2) $T = 1.45$ K and $E_0 = 2.08$ meV. Instrumental resolution in the range of peaks are shown by the horizontal lines. Spectra are normalized to the single-particle peak areas.

the order of 0.94), the probability of the double scattering in He diminishes owing to further decrease in the total cross section and to the possibility of scattering only at certain angles. So, it might be assumed that the effects of multiple scattering in these experiments are insignificant.

The detector system of the spectrometer enabled measurements of the intensity of scattered neutrons in a wide range of scattering angles θ from 5 to 133.7°. For some angles θ, a bunch of kinetics laws is plotted in Fig. 1 for the initial energy of 2.08 meV. The experimental spectra were measured at θ=const, therefore, the kinematics relation between the wave-vector transfer q and energy ε was defined by

$$q=k_0-k\ ,\quad \varepsilon=E_0-E\ ,\quad q=0.695[2E_0-\varepsilon-2\cos\theta\sqrt{E_0(E_0-\varepsilon)}]^{1/2}\ , \tag{4}$$

where k_0 and k are, respectively, wave vectors of incident and scattered neutrons. Uncertainty in the q value, connected with finite sizes of the detector and sample, $\Delta q \sim 0.06$ Å^{-1} for small q and for large q it is somewhat smaller. A few measurements were carried out with $\Delta q \sim 0.02$ Å^{-1}.

It is seen from Fig. 1, that simultaneous study of quite a large part of the dispersion curve is possible in this experiment. Measurements at larger q require higher initial energies of neutrons. The spectra were normalized by the intensity of elastic scattering on vanadium. The background owing to a low energy of neutrons or to a large time of their flight in measurements performed far from the reactor pulse, produced a negligible influence on the results.

In this experiment, measurements were carried out at the initial neutron energies E_0=1.6, 2.08, 2.45, 3.5 meV and temperatures T=0.42, 0.45, 1.4, 1.45, 1.5, 1.72, 2.0, 2.05, 2.21, 2.25 K in the range of the wave vector transfers from 0.08 to 2.5 Å^{-1}.

III. MEASUREMENT RESULTS

A. Description of the shape of neutron inelastic peaks

The shape of experimental peaks of neutron scattering was analyzed on the energy scale; to this end, the intensity measured as a function of the scattering angle and time of flight of neutrons was transformed to the dynamic structure factor $S(q,\varepsilon)$:

$$S(q,\varepsilon)\propto(E_0^2/E^2)d^2J(\theta,t)/d\Omega\, dt\ , \tag{5}$$

where t is the width of a time channel and J is a count in the channel.

In analyzing the shape of peaks, we consider both temperature and wave vector dependencies in the *superfluid and normal* phases of liquid helium separately. Besides, we could distinguish *three* characteristic regions of the wave vector q for which peaks are also different in shape. These are the initial *phonon* part of the dispersion curve, when $q<0.4$ Å^{-1}, the *maxon-roton* region of excitations, where $q>0.65$ Å^{-1}, and the so-called *transition* region, where $0.4<q<0.65$ Å^{-1} (the region "*Y*").

As we concentrated on the description of the vicinity of peaks, our data can be fitted equally well by Gaussians or Lorentzians convolved with the Gaussian resolution function. We did not try to describe high-energy tails and therefore omitted a discussion of the sum rules or a finiteness of the first moment of $S(q,\varepsilon)$. The problem of sum rules and detailed balance will be considered in a subsequent paper.

To analyze experimental curves, the Upeak program[33] has been used, which is intended for decomposition of the experimental distributions into their components on the basis of the few-parameter approximation with the use of the real form of the models of lines.

The Lorentzian curve has been taken in the form

$$L_x(q,\varepsilon,T)=\frac{1}{2\pi}\frac{Z_z(q)W_x(q,T)}{[\varepsilon-\varepsilon_x(q,T)]^2+[W_x(q,T)/2]^2}\ ,$$

where x denotes (*os*), (*n*), and (*w*) components.

1. Superfluid phase

In the *maxon-roton* region, a one-particle *sharp* peak of neutron scattering is ill described by a single Gaussian (GG) or a single Lorentzian (LG). The notation (GG) or (LG) means that the corresponding function is convolved with the Gaussian resolution function of the spectrometer. A two-Gaussian model (GG+GG) and a two-Lorentzian model (LG+LG) provide a better description of the sharp peak (in terms of χ^2, the correlation coefficients of the model parameters, and other statistical criteria of the approximation). Two components of the scattering peak differ significantly in width (typical examples of the decomposition are drawn in Fig. 3), therefore, we will call one of them the narrow component (*n*); and the other, the wide component (*w*). To demonstrate uniqueness of the fit, we have added the result of the single Lorentzian fit in Fig. 3(b) to compare it with results coming from the two-Lorentzian description.

In the *phonon* region of the spectrum, the narrow and wide components are observed for neutron scattering, too. For the reasons to be understood from a subsequent consideration, the narrow component here may be different in nature from the component (*n*) and we will denote it by (*os*). The broad component (*w*) is well seen in this region only at about T_λ and at lower temperatures its intensity decreases, thus making its separation difficult.

In the *transition* region "*Y*," the picture of neutron scattering is the most complicated. Interpolating the description of peaks in terms of components (*n*), (*os*), and (*w*) into the *Y* region, one can expect that all three components exist simultaneously. However, low incident energy chosen for good resolution does not permit measurements of the intensity at the energy transfer greater than ~ 1.5 meV. Therefore, neither the peak position nor the width of the component (*w*) can be determined accurately. We can conclude only that, most likely, the component (*w*) gets strongly damped in this region. The component (*os*), which is well defined on the left side of the *Y* region, becomes hardly separable near the right boundary at $q \sim 0.65$ Å^{-1}. On the contrary, the component (*n*),

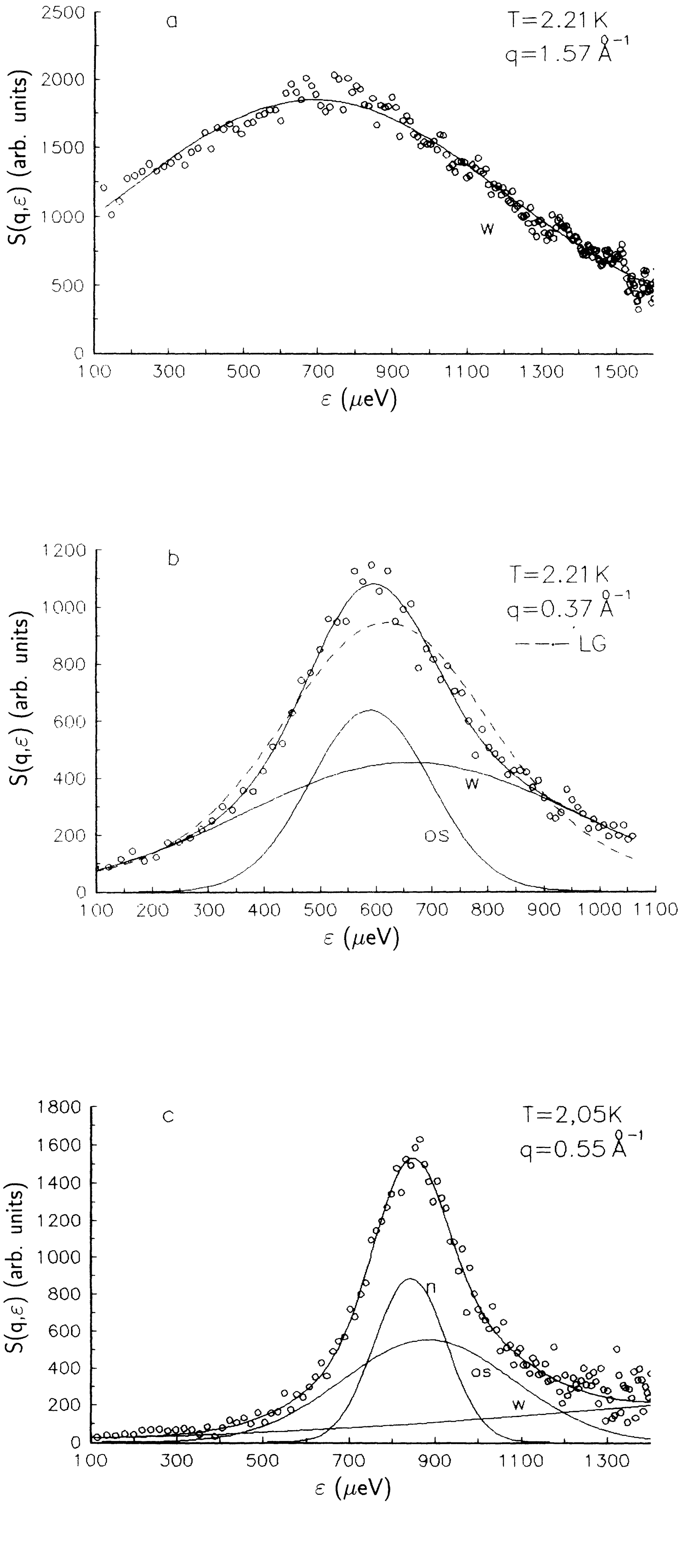

FIG. 3. $S(q,\varepsilon)$ and its decomposition components at various temperatures and wave vectors. For comparison, the single Lorentzian fit (LG) is shown in (b).

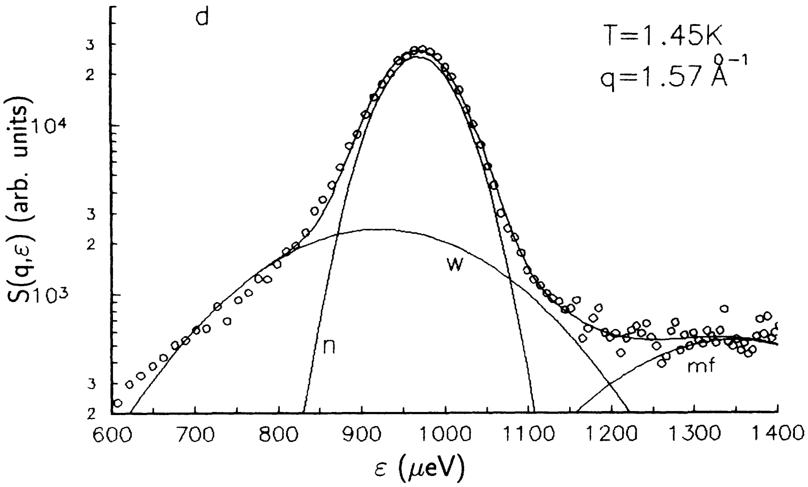

FIG. 3. (*Continued*).

with decreasing q approaches the component (*os*), and they become hardly distinguishable when $q < 0.48$ Å^{-1}.

2. *Normal phase*

Above T_λ in the *maxon-roton* part of the spectrum, only broad peaks of scattering (w) are observed, and they are well described by one GG or one LG. In the *phonon* region, besides the broad component (w) a narrow component (*os*) is seen. In the *transition* region "Y," the latter component becomes rapidly attenuating and above $q \sim 0.65$ Å^{-1} it is not observed at all. The broad component in the transition region is ill defined. The narrow component (n) typical of He-II is not observed above T_λ.

B. Dispersion curves

Describing the dispersion curves, we start with the *maxon-roton* part of the spectrum where $q > 0.65$ Å^{-1}. In the superfluid phase, the dispersion curves of the narrow and broad components are close to each other. Distinction between $\varepsilon_n(q)$ and $\varepsilon_w(q)$ is less than $\sim 10\%$. However, at all temperatures $T < T_\lambda$, the whole dependence $\varepsilon_w(q)$ tends to shift towards smaller values of q as compared with $\varepsilon_n(q)$. As a result, maxima and minima of the corresponding dispersion curves do not coincide and the curves are intersected near a maximum and, probably, near a minimum [see Figs. 4(a) and 4(b)]. The temperature dependences for both curves are rather weak (see Fig. 5). When crossing T_λ, the narrow component disappears, and the dispersion curve for $\varepsilon_w(q)$ does not change substantially [see Figs. 4(c) and 5].

In the *phonon* part of the spectrum and in transition region and the dispersion laws for the components (n) and (*os*) do not differ [Figs. 4(a) and 4(b)]. The dispersion curve for the broad component $\varepsilon_w(q)$ is defined here less accurately but, apparently, lies above $\varepsilon_{os}(q)$. The temperature dependences of $\varepsilon_{os}(q)$ and $\varepsilon_w(q)$ in this part of the spectrum are also weak and do not feel the transition to the normal phase (see Fig. 5). Further details about the shape of the dispersion curve for components (*os*) can be found in Sec. IV C.

C. Integral intensities

In the *superfluid* phase, the dependences of integral intensities on the wave vector for narrow and broad components $Z_n(q)$ and $Z_w(q)$ in the *maxon-roton* region are similar in nature. These dependences are illustrated in Figs. 6(a) and 6(b) at $T=1.45$ and 2.05 K. The analysis shows that the ratio of intensities $\eta(q)=Z_n(q)/[Z_n(q)+Z_w(q)]$ at any temperature has no q dependence (see Fig. 7). However, this ratio strongly depends on the temperature. Figure 8 shows the dependences $Z_n(T)$ and $Z_w(T)$ for $q \sim 1.6$ Å^{-1}. It is seen that the narrow component of scattering dominates at low temperatures and disappears when approaching T_λ. On the contrary, the intensity of the broad component sharply decreases with decreasing T. In the *normal* phase of liquid ^{4}He, only broad scattering peaks (w) remain for which the $Z_w(q)$ dependences [Fig. 6(c)] are similar in nature to the dependence of the broad component in the superfluid phase.

Now let us consider the *phonon* part of the dispersion curve for $q < 0.65$ Å^{-1}. In contrast to $Z_n(T)$ (Fig. 8), the temperature dependences $Z_{os}(T)$ for different q (see Fig. 9) at $T > T_\lambda$ do not vanish. Therefore, it may be assumed that in the superfluid phase the narrow component (*os*) in the phonon part consists of two components close in position and width: a narrow scattering peak (*os*), whose intensity weakly depends on the temperature and a narrow peak (n), whose intensity changes with temperature in the phonon region in the same way as in the maxon-roton region.

Within this assumption, we could attempt to estimate the intensities of these two components in the superfluid phase using the following procedure: for every q at temperatures below the λ point, the corresponding values of $Z_{os}(q)$ at $T=2.21$ K were subtracted from the total intensity $Z_{os}(T)$. The obtained values can be considered as true values of $Z_n(q)$. Figures 6(a) and 6(b) (inset) show the dependences $Z_{os}(q, T=2.21$ K$)$ and $Z_n(q)$ in the phonon part of the spectrum. If we use these values of $Z_n(q)$ for evaluating η at small q (see Fig. 7), we obtain a natural continuation of the horizontal straight line.

It is useful to compare our results for $Z(q)$ with the

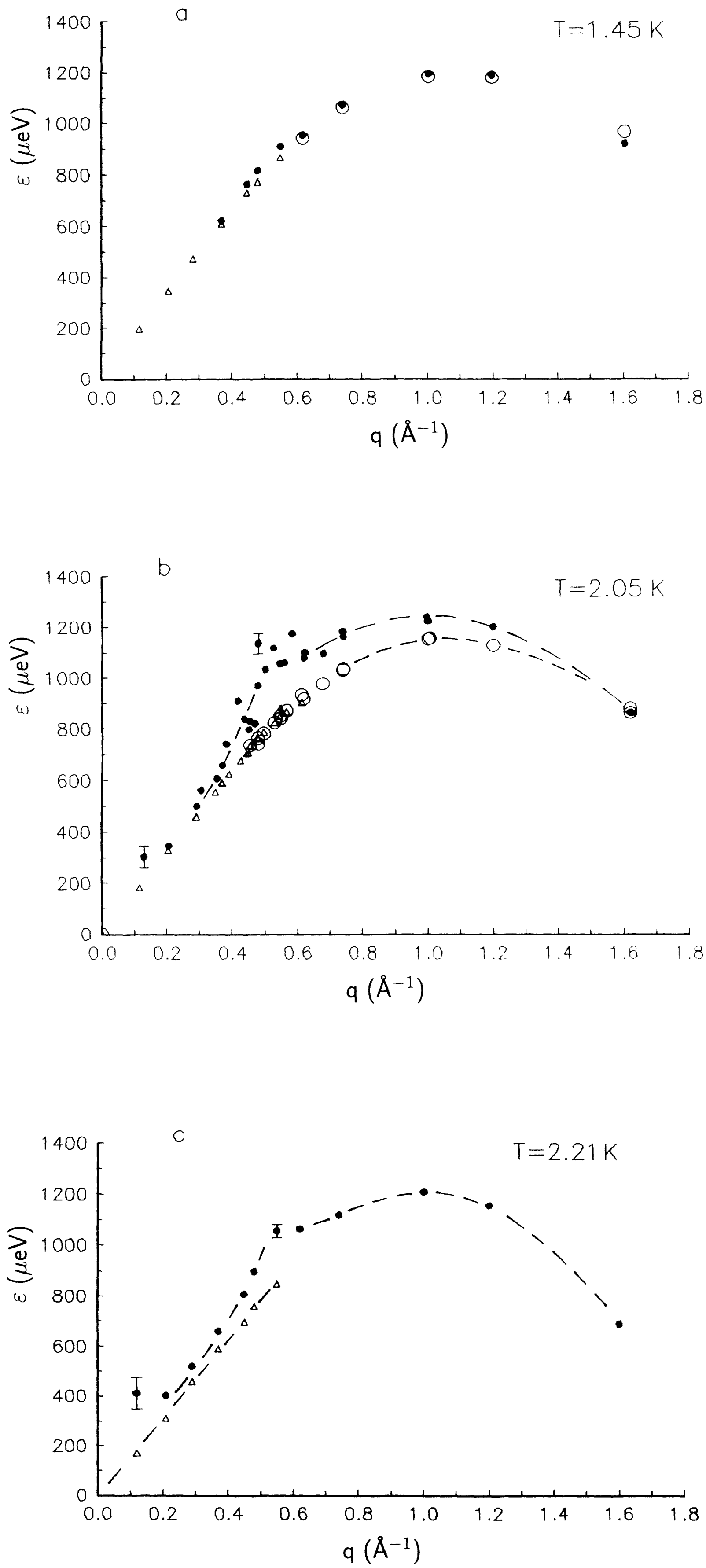

FIG. 4. Dispersion curves at (a) $T=1.45$ K; (b) $T=2.05$ K ; (c) $T=2.21$ K for the components: (n) open circles, (w) closed circles, and (os) triangles.

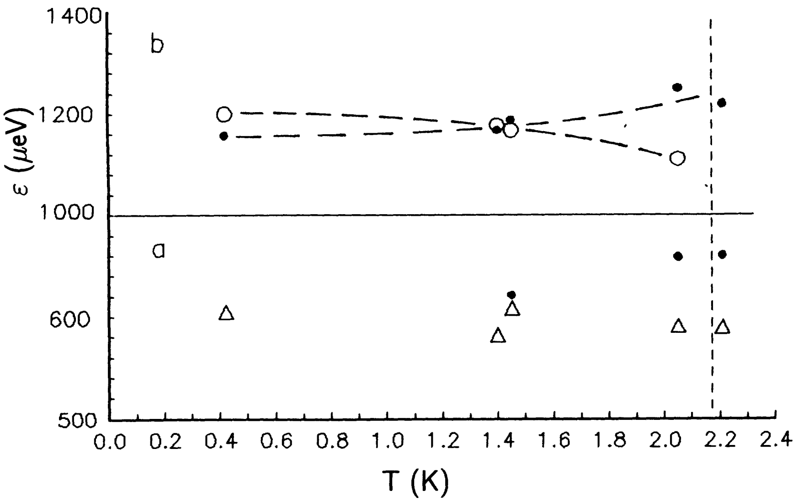

FIG. 5. Temperature dependence of the excitations energy: (a) $q = 0.37$ Å^{-1}; (b) $q \sim 1$ Å^{-1}; (n) open circles, (w) closed circles, and (os) triangles.

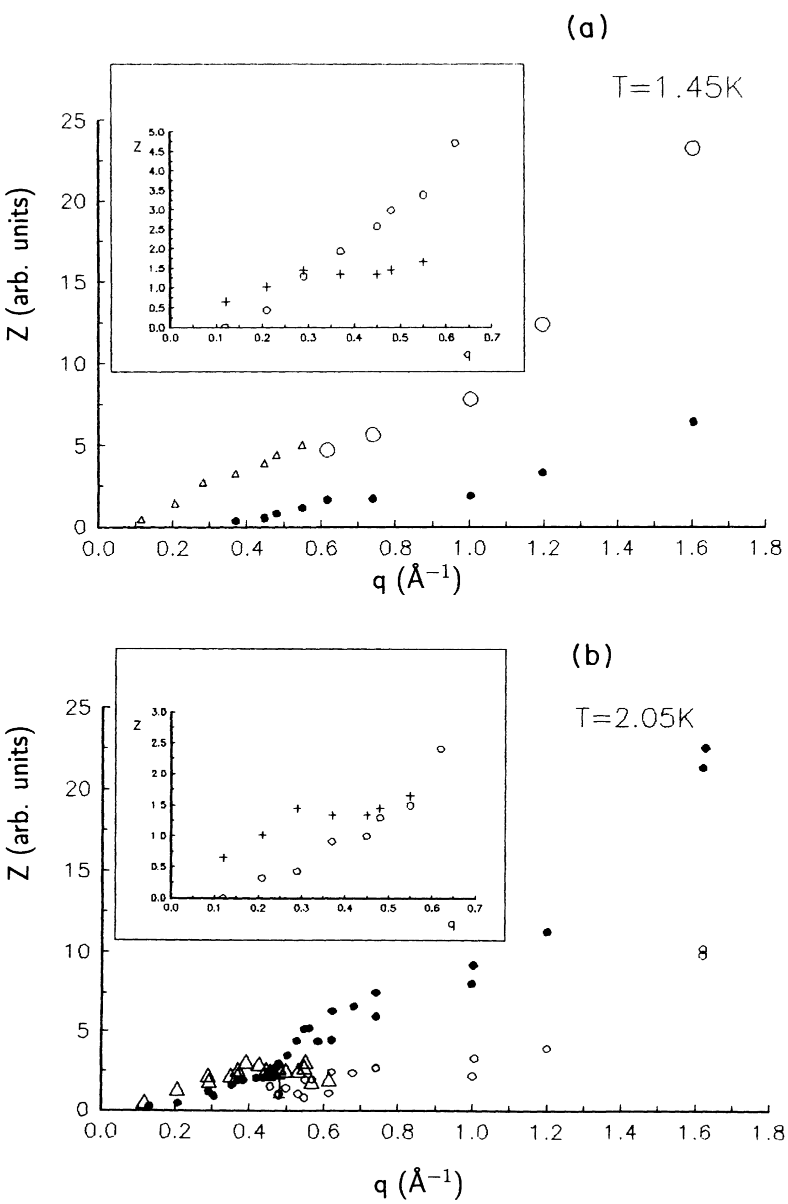

FIG. 6. Wave-vector dependence of the component areas at: (a) $T = 1.45$ K; (b) $T = 2.05$ K; (c) $T = 2.21$ K. (n) open circles, (w) closed circles, and (os) triangles. Two-part-decomposition of the (os) component [(os) component at $T = 2.21$ K, pluses and (n) component, open circles] is shown in the inset. (d) The contribution $Z(q)$ of the one-phonon excitations to the total scattering $S(q)$ at 1.1 K from Ref. 7.

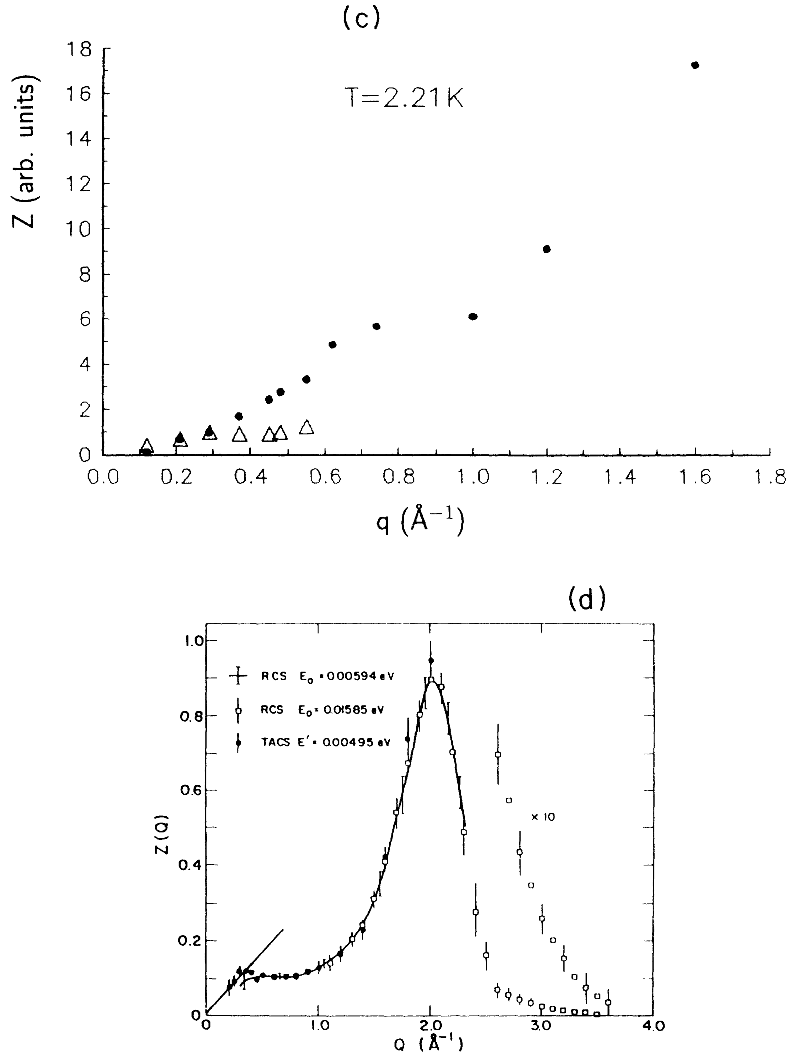

FIG. 6. (*Continued*).

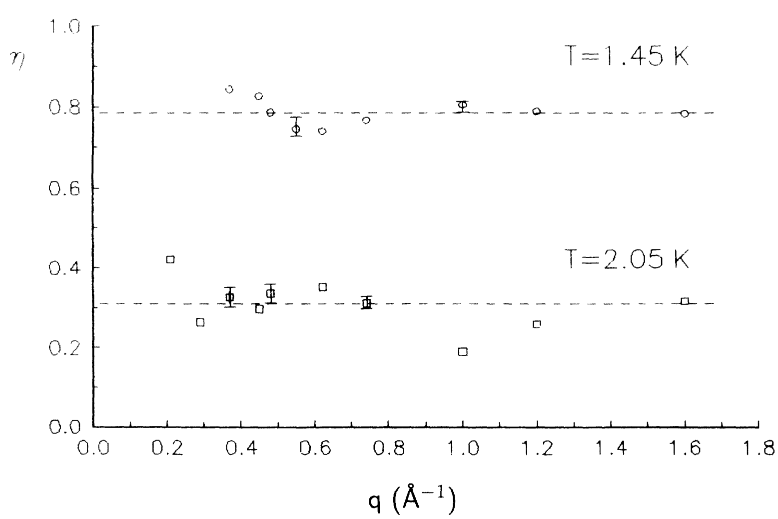

FIG. 7. $\eta(q)$ at two temperatures. Dashed lines show the average η.

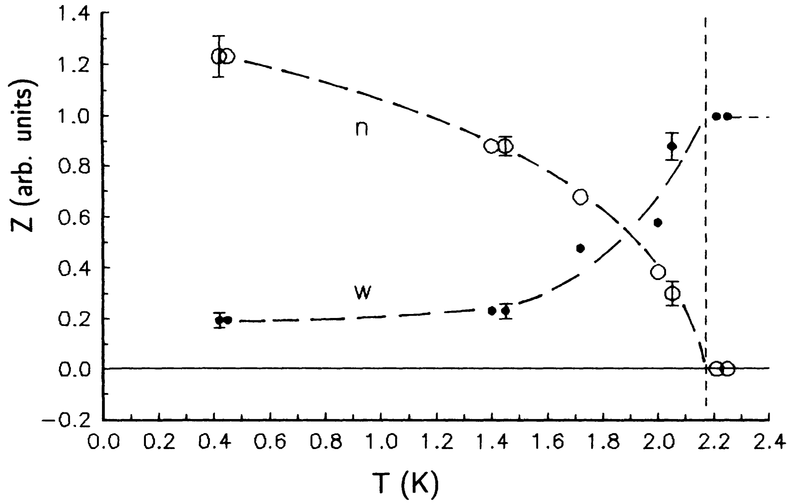

FIG. 8. Temperature dependence of the component areas: (n) open circles, (w) closed circles. Curves are normalized to the unit for the (w) component area at $T > T_\lambda$. $q = 1.6$ Å^{-1}.

data obtained by Cowley and Woods (CW).[7] Due to the difference of temperatures and momentum transfers, direct comparison of $Z(q)$ with CW measurements is difficult. Their data for temperature $T = 1.1$ K are shown in Fig. 6(d). The summation of intensities of all components for temperature $T = 1.45$ K leads to the similar q dependence.

D. Widths

Widths of peaks $W_{in}(q,T)$ were determined by subtracting the peak width at the lowest temperature $T = 0.42$ K from the experimental widths $W(q,T)$, without the Waller-Froman correction and the correction for the uncertainty Δq.

In the maxon-roton region of the spectrum, the dependencies $W_{nin}(q)$ and $W_{win}(q)$ are relatively weak for the superfluid phase at all temperatures; they are drawn in Figs. 10(a) and 10(b) for temperatures 1.45 and 2.05 K. In the normal phase, the widths of broad peaks are also weakly dependent on q [Fig. 10(c)]. The width of the narrow component (os) steeply increases in the transition region "Y." This displays a rapid decay in a relatively narrow interval of wave vectors. The width of the broad component (w) strongly depends on q in the phonon region of the spectrum. In the transition region, as said above, this component may have large widths and is hardly separated (see Fig. 10). All the components of neutron scattering in ^{4}He possess rather a strong temperature dependence of the width [see Figs. 11(a) and 11(b)]. *Summarizing* we emphasize that there exist, probably, three different types of excitation in liquid ^{4}He: (n), (os), and (w), which appear in different ways depending on the temperature and wave vector. Two typical regions of essential transformations of the energy spectra can be distinguished for excitations in liquid helium. At first, strong qualitative and quantitative changes in the nature of neutron scattering in helium occur in a very narrow interval of temperatures or at the point of the superfluid transition T_λ.

Second, explicit changes in the character of excitations in superfluid and normal helium take place in a narrow range of wave vectors (0.5–0.65) Å^{-1} when passing from phonons to maxons. Possible origins of both of these transformations will be discussed below.

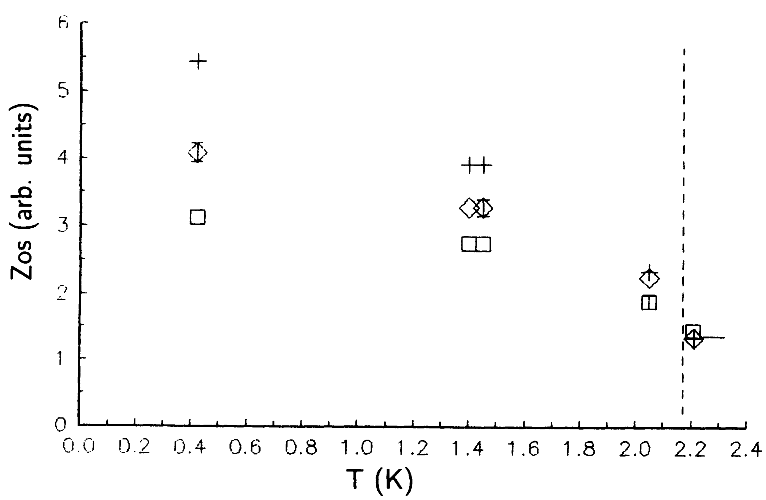

FIG. 9. Temperature dependence of the (os)-component areas: $q = 0.28$ Å^{-1} squares, $q = 0.37$ Å^{-1} diamonds, and $q = 0.45$ Å^{-1} pluses.

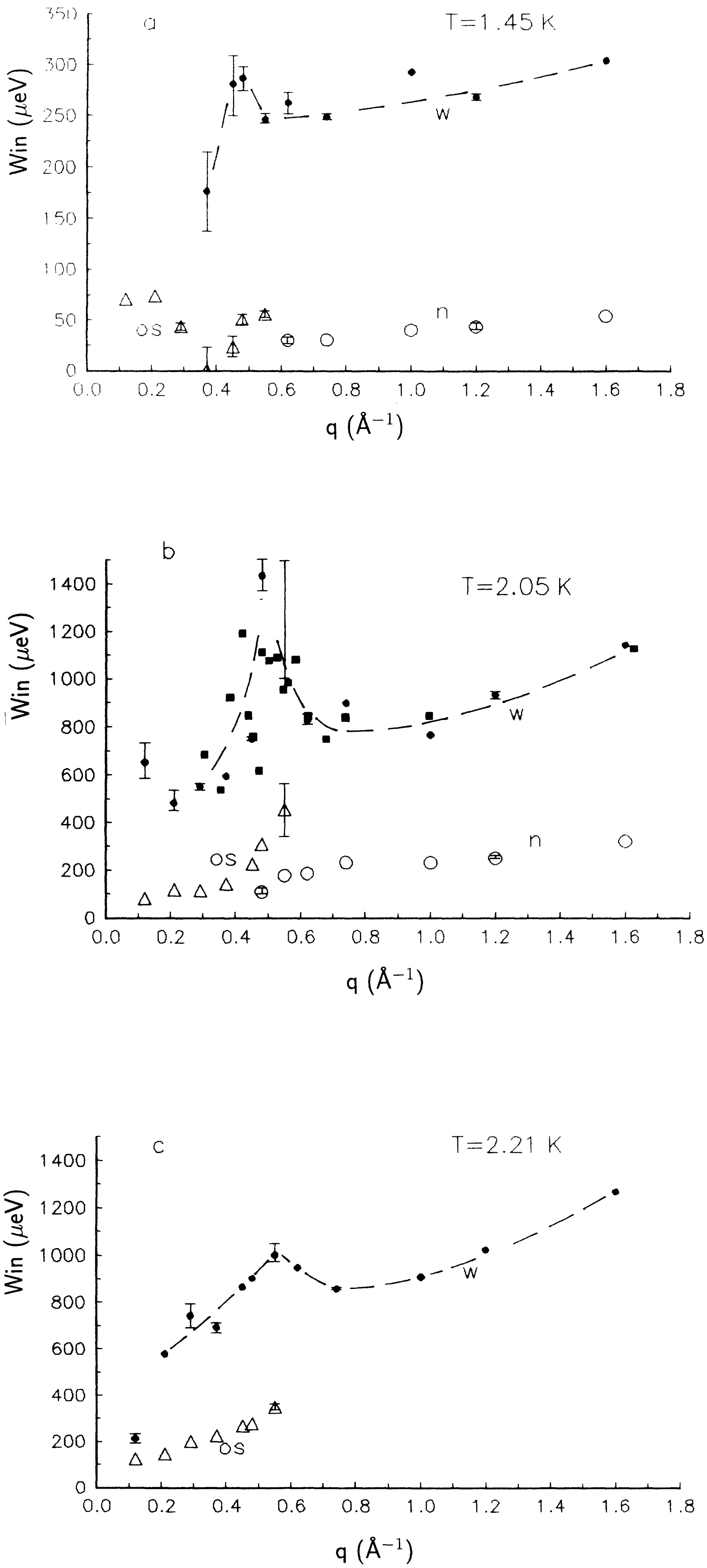

FIG. 10. q dependence of intrinsic widths of peaks at (a) $T=1.45$ K; (b) $T=2.05$ K; (c) $T=2.21$ K for the components: (n) open circles, (w) closed circles, and (os) triangles. (w)-component data with $\Delta q \sim 0.02$ Å^{-1} closed squares.

IV. COMPARISON OF THE OBTAINED RESULTS WITH DATA BY OTHER AUTHORS

A. Two-component structure of neutron-scattering spectra in liquid helium

The two-component character of the intensity of inelastically scattered neutrons in superfluid helium in the maxon-roton region was revealed in 1978. Woods and Svensson[34] have found that their results for the dynamic structure factor $S(q,\varepsilon)$ are well described by the formula

$$S(q,\varepsilon)=n_sS_s(q,\varepsilon)+n_nS_n(q,\varepsilon)\frac{1-\exp(-\varepsilon/kT_1)}{1-\exp(-\varepsilon/kT)}\ , \quad (6)$$

where $n_s=\rho_s/\rho$ and $n_n=1-n_s$, whereas $S_n(q,\varepsilon)$ contains only the intensity of a peak of normal He-I at $T_1>T_\lambda$. This assumption was supported by the fact that the experimentally determined $S(q,\varepsilon)-\rho_nS_n(q,\varepsilon)$ for wave vectors $q=(1.5-2)$ Å^{-1} behaved as $A\rho_s$, where $A=$const, with changing temperature. Expression (6) means that neutrons are scattered from the normal and superfluid components independently and in different ways. Attempts were undertaken to find a theoretical interpretation for that picture of scattering,[35,36] which made the basis for formulating the Griffin-Glyde concept mentioned in the Introduction. Also, the validity of the Woods-Svensson decomposition (6) has been open to question by recent experimental works.[24,27] It turns out that a more accurate consideration of multiphonon contributions to the one-particle intensity of neutron scattering destroys the empirical rule of decomposition (which can be clearly observed in analyzing experiments under pressure).

Recently, analyzing the experimental data on neutron scattering in helium under pressure in the maxon-roton region, Glyde and Griffin[25,26] have concluded that the structure of the scattering peaks near the roton consists of two components; however, this idea has not yet been developed.

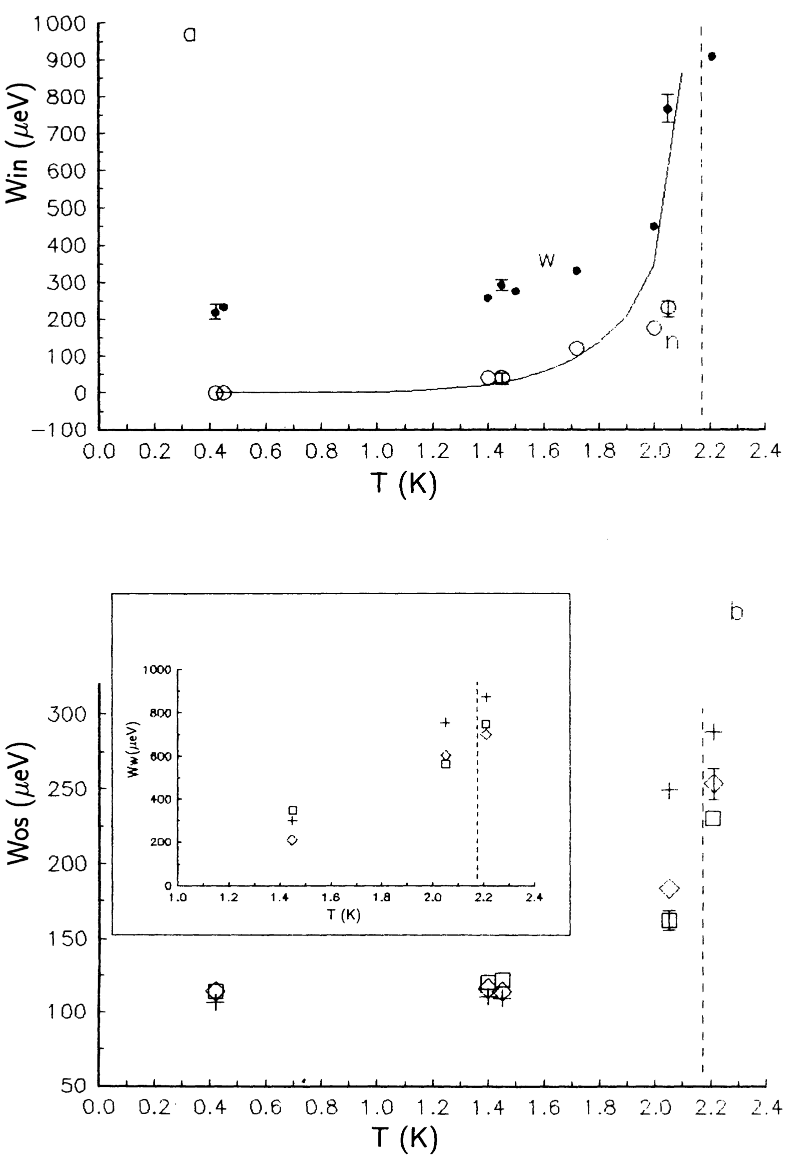

FIG. 11. Temperature dependence of intrinsic widths of peaks. (a) $q\sim1$ Å^{-1}. (n) open circles, (w) closed circles. Resolution is subtracted. The solid curve shows $W(T)$ [Eq. (9)]. (b) (os) component and (w) component (see inset). $q=0.28$ Å^{-1} squares, $q=0.37$ Å^{-1} diamonds, and $q=0.45$ Å^{-1} pluses. Resolution is not subtracted.

As follows from our results, the *sharp* peak of neutron scattering is to be represented as a superposition of two components after extracting the multiphonon scattering. These components appear in attempts to find the most adequate mathematical description for experimental peaks.

B. Parameters of excitation spectrum in helium

A comparison of our experimental results with data by other authors is a rather serious problem. First, in earlier works, the sharp peaks of neutron scattering in helium were, as a rule, described as one-component structures. Second, the most precision measurements have recently been carried out by other authors only for certain values of the wave vector; in particular, for the pressure of saturated vapors at $q=0.4$ Å^{-1} (phonons) and $q=1.92$ Å^{-1} (rotons).[24] Our data on the parameters $\varepsilon(q)$, e.g., for $q=0.37$ Å^{-1} (see Fig. 5) are in good agreement with the data of Ref. 24. Decomposition of the sharp peak of neutron scattering into several components with completely different dependencies $Z(T)$ is a result of this work and cannot be compared to the known behavior of the total area of the peak as a function of the temperature.

It is also difficult to compare the data on intrinsic widths of the scattering components. In our data we took the width of resolution to be equal to the experimental width at $T=0.42$ K. The most accurate results were obtained in experiments by Mezei and Stirling.[37] Our results coincide for $T<1.72$ K.

C. Anomalous dispersion

Here we will touch upon the problem that has been intensively discussed in Refs. 38 and 39. In Refs. 40 and 41 it has been discovered that the precision measurements of $\varepsilon(q)$ on the initial part of the dispersion curve on a certain part lies above the straight line $\varepsilon=cq$. These measurements were performed at temperatures (1.1–2.3) K. The phenomenon of the phase velocity of excitations exceeding the velocity of the first sound has been called the anomalous dispersion. From our data plotted in Fig. 12 for various temperatures and narrow components (*os*) and (*n*) it is seen that the anomalous dispersion is observed for $T<T_\lambda$ at all the measured wave vectors $0.08<q<0.65$ Å^{-1}. When $T>T_\lambda$ and $q<0.3$ Å^{-1}, the dispersion curve approaches the straight line corresponding to the first-sound velocity, i.e., a region of transition from the first to zero sound is observed. As it is also seen from Fig. 12, the dispersion curve intersects the straight line of the first-sound velocity in the region $q\sim(0.6-0.7)$ Å^{-1}; that quantity decreases with temperature; in general, these results are in agreement with the data of the most precise earlier measurements.[41]

V. PHYSICAL MODELS OF FORMATION OF THE EXCITATION SPECTRUM IN LIQUID HELIUM

Direct theoretical calculations of the spectrum of excitations in liquid ^{4}He on the basis of first principles are still difficult as no consisent microscopic theory of liquid ^{4}He exists as of yet. Studies along this line (see, e.g., Ref. 43) cannot be considered as satisfactory, at least, quantitatively. Below, we will examine the obtained results on the basis of several physical models.

We start with the Glyde-Griffin conception,[25] according to which there appears an extra system of poles connected with the spectrum of quasiparticles in the superfluid phase of helium for the dynamic susceptibility $\chi(q,\varepsilon)$, in addition to the systems of poles typical of the normal phase. This means that in He-II in experiments on the neutron scattering, branches of energy excitations typical of the superfluid phase are added to those specific for the normal phase.

From analysis of the present results it can be concluded that qualitatively this picture is observed. In the *normal* phase of liquid ^{4}He, two branches of excitation are seen. One of them (*w*) is observed throughout the whole studied region of wave vectors q and is characterized by large width of peaks. The second branch (*os*) is clearly seen at small q and decays rapidly at $q\sim(0.5-0.65)$ Å^{-1} (Fig. 10). Both the branches are observable in *superfluid*

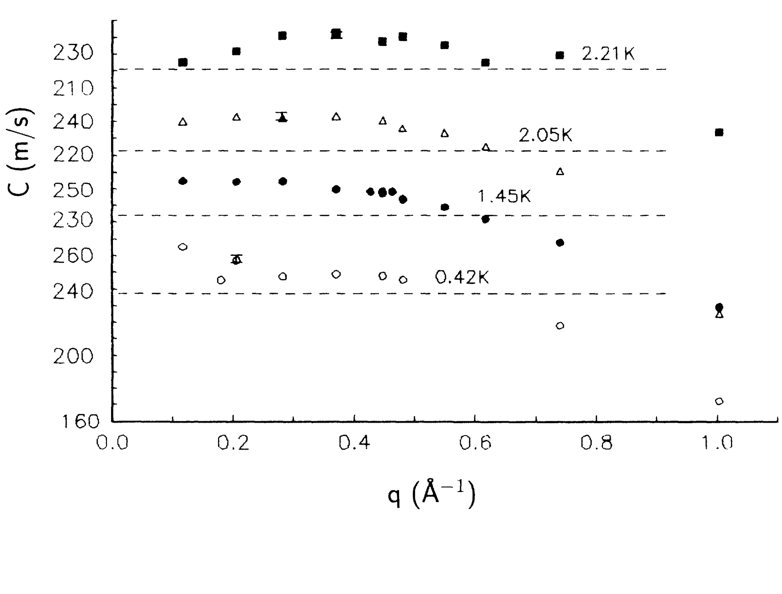

FIG. 12. Velocity of sound at various temperatures for the components (*os*). Liquid-helium first-sound velocity is shown by horizontal dashed lines (Ref. 42).

helium as well. Their dispersion laws, behavior of intensities, and widths as functions of q are similar to the corresponding dependencies for the normal phase. It is to be noted that the intensity of the broad component (w) strongly depends on the temperature (Fig. 8) and thus it is difficult to distinguish its contribution at low temperatures, especially in the region of small q.

Besides the above two components of neutron scattering in the *superfluid phase,* there appears one more branch corresponding to the narrow component (n). Its intensity strongly depends on the temperature (see Fig. 8) and at low T is dominating throughout the whole picture of neutron scattering. The narrow component (n) is clearly seen in the maxon-roton region of the spectrum up to $q \sim 0.5$ Å^{-1} where it approaches the component (os) and at still lower q it merges with (os).

What is the physical meaning of all the described branches of excitation? We can make the following assumptions for answering to that question:

The *narrow component (os)* typical of the region of small q in the *normal* and *superfluid* phase of liquid ^{4}He is most likely a branch of collective excitations of the type of zero sound. This problem has been discussed recently in detail (see, e.g., Ref. 24). This branch is typical of all liquids including helium-3 and liquid metals. The velocity of zero sound exceeds the velocity of first sound and thus a positive anomaly of the dispersion law is observed [which is also seen for helium-3 (Ref. 44)].

As follows from our results, this collective branch of excitations (os) at a certain value of the wave vector $q \sim (0.5-0.65)$ Å^{-1} widens to a great extent and than decays. Note that this attenuation of zero sound is typical of all van der Waals liquids where it is not observed at wave vectors above $(0.8-1.0)$ Å^{-1}.

The *wide component (w)* is observed in both phases of liquid helium. Its nature is still unclear; several interpretations for its physical meaning are put forward.

In particular, according to Ref. 26, this mode of scattering is related to the neutron scattering on thermally excited quasiparticles. For liquid-Fermi systems the theory of these excitations is well developed and used for interpreting data on the neutron scattering in liquid helium-3.[44] An extension to the Bose systems has been made in Refs. 35 and 36. The physical meaning of these processes consists of the energy transfer from the scattering neutrons to the thermally excited quasiparticles already existing in the system (phonons, maxons, rotons). A distinctive feature of the energy spectrum of these excitations is that the dispersion curve is given either by a broad strip or by a continuum where a certain range of ε corresponds to every value of q. Therefore, peaks of the neutron scattering on these excitations should be of a large width. Unlike the processes of production of quasiparticles, the above scattering mechanism is always connected with density fluctuations and, according to the Glyde-Griffin conception, should be observed in both the phases of ^{4}He. The intensity of excitations of that type should rapidly decrease with lowering temperature as the number of thermally excited quasiparticles in the liquid diminishes considerably.

The *narrow component (n)* observed only in the superfluid phase of ^{4}He can be identified with the Landau dispersion curve for elementary excitations. In addition to the above-given interpretation of the wide and narrow components, another interpretation is possible on the basis of comparison of the dispersion curves of excitations in quantum and classical liquids.

Experiments on the neutron scattering in metals, liquid hydrogen, and some other liquids in a certain range of momentum transfer give dispersion curves similar to the Landau curve in liquid helium, but with a much larger width. These branches can be associated with the quasicrystal nature of liquids with respect to short-wave excitations with wavelengths of an order of the interatomic distance up to several coordination spheres.

Liquid helium being essentially a quantum liquid retains some properties of a classical liquid. In the simplest approach based on the variational principle the phonon-roton dispersion curve $\varepsilon(q)$ is connected with the structure factor $S(q)$ by the relation

$$\varepsilon(q)=\frac{\hbar^2 q^2}{2mS(q)} . \tag{7}$$

As follows from the well-known Feynman ideas, due to the identity of particles, at small q and $T=0$ phonon excitations with the wave function

$$\Psi=\left[\sum_s \exp(iqr_s)\right]\Phi , \tag{8}$$

are the only possible excitations of a liquid. At finite temperatures and growing q up to a value of an order of the inverse distance between particles, the picture changes. Small vibrational motions of atoms in a harmonic wave and diffusion motions of individual atoms become of the same order. The wave function (8) remains to obey the variational principle but its uniqueness cannot be inferred now from the same considerations as for small q. Therefore, we can (and should) admit the existence of wave functions of another type corresponding to the normal state of a liquid. These wave functions should describe the quasicrystal nature of the motion of helium atoms and are to be localized around slowly diffusing centers whose motion is described by classical variables. Collective excitations of this normal component correspond to quasicrystal phonons in classical liquids. A large width of these excitations is either due to the number of coordination spheres being small or due to the coherence length being short. Therefore, the relative contribution of intensities of the narrow and broad peaks is one more experimentally measured parameter of long-range order.

We recall once again that in the narrow *transition Y region* of wave vectors, $(0.5-0.65)$ Å^{-1}, all the components of neutron scattering have a singularity. The zero-sound (os) mode is here rapidly decaying; the wide component (w) has singularities in the dependencies $W_w(q)$ and $Z_w(q)$ (see Figs. 6 and 10); the narrow component (n) merges with or transforms into the component (os). In this region of q, the anomalous dispersion disappears, i.e., this curve intersects the line of the sound velocity.

Both of the proposed interpretations of the multicomponent structure of the spectrum do not explain the above singularities. It can only be noted that the interpretation of the wide component as the spectrum of "normal" phonons due to the quasicrystal structure of a liquid predicts widening of the peaks with decreasing q. However, narrowing of the peaks in the phonon region of the spectrum remains unclear. Iordanskii and Pitaevskii[39] showed that at the point of intersection of the dispersion curve of phonons with the line of the first sound, there should be observed a sharp change in the width of phonons due to increase in the probability of their decay. It is clear that the explanation of the nature of rearrangement of the excitation spectrum in the range of transition from phonons to maxons requires further experimental and theoretical studies.

As only the narrow component represents the spectrum of quasiparticles, it is worthwhile to compare just the parameters of this component with the predicted properties of elementary excitations in superfluid ^{4}He. This first of all concerns the width of the excitation peak. The quantitative formula for the roton widths has been derived by Landau and Khalatnikov:[47]

$$W(T)=94\sqrt{T}\,\exp(\Delta/kT)\ . \tag{9}$$

In view of the dependence $W_n(q)$ being relatively weak (see Fig. 10), we can compare our results with formula (9), for instance, for $q\sim 1$ Å^{-1}, i.e., in the maxon region [see Fig. 11(a)]. As it is seen, agreement may be considered satisfactory at low temperatures. Around the λ point, formula (9) gives a larger value.

Note that the most accurate measurement of the width of one-particle peaks by the neutron scattering have been obtained by Mezei and Stirling[37] on a spin-echo spectrometer at ILL (Grenoble) and they coincide with formula (9).

The problem of the amount of Bose condensate in superfluid He-II has been considered starting with papers by London,[48] Bogolubov,[2] Belyaev[15] up to the present. In particular, it follows from Refs. 2, 15, and 25 that the sharp peak [our component (n)] in the maxon-roton region of the spectrum is connected with elementary excitations in He-II and its intensity is determined by the density of the Bose condensate (n_0). According to Ref. 26,

$$Z_n(T)\sim n_0(T)\ . \tag{10}$$

Though the problem of temperature dependence of the Bose-condensate density is not yet solved completely,[46] the qualitative relation holds obviously valid for the observed component (n). Like the Bose-condensate density, that component is absent in the normal phase, appears only below the λ point, and rapidly grows with decreasing temperature. Figure 13 shows the temperature dependence of the relative density of the Bose condensate obtained in Refs. 45 and 49 and compared with the dependence $Z_n(T)$ found in the present work. For the normalization of data, we took the temperature range (0.4–0.5) K. The data turn out to be in reasonable agreement.

VI. CONCLUSION

The modern experimental facilities of the complex IBR-2 and DIN-2 in JINR (Dubna) permit the detailed research of inelastic scattering in ^{4}He. The elementary excitations have been the subject of our interest while the multiphonon processes were effectively suppressed in the experiment. The results were represented via the fit of the initial experimental data by the Gauss-Gauss and Gauss-Lorentz convolutions and it encouraged us to follow the evolution of the peak of the scattering as a function of T and q.

As expected, the sharp change of the peak happens at the point of the λ transition. In the normal phase, the complex structure of peaks consisting of two components (os) and (w) is observed in the phonon region only. The structure becomes more complicated and the third branch (n) appears for all the q values when $T<T_\lambda$.

The origin of the spectrum, in brief, is in accordance with the Griffin-Glyde theory. The (n) component may be identified as the result of the quasiparticle excitations. In the normal state the narrow (os) phonon branch may be explained as the zero-sound mode, and as the superpo-

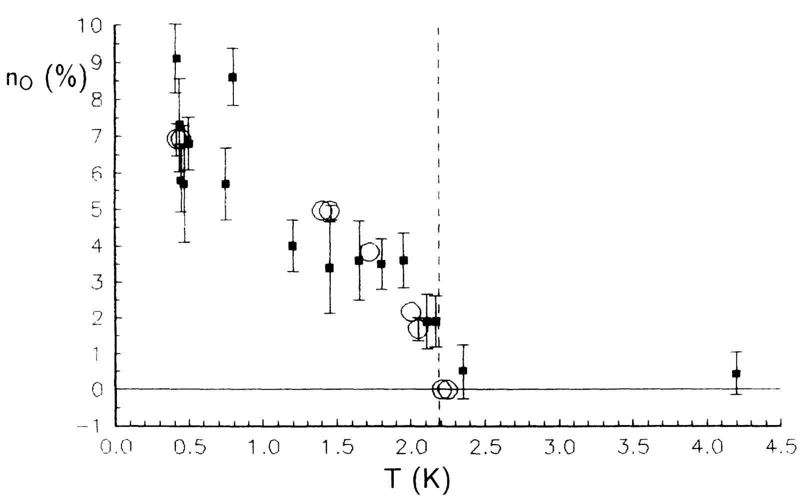

FIG. 13. Bose-condensate estimation. Closed boxes represent results from Ref. 49; empty circles present values normalized to the n_0 values at temperature region (0.4–0.5) K.

sition of such a mode with the phonon part of quasiparticle excitation in the superfluid phase. The (w) component may be understood as the collective excitations of the phonon type, usual for the classical liquids. As to the mechanism of "interaction" between these three branches, Griffin and Glyde's idea about the hybridization of quasiparticles with the density fluctuations due to the presence of Bose condensate seems to be adequate with the picture presented above.

Special attention must be paid to the anomalous dispersion of the (w) branch, to the contributions of the various excitations to the thermodynamical properties of ^{4}He, and to the Y region in the q variable between phonon and maxon parts of the spectrum.

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