Brief Reports

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Reanalysis of the condensate fraction for ^{4}He from neutron scattering data

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New data analysis has been performed on three neutron scattering experiments that previously gave widely different values for the Bose-Einstein condensate fraction in ^{4}He. With the new analysis, the experimentally determined values are in good agreement suggesting a condensate fraction of about 10%.

There is still great interest in the possibility of Bose-Einstein condensation taking place at low temperatures in ^{4}He. One of the best ways of examining this possibility is with neutron scattering, and a number of experiments have been done in the last several years. These experiments are based on the proposal by Hohenberg and Platzman[1] to use high-energy neutrons to separate scattering from the atoms that have undergone Bose-Einstein condensation from the atoms that are in the normal state. Unfortunately this separation requires neutron energies and resolutions much higher than have been achieved to date. The scattering from low-temperature ^{4}He thus consists of two parts that are combined together, and a separation must be made if a condensate fraction is to be determined. This report is concerned with three experiments that have been performed at Oak Ridge National Laboratory and that have suggested widely different values for the condensate fraction.

The first of these is a high-accuracy experiment using the triple-axis technique with a fixed incoming energy of 182.47 meV and a fixed scattering angle of 135°.[2] The data were analyzed by fitting $S(\mathbf{Q},\omega)$ with three functions and performing a least-squares analysis which suggested a condensate fraction of 2.4%. The analysis was complicated by the fact that the scattering distributions were definitely non-Gaussian, even at 4.2 K. We will refer to this experiment as experiment 1.

Some time after experiment 1 was completed, a much better way of analyzing data from such experiments was developed by Martel *et al.*,[3] Woods and Sears,[4] and Sears, Svensson, Martel, and Woods.[5] Their method relied on symmetrizing the data about the recoil energy $Q_0^2/2M$ to minimize final-state interaction effects. For experiment 1 the calculated recoil energy was 106.44 meV while the center of the scattering distribution was found to be 106.22 meV, so symmetrizing the data is not so important. However, one must remember that the data were taken at constant angle so that the relation between the momentum distribution $n(\mathbf{p})$ at constant angle and at constant Q given in Ref. 6 must be used.

Once $n(\mathbf{p})$ has been established, the condensate fraction can be determined as shown in Ref. 5. $n(\mathbf{p})$ is written in the form

$$n(\mathbf{p})=n_0\delta(\mathbf{p})+(1-n_0)n^*(\mathbf{p}) ,$$

where $n^*(\mathbf{p})$ is the momentum distribution for the uncondensed atoms. It is best to use a measurement for this distribution that is taken at a temperature just above the λ point. Experiment 1 used a temperature of 4.2 K for this measurement which is probably all right since the momentum distribution changes little between 4.2 K and the λ point. However, one must be careful to take the density change of ^{4}He into account. The condensate fraction is then given by

$$n_0=\varepsilon/(1-\beta+\gamma) ,$$

where

$$\varepsilon=4\pi\int_0^{p_c}[n(\mathbf{p})-n^*(\mathbf{p})]p^2dp ,$$

and

$$\beta=4\pi\int_0^{p_c}n^*(\mathbf{p})p^2dp .$$

p_c is the point where $n(\mathbf{p})-n^*(\mathbf{p})$ becomes negative and γ is a correction term that becomes larger near the λ temperature. $n(\mathbf{p})$ was obtained from the 1.2 and 4.2 K data from experiment 1 and ε and β were determined. From this, the condensate fraction was determined and is given in Table I along with the other parameters of interest. A plot of the important quantity $n(\mathbf{p})-n^*(\mathbf{p})$ is shown in Fig. 1. The data are quite accurate although not many points are available at the higher momentum values.

The second experiment to be considered,[6] which we will denote experiment 2, is a time-of-flight experiment undertaken to obtain higher-momentum-transfer results. The

TABLE I. Condensate fraction and associated parameters.

Experiment	T (K)	P_c (Å^{-1})	ε	β	γ	n_0
1	1.2	0.92	0.063	0.40	0.045	0.10 ± 0.02
2	1.2	0.92	0.067	0.49	0.045	0.12 ± 0.04
3	1.5	0.89	0.076	0.27	0.091	0.09 ± 0.02
	0.47	0.90	0.077	0.28	0.007	0.105 ± 0.02

incident energy was 189.4 meV, and a scattering angle of 151.75° was used. This resulted in a momentum transfer of 14.79 Å^{-1} which was about the value used in experiment 1. $n(\mathbf{p})$ had already been determined for this case, so to get the condensate fraction, only ε and β need to be determined. The data in this case are not so accurate, so the condensate fraction cannot be determined with great precision. The original estimate of the condensate fraction of 1.8% was obtained by comparing the measured momentum distribution with a calculated one. The new value of the condensate fraction along with the ε and β values for experiment 2 are shown in Table I.

The third experiment, experiment 3, is a time-of-flight experiment done for a large number of momentum values in the range of 5–7 Å^{-1}. It has already been analyzed using the above procedure and is discussed in Ref. 7. The condensate fraction and other parameters of importance are given in Table I.

We see from Table I that the experiments are all consistent with each other and suggest a condensate fraction of about 10%. This value is also in good agreement with that found in independent experiments[5] at other laboratories. The lower value of the condensate fraction found earlier for experiments 1 and 2 resulted from only considering changes near the peak of the scattering function, while the new analysis considers the whole peak, particularly that part up to p_c. The experimental data obtained

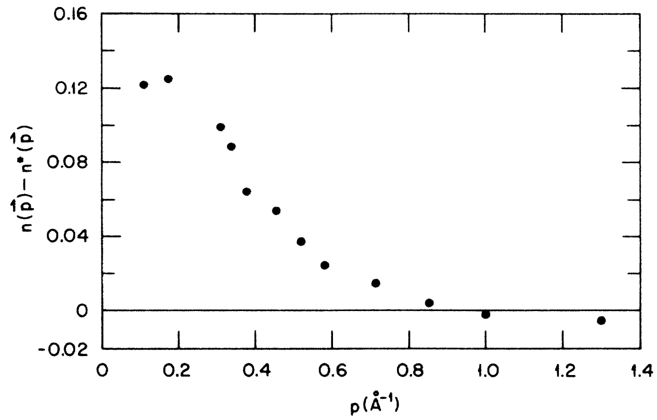

FIG. 1. $n(\mathbf{p}) - n^*(\mathbf{p})$ determined for experiment 1.

in each case are thus correct, and different values of the condensate fraction result from differences in the analysis used. There is nothing to guarantee that the new analysis in fact gives the correct condensate fraction. Griffin[8] has recalculated the quantity γ, and his new results suggest that the condensate fraction may be lower than that given in Table I. The new analysis does give a consistent value for the condensate fraction even with very different types of experiments. Indeed there seems to be no particular advantage in going to momentum transfers in the range 15–30 Å^{-1} since a separate contribution from the condensate probably cannot be observed. The question may only be fully resolved by going to very high momentum transfers and resolutions so that a clear peak from the condensate can be seen.

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