THERMAL PROPERTIES OF SOLID He^4

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The predicted[1] anomalous thermal properties of solid He^3, in the absence of qualitative modifications of the nuclear paramagnetism of the anomalous liquid in equilibrium with it, along the phase separation line, raised the following problem. Do the anomalous thermal properties of liquid He^4 persist also in the solid at, or near, the melting line or not? Results obtained in the study of this problem are presented here, a detailed account being reserved for a later paper.

The anomalous thermal properties of liquid He^4 occur over that area of the state surface, which projected on the pressure-temperature, (p, T), plane is enclosed by the lines $p_0(T)$, $p_m(T)$, $T_\alpha(p)_{\rm II}$, and $T_\alpha(p)_{\rm I}$. These are, respectively, the saturation and melting pressure lines, and the loci of the temperatures of vanishing isobaric volume expansion coefficients. Empirical information[2] is fairly complete on the first two, it is only fragmentary on the loci,[3] with $T_\alpha(p)_{\rm I}$ being a line in the He^4 I region, quite close to the locus of lambda points, $T_\lambda(p)$. The following relations describe the anomalous thermal properties of liquid He^4 at or near the melting line, V and S standing for its volume and entropy:

$$\alpha_p(p_m)=[V(p_m)]^{-1}(\partial V/\partial T)_p\leq 0;\quad [\partial S(p_m)/\partial p]_T\geq 0;$$
$$(\partial T/\partial p)_S\leq 0;\quad T_\alpha(p_m)_{\rm II}\leq T\leq T_\alpha(p_m)_{\rm I}. \tag{1}$$

We have to invoke now the experimental rule, of thermodynamic character,

$$\alpha_{p,l}(p_m)\geq\alpha_{p,s}(p_m), \tag{2}$$

which states that, in normal substances, the isobaric volume expansion coefficent $\alpha_{p,l}$ of the liquid, in equilibrium with the solid along the $p_m(T)$ line, is larger than, or at least equal to, that of the solid, $\alpha_{p,s}$. If the liquid is anomalous, as described by (1), one proves that (2) must be generalized to

$$|\alpha_{p,l}(p_m)|\geq|\alpha_{p,s}(p_m)|. \tag{3}$$

One also proves that equalities in (2) and (3) are allowed only at isolated p_m values, where the α_p's vanish. In the He isotopes, this occurs, by the Nernst theorem, at the absolute zero. Relations (1) and (3) lead unambiguously to two possible thermal behaviors of solid He^4:

I. In this case of least anomaly, the solid has normal thermal properties with the exception of the isolated states $T_\alpha(p_m)_{\rm II}$ and $T_\alpha(p_m)_{\rm I}$, where $\alpha_{p,s}(p_m)$ vanishes. This property must have at least one maximum below $T_\alpha(p_m)_{\rm II}$ and one between it and $T_\alpha(p_m)_{\rm I}$. The solid entropy $S_s(p)$ must have pressure maxima at the zeros of $\alpha_{p,s}$.

II. Alternatively, solid He^4 along or near $p_m(T)$ must be completely anomalous, with the set of properties (1), with zeros of $\alpha_{p,s}$ at $T_\alpha(p_m)_{\rm II}$ and $T_\alpha(p_m)_{\rm I}$.

Analysis of experimental data available to date[2] on liquid and solid He^4, along $p_m(T)$, at $T\gtrsim 1.1-1.2°K$, yields, through the rigorous formula,

$$\alpha_{p,s}(p_m)=[V_s(p_m)]^{-1}(dV_s/dT)+\kappa_{T,s}(p_m)(dp_m/dT), \tag{4}$$

$\kappa_{T,s}$ being the isothermal compressibility, negative $\alpha_{p,s}$ values below about 1.50 - 1.55°K. Only upper limits of $\alpha_{p,s}(p_m)$ could, however, be obtained because only approximate upper limits of $\kappa_{T,s}$ were available. The actual intermediate zero of $\alpha_{p,s}(p_m)$, if below $T_\alpha(p_m)_{\rm I}$, must be higher than 1.55°K. Accordingly, solid He^4 is completely anomalous over, at least, a limited range of the interval $[T_\alpha(p_m)_{\rm I}-T_\alpha(p_m)_{\rm II}]$ and, probably, over a pressure range above $p_m(T)$.

These results lend support to the idea developed[1] in connection with He^3, and verified experimentally,[4] that quantum effects, together with the pertinent statistics,[5] responsible for the thermal anomalies of the liquid isotopes, persist over limited regions of the solid phases of the He isotopes. The role played by the "normal" fluid in the solidification clearly emerges in these studies. The existence of a shallow minimum of $p_m(T)$, at $T\lesssim T_\alpha(p_m)_{\rm II}$ (~1.0°K) is predicted if the dominant thermal excitations of the solid are phonons at low temperatures.

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REGULARITIES OF (d, α) REACTIONS IN HEAVY ELEMENTS*

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We are presenting the preliminary results of a survey of (d, α) reactions in heavy elements with an incident deuteron energy of 15 Mev. A proportional counter-scintillator telescope was used in conjunction with a 256-channel analyzer to obtain energy distributions with a precision of 0.3 Mev and resolution varying between 4 and 8 %.

The resulting energy distribution of alphas emitted at 90° (Fig. 1) shows two strong groups which vary regularly with atomic number. Data taken at 120°, 60°, and 30° indicate similar structure; although relative intensities change, the peaks show little or no energy shift with angle. The differential cross section at 90° falls off rapidly by a factor of 30 between $_{29}$Cu and $_{52}$Te. This decrease is associated with the rapid disappearance of the low-energy group around $Z = 50$. At this point the distribution consists predominantly of the high-energy peak which has a relatively constant cross section (~0.25 mb/sr) for increasing atomic weight. Positions of both high- and low-energy groups have been compared with known ground-state transition energies in Fig. 2. From this plot it is evident, from the separation of the ground states and the experimentally determined high-energy peaks, that the ground states are weakly excited for all nuclei investigated. In addition, there seems to exist no correlation between the ground states and the high-energy peaks. This rules out the possibility that the peaks are due to the excitation of collective states, as the latter occur at excitation energies which vary slowly with mass number.

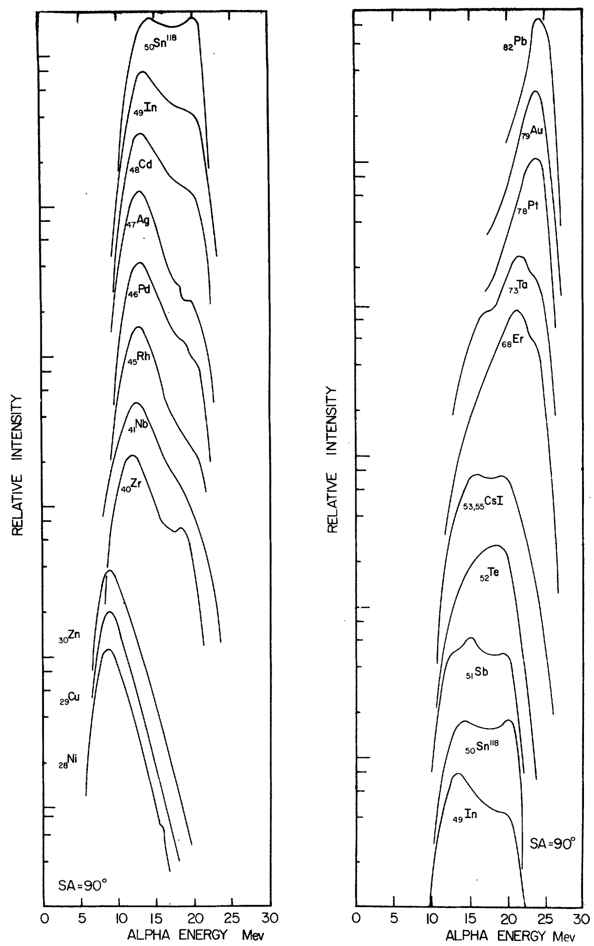

FIG. 1. Energy distributions for alpha particles emitted at 90°.

An outstanding feature of the high-energy group is the slow regular variation of peak energy with atomic number. This effect is most apparent in the transition region from $_{45}$Rh to $_{50}$Sn, where the peak shifts by less than 0.5 Mev. Supplementary data taken on the seven most abundant isotopes of Sn also show the high-energy peak in the same position.

Variations in the energy distributions as a function of scattering angle are shown for $_{79}$Au,