KFKI-1980-02

F. MEZEI

μeV RESOLUTION STUDY OF EXCITATIONS IN SUPERFLUID ^{4}He BY NEUTRON SPIN ECHO

Hungarian Academy of Sciences

CENTRAL RESEARCH INSTITUTE FOR PHYSICS

BUDAPEST

KFKI-1980-02

µeV RESOLUTION STUDY OF EXCITATIONS IN SUPERFLUID ^{4}He BY NEUTRON SPIN ECHO

F. Mezei

Central Research Institute for Physics
H-1525 Budapest, P.O.Box 49, Hungary

and

Institut Laue-Langevin
156X, 38042 Grenoble Cedex, France

HU ISSN 0368 5330
ISBN 963 371 621 7

ABSTRACT

By the use of the newly developed neutron spin echo method neutron scattering studies of elementary excitations can now, for the first time, be extended to the μeV resolution range. The first such experiment is described, and its results are shown to complement substantially previous knowledge on the temperature dependence of the energy and lifetime of the roton excitation and the suggested onset of three phonon decay beyond the roton minimum in superfluid ^4He.

АННОТАЦИЯ

При помощи разработанного недавно метода нейтронного спинового эха впервые стало возможным расширить исследования элементарных возбуждений, проводящихся методом нейтронного рассеяния, на область с мкэВ-ым разрешением. В статье описывается первый эксперимент такого рода, и приводятся результаты с целью углубления сведений относительно температурной зависимости энергии и длительности жизни ротонного возбуждения, а также и возникновения предсказанного трехфононного распада ниже минимума ротона в сверхжидком ^4He.

KIVONAT

A nemrégiben kifejlesztett neutron spin echo módszer segitségével most, első izben, lehetővé vált az elemi gerjesztések neutronszórással történő vizsgálatainak a μeV-os felbontási tartományra való kiterjesztése. Az első ilyen kisérlet leirását tartalmazza a cikk. Az eredmények lényegesen kiegészitik a szuperfolyékony ^4He folyadék roton gerjesztésének energiájára és élettartamára, valamint a megjósolt három-fononos bomlás roton minimumon tuli fellépésére vonatkozó ismereteinket.

Neutron Spin Echo [1] /NSE/ represents a conceptually new approach in inelastic neutron scattering. The basic originality of the method is that it makes the energy transfer resolution independent of the monochromatization of the incoming and outgoing beams. Thus it offers improved resolution /up to two orders of magnitude in certain cases/ under good or acceptable neutron intensity conditions. NSE can most simply be applied to quasielastic scattering effects like diffusion [2] or spin relaxation [3]. The author has introduced earlier the generalized scheme for the use of NSE in the study of elementary excitations [4]. The present letter reports the first such results, viz. the temperature dependence of the roton energy and linewidth between 0.96 and 1.4 K, and the suggested onset of three phonon decay beyond the roton minimum were studied in superfluid ^{4}He.

The method. The scheme of experiment made at the Institut Laue-Langevin on the specially modified IN11 NSE spectrometer [5] is shown in *Fig. 1.* In NSE the initially polarized neutrons perform Larmor precessions during their flight through a well defined magnetic field region both before and after the scattering. The total Larmor precession angle φ is given [1] by the difference of the outgoing and incoming precession angles:

$$\varphi = \varphi_1 - \varphi_0 = \gamma_L \ell H_1/v_1 - \gamma_L \ell H_0/v_0 = \varphi(v_0, v_1) \qquad (1)$$

where γ_L=2.916 kHz/Oe, ℓ is the length of the field regions, H_1 and H_0 are the outgoing and incoming field strengths, v_1 and v_0 the respective velocities for the considered neutron. /For the moment the "field tilt coils" in *Fig. 1* are set aside./ The basic idea of NSE is to use φ for the measurement of the neutron energy change $\hbar\omega = E_0 - E_1 \equiv \frac{1}{2}mv_0^2 - \frac{1}{2}mv_1^2 = \hbar\omega(v_0, v_1)$, while the momentum change is determined by a background spectrometer, constituted in this case essentially by the velocity selector and the graphite crystal /*Fig. 1*/. Since φ and ω are basically different functions

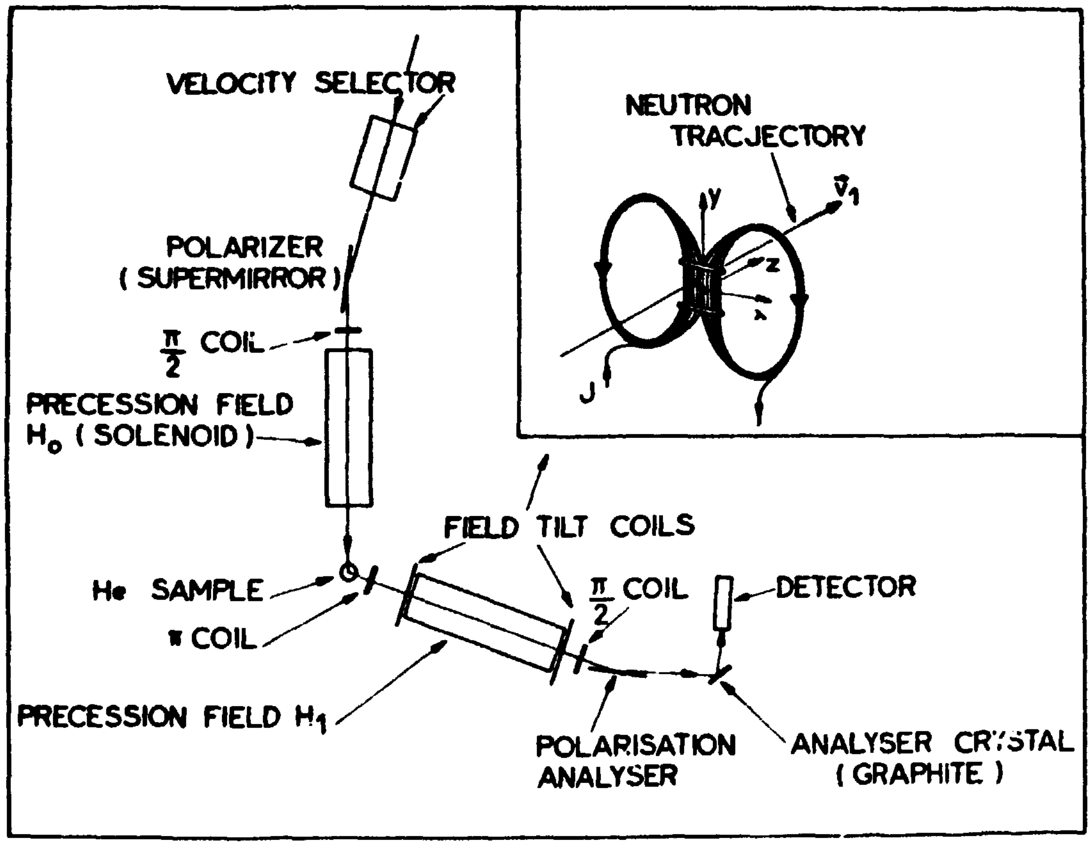

Figure 1.

Scheme of NSE experiment for studying elementary excitations in superfluid ^4He

of v_o and v_1, φ can only be a measure of ω locally, with respect to some average values $\bar{\varphi}=\varphi(\bar{v}_o,\bar{v}_1)$ and $\bar{\omega}=\omega(\bar{v}_o,\bar{v}_1)$,

$$\varphi - \bar{\varphi} = t(\omega - \bar{\omega}) \quad , \qquad (2)$$

where t is a constant, and the bar stands for the average. This is the fundamental equation of NSE, which is readily found to be fulfilled to first order in $\delta v_i = v_i - \bar{v}_i$ if and only if

$$\hbar\gamma_L \ell H_i = tm\bar{v}_i^3 \quad . \qquad (3)$$

Here and in what follows i=0,1. In the general case of dispersive elementary excitations we want to measure ω with respect to the dispersion relation $\omega_d(\vec{\kappa})$, where $\vec{\kappa}=m(\vec{v}_1-\vec{v}_o)/\hbar$. Thus in Eq.(2) $\bar{\omega}$ will be replaced by $\omega_d(\vec{\kappa})$, /the averages $\vec{\bar{v}}_o$ and $\vec{\bar{v}}_1$ are assumed to correspond to a point on the dispersion relation/ and this generalised NSE condition can be fulfilled [4] if φ_o and φ_1 depend not only on the absolute value of v_o and v_1, as in Eq.(1), but also on their directions, i.e. in differential form

$$\delta\varphi_i = -\gamma_L \ell H_i (\vec{n}_i \delta\vec{v}_i)/\bar{v}_i^2 \quad , \tag{4}$$

where the normalisation $(\vec{n}_i\vec{\bar{v}}_i)=\bar{v}_i$ is chosen.
The NSE condition is now found [4, 6] to be satisfied to first order in $\delta\vec{v}_i = \vec{v}_i-\vec{\bar{v}}_i$ if

$$\vec{n}_i \parallel (\vec{\bar{v}}_i + \mathrm{grad}\ \omega_d) \quad ,$$
$$\hbar\gamma_L \ell H_i = tm\bar{v}_i[\bar{v}_i^2 + (\vec{\bar{v}}_i \cdot \mathrm{grad}\ \omega_d)] \tag{5}$$

In practice Eqs.(3) or (5) are used to determine $\vec{n}_i$, H_o/H_1 and t.

The experiment. In Ref. 4 I proposed a method to realize Eq.(4) by the use of rectangular precession field regions tilted with respect to the mean beam direction. For the solenoidal precession fields in this case, however, a better adapted solution is offered by the "figure 8" coils developed in the early days of polarized neutron work at Kjeller [7] and shown as "field tilt coils" in *Fig. 1.* When a neutron crosses the flat monolayer of wires at the center of the "8" it goes through the interior of a certain number n of winding loops /see the insert/. For moderate activating currents J only the component of the "figure 8" coil field parallel to H_1 /i.e. the mean beam direction/ has to be considered, and the precession field integral $H_1\ell$ will be modified for the particular neutron by $\pm$ $4\pi nJ/c$, where the sign corresponds to the sense of the windings traversed: clockwise to the right of the center /where n=0/ and counter-clockwise to the left. With two of these coils activated in the opposite sense at both ends of the precession field coil H_1 /*Fig. 1*/ we find

$$\varphi_1 = \gamma_L \ell H_1/v_1 + 4\pi NJ(x_1-x_2)/cv_1 \quad , \tag{6}$$

where N is the number of windings per unit length in the wire layer, x_1 and x_2 are the x coordinates of the neutron trajectory at the first and second "figure 8" coils, respectively. Thus we obtain the directional dependence of φ_1 required by Eq.(4) with $\vec{n}_1 = (n_x, n_y, n_z) = (4\pi JN/c\ell H_1, 0, 1)$. The corresponding field tilt angle is given as $\vartheta_1 = \arctan(n_x/n_z)$. Note that $z \parallel H_\perp$ is the mean beam direction. In this first trial experiment no tilt coils were used for H_o, the beam cross section was rather reduced instead when necessary.

In the experiment the x and y components of the precessing polarization are measured, i.e. the $\langle\langle\cos\varphi\rangle\rangle$ and $\langle\langle\sin\varphi\rangle\rangle$ averages for the outgoing beam. The NSE polarization "signal" P_{NSE} is given as $P_o(\langle\langle\cos\varphi\rangle\rangle^2 + \langle\langle\sin\varphi\rangle\rangle^2)^{1/2}$, where P_o is the polarization efficiency of the NSE setup, and by definition $\bar{\varphi} = \arctan(\langle\langle\sin\varphi\rangle\rangle/\langle\langle\cos\varphi\rangle\rangle) + 2\pi n$. In practice it is possible but tedious to measure H_o and H_1 sufficiently precisely for $\bar{\varphi}$ to be given an absolute, rather than a relative meaning. For a Lorentzian phonon line given by the scattering function $S(\vec{\kappa},\omega) = \gamma/\{\gamma^2 + [\omega-\omega_d(\vec{\kappa})]^2\}\pi$, we obtain by the generalised Eq.(2)

$$P_{NSE}=P_o\int S(\vec{\kappa},\omega)\cos[t(\omega-\omega_d)]d\omega=P_o\exp(-\gamma t) \quad , \qquad (7)$$

where the integration extends over the transmission function /"resolution ellipsoid"/ of the background spectrometer, which should be broad compared with γ /i.e. the integration can be taken from $-\infty$ to ∞/ if high NSE resolution is required. In addition, a relative change of the phonon energy $\delta\omega_d$ shows up as a change of the phase angle $\delta\bar{\varphi} = t\delta\omega_d$. In the experiment P_{NSE} was measured vs. $t \propto H_o$ at constant H_o/H_1 [cf. Eqs.(3), (5)], and γ was determined from Eq.(7).

The tuning of the spectrometer in order to fulfill the NSE condition consists of setting the H_o/H_1 and the field tilt vectors $\vec{n}_o$ and $\vec{n}_1$ to the values given by Eq.(3) or Eq.(5). Experimentally, these values correspond to a maximum of the NSE signal [6]. This is nicely borne out by the NSE tuning curves shown in *Fig. 2*, where the arrows indicate the calculated values of the parameters, as summarized in *Table I*. Note that the differences in H_o/H_1 between different lines mainly come from differences in the slopes $d\omega_d/d\kappa$.

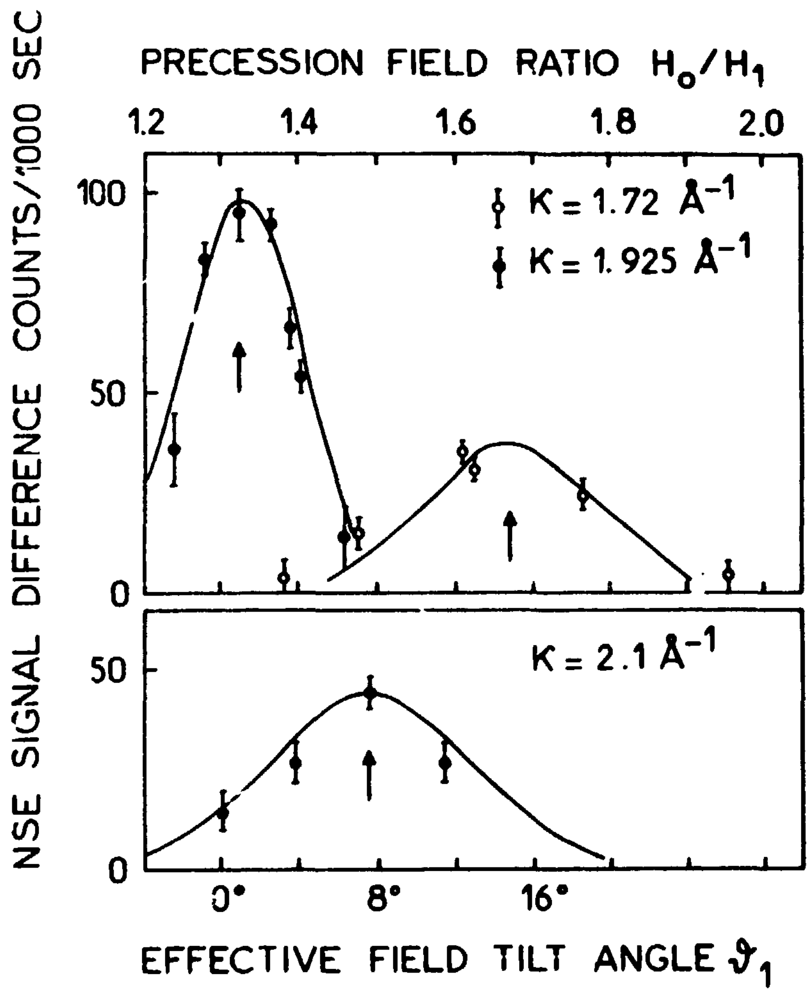

Figure 2.

Sample tuning curves for NSE parameters /The lines correspond to the expected shape./

Table I.

NSE parameters for various phonons in ^4He

($\bar{E}_1$ = 3.63 meV)

κ (Å^{-1})	$d\omega_d/d\kappa$ (meVÅ)	$\bar{E}_o$ (meV)	H_o/H_1	ϑ_o (o)	ϑ_1 (o)
1.72	-0.96	4.49	1.69	-6.1	-9.2
1.92	0	4.38	1.32	0	0
2.10	1.22	4.48	0.99	8.5	7.6

The conceptual difference between the classical and the NSE approach is that in the first case the measured energy transfer is given as the difference between two measured beam averages: $\frac{1}{2}m\langle\langle v_0^2\rangle\rangle-\frac{1}{2}m\langle\langle v_1^2\rangle\rangle$ whereas in NSE the beam average of a difference quantity $\langle\langle\varphi_1-\varphi_0\rangle\rangle$ is measured directly.

Results. In this first NSE experiment of this kind a few phonon groups were studied in superfluid ^{4}He. The results obtained at various temperatures T for the linewidth $\gamma(T)$ and for the change of the energy $\Delta(T)$ of the roton excitation /κ=1.92, cf. *Table I*/ are shown in *Fig. 3* together with results of previous studies.

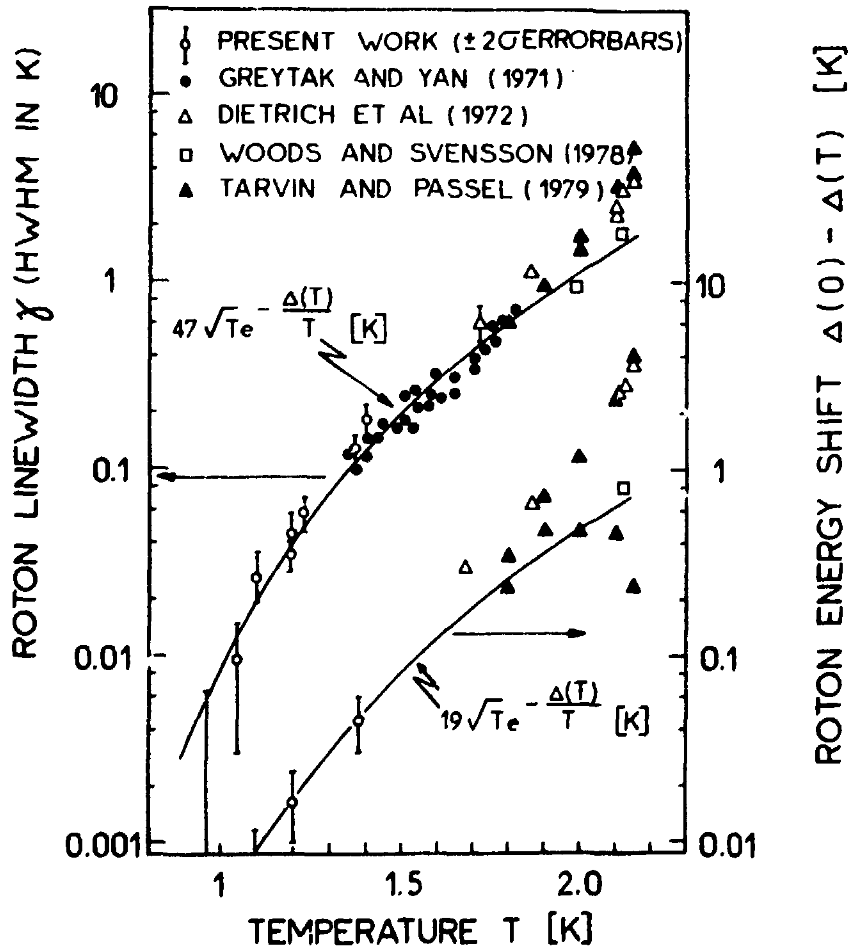

Figure 3.

Comparison of present results on the temperature dependence of the roton energy and linewidth with previous Raman scattering [Ref. 8] and neutron scattering [Refs. 9, 10, 11] data, and with theoretical predictions

The scatter in the classical neutron scattering data, limited to temperatures where $\gamma(T)$ and $\Delta(T) \approx 8$ K are comparable, was shown [10, 11] to be due to ambiguities in the data reduction procedures. On the other hand it is remarkable that the Raman scattering results [8] /dots/, obtained indirectly by the use of the two roton bound state theory [12], are consistent with the direct neutron scattering observations.

The first Born approximation theory of the roton-roton interaction by Landau and Khalatnikov [13] /LK/ predicts that $\gamma(T)=47\sqrt{T}\,\exp[-\Delta(T)/T]$, where all quantities are measured in K, and the coefficient 47 was calculated from normal fluid viscosity data. Furthermore it has been pointed out [14] that within the LK framework there is a roton-roton contribution to $\Delta(T)$ too, which has the same temperature dependence. A fit to the present NSE results then gives $\Delta(0)-\Delta(T)=19\sqrt{T}\,\exp[-\Delta(T)/T]$, which leads to values about two times smaller than previously accepted [15]. /As a matter of fact 0.96 K was the lowest T in this experiment, and the extrapolation to T=0 was made using this expression./ The values for $\Delta(T)$ thus obtained with $\Delta(0)=8.62$ K were in turn used for the calculation of the LK prediction for $\Delta(T)$ /upper curve in *Fig. 3*/. The excellent absolute agreement over more then two orders of magnitudes in γ, without any fitted parameter, indicates that the roton lifetime is indeed dominated by the roton-roton processes for the temperatures shown, with possible deviations between 2 K and the λ point. However, the magnitude of $\gamma(T)$ turns out to be much too big for the first Born approximation to be applied, and actually it is about 4 times bigger than the upper /unitarity/ limit for single channel scattering processes, brought about by the final state interactions. Interestingly, the present new values for $\Delta(0)-\Delta(T)$ also turn out to be about 4 times bigger than the same type of limit [15]. Furthermore, within their range of validity, the Born and HF approximations predict that $[\Delta(0) - \Delta(T)] \gtrsim \gamma(T)$, in strong contrast to the present results. This is additional evidence that a strong coupling theory has to be used. Following Fomins suggestion of several helicity channels, the present $\gamma(T)$ and $\Delta(0)-\Delta(T)$ data, and in particular their ratio, can be explained by a minimum of seven scattering channels with an average effective coupling constant $g_4=1.2\times10^{-38}$ ergcm^3, if for each channel $-10^{-38} \gtrsim g_4 \gtrsim -1.8\times10^{-38}$ ergcm^3. It is worth noticing, that if the present theoretical curves proved to be adequate for T>1.8 K too, as seems to be the case for the data of Ref. 11, this would prove that both $\gamma(T)$ and $\Delta(0)-\Delta(T)$ are dominated by the roton-roton processes in the entire temperature range above 1 K.

Another high resolution problem has been touched on in this experiment: the eventual onset of phonon emission decay for phonons with momenta above 2.1-2.2 $Å^{-1}$ /Pitevski broadening/. I found no such effect and the 70 % confidence level upper limits for the decay rate at 1 K which I have been able to establish up to now are: 20, 40, 40 and 20 mK at 2.1, 2.2, 2.3 and 2.4 $Å^{-1}$, respectively. Following the analysis of Ref. 16 this indicates that the presumed linear section of the dispersion curve, which should start at κ=2.25 $Å^{-1}$, ends below 2.4 $Å^{-1}$, if it exists at all.

The present experiment is the first in which energy resolutions around 1 μeV /1 part in 10^3 in energy transfer/ have been attained in a neutron scattering study of elementary excitations. For the investigated cases this means a 20-40 fold improvement compared with classical methods, which should be typical for the method, as it was shown by the Monte Carlo simulation calculations I have performed to assess the higher order terms neglected in Eq.(2). The NSE has, in addition, the interesting feature that it is selective for the slope of the dispersion curve /cf. *Fig. 2*/.

It appears to me that the present results convicingly show both the feasibility of the NSE method for the high resolution study of elementary excitations /lifetime and energy shift effects, crossing branches and hybridization, etc./ and the physical interest of such experiments.

I wish to acknowledge several stimulating discussions with numerous colleagues, in particular with Roger Pynn and Fred Zawadowski.

REFERENCES

[1] F. Mezei, Z. Physik 255, 146 /1972/
[2] D. Richter, J. B. Hayter, F. Mezei, and B. Ewen, Phys. Rev. Lett. 41, 1484 /1978/

[3] F. Mezei, and A. P. Murani, Proc. Neutron Scattering Cond., Jülich, August 1979, J. Mag. M. Mat. /*in Press*/
[4] F. Mezei, in Neutron Inelastic Scattering 1977 /IAEA, Vienna, 1978/, p. 125
[5] P. A. Dagleish, J. B. Hayter, and F. Mezei, to be published
[6] R. Pynn, J. Phys. E 11, 1133 /1978/; F. Mezei, in IIIrd International School on Neutron Scattering /JINR, Dubna, 1978/; same authors in Neutron Spin Echo, Proc. of an ILL workshop, /Springer Verlag, to be published/
[7] K. Abrahams, O. Steinsvoll, P. J. M. Bongaarts, and P. W. de Lange, Rev. Sci. Inst. 33, 524 /1962/
[8] T. J. Greytak, and J. Yan, In Proc. 12th Int. Conf. on Low Temperature Physics, edited by E. Kanda /Academic Press, Kyoto, 1971/ p. 89
[9] O. W. Dietrich, E. H. Graf, C. H. Huang, and L. Passel, Phys. Rev. A5, 1377 /1972/
[10] A. D. B. Woods, and E. C. Svensson, Phys. Rev. Lett. 41, 974 /1978/
[11] J. A. Tarvin, and L. Passel, Phys. Rev. B19. 1458 /1979/
[12] See e.g. A. Zawadowski, Quantum Liquides, edited by J. Ruvalds and T. Regge /North Holland, Amsterdam, 1978/ p. 293
[13] L. D. Landau, and I. M. Khalatnikov, Zh. Eksp. Teor. Fiz. 19, 637 /1949/
[14] J. Ruvalds, Phys. Rev. Lett. 27, 1769 /1971/
[15] I. Tüttö, J. Low Temp. Phys. 11, 77 /1972/
[16] J. Jäckle, and K. W. Kehr, Phys. kondens. Mat. 16, 265 /1973/

Kiadja a Központi Fizikai Kutató Intézet
Felelős kiadó: Krén Emil
Szakmai lektor: Zawadowski Alfréd
Nyelvi lektor: Harvey Shenker
Példányszám: 340 Törzsszám: 80-11
Készült a KFKI sokszorositó üzemében
Budapest, 1980. január hó