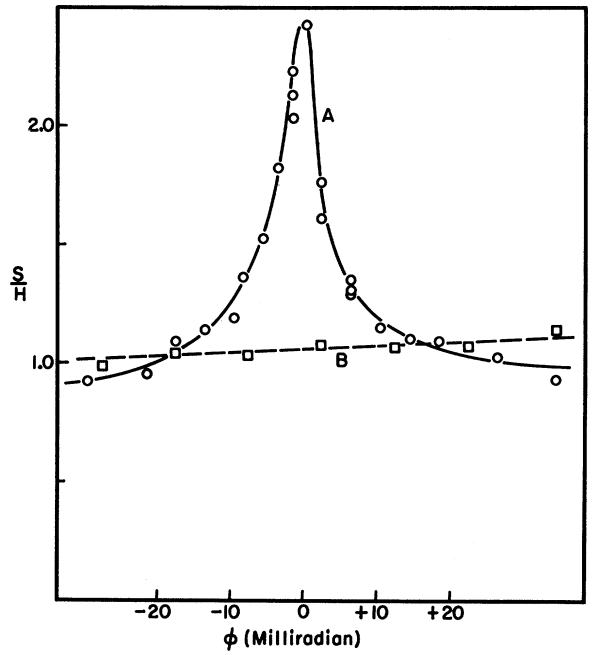

FIG. 1. The relative change measured in the ratio of soft quanta to hard quanta (S/H) as the crystal was turned through ϕ with $\psi \simeq 0$ (curve A) and $\psi \simeq 20$ milliradians (curve B).

axis (both normal to the electron beam) by angles ϕ and ψ, respectively. Usually a change in either ϕ or ψ caused only a small gradual change (Fig. 1, curve B) in S/H, due perhaps to the changed aspect of the crystal as seen by the beam. But for one particular combination of ϕ and ψ S/H is about doubled (curve A). The half-width of the effect is about 0.3°, both for ϕ and ψ. If we assume that the change in S/H is chiefly caused by the enhancement of radiation around 100 Mev, we find $A = 4 \times 10^{-7}$ cm and $\Delta\phi = 4$ mrad in reasonable agreement with the observed width.

There seems little doubt that the enhancement we find is the Überall effect even though it is much smaller than $A/a \simeq 10$. It would have been desirable to verify the polarization, but our work had to be stopped at this point. We can offer no explanation for the negative result of Panofsky and Saxena[4]; compared to their arrangement, the strong collimation we used and the fact that our counter S was sensitive down to low x-ray energies would both tend to increase the coherence effect.

We wish to thank E. Belmont of the Red Bank, New Jersey, Division of Bendix Aviation Corporation for supplying us with germanium crystals and Dr. R. R. Addiss and Mr. R. L. Schwoebel for orienting them by taking Laue photographs. One of us (O.R.F.) is most grateful to Professor R. R. Wilson for the hospitality extended to him at the Newman Laboratory of Nuclear Studies during his sabbatic leave from the University of Cambridge, Cambridge, England.

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DE-EXCITATION OF μ-MESONIC ATOMS

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Experiments by Stearns and Stearns[1] have shown that during the de-excitation of a μ-mesonic atom, as the μ seeks its ground state, some nonradiative process competes much more favorably with radiative transitions than does the usual Auger process.[2] It has been suggested[3] that collisions with neighboring atoms could cause the μ meson to fall from the $2p$ to the $1s$ level, with the released energy used to eject an electron from the colliding atom. The size of this effect was found to be too small to explain Stearns' data.[4]

The subject of this Letter is the possibility of collisional de-excitation of the radiating $2p$ mesonic atom level to the metastable $2s$ level, whose radiative lifetime is long enough to permit Auger

Table I. Splitting of the $2p_{1/2}$ and $2s_{1/2}$ levels in μ-mesonic atoms, arising from vacuum polarization and finite nuclear size. For low Z the $2s$ level lies below the $2p$ level in energy.

Atom:	H^1	He^4	Li^7	Be^9	B^{11}	C^{12}	O^{16}
$(E_{2p_{1/2}} - E_{2s_{1/2}})$ in ev	0.21	1.5	3.0	4.6	1.5	-7	-60

or other nonradiative decay from the $n=2$ to the ground $n=1$ state. Table I summarizes the μ-mesonic $2s-2p$ splittings in the elements $Z \leq 8$, based on the calculations of Foldy and Eriksen,[5] but corrected for newer values of nuclear radii.[6] The cross-over of the $2p$ and $2s$ levels at $Z \cong 5$ results from the different Z dependence of the vacuum polarization and nuclear size effects. Thus, since the $2p-2s$ splittings typically are larger than thermal energies, for $Z>5$ collisions are almost always energetically incapable of raising the $2p$ level to the $2s$; for $Z \leq 5$, on the other hand, collisions can de-excite the $2p$ to the $2s$, but a mesonic atom in the $2s$ state only very infrequently is raised back to the $2p$. It is provocative that the deficiency in K-series x-rays is observed in precisely those elements $Z \leq 5$ in which the $2s$ level lies below the $2p$ (compare Table I with Fig. 7 of Stearns and Stearns[1]).

Because the $2p-2s$ energy change ΔE is so much smaller, and because the proton and μ-meson masses are more nearly matched then the μ-meson and electron masses, collisional $2p-2s$ de-excitation with the colliding atom carrying off kinetic energy ΔE is much more probable than the $2p-1s$ mechanism previously considered,[3] wherein the electron had to carry off the much larger energy release. For instance in hydrogen, for a collision between a μ-mesonic atom and a proton, the $2p-2s$ de-excitation cross section in Born approximation is

$$\sigma_{\text{Born}} = \frac{18\pi^3 e^4}{\hbar^2 v_0}\left(\frac{M}{\Delta E}\right)^{1/2} a_\mu^{\,2},$$

which, with $\Delta E = 0.2$ ev, $a_\mu = a_0/200$, and incident velocity[3] $v_0 \cong 10^6$ cm/sec, is about $500\pi a_0^{\,2}$, many orders of magnitude larger than the Born estimate[4] for $2p-1s$ de-excitation.

To explain the Stearns' K-series data, the de-excitation cross section would not have to be larger than about $10\pi a_0^{\,2}$. Unfortunately Born approximation is unreliable and gives a large overestimate at these low energies, especially when ΔE is so small. A better estimate is $\sigma \cong \frac{1}{2}\pi b^2$, where b is the largest impact parameter for which the collision is nonadiabatic, i.e., for which $\omega^{-1}[dM(t)/dt] > \Delta E = \hbar\omega$ where

$$M(t) = \langle \psi_{2s}(r_\mu) \left| \frac{e^2}{|\vec{r}_\mu - \vec{R}|} \right| \psi_{2p}(r_\mu) \rangle$$

and $R(t)$ is the position of the colliding proton. For μ-hydrogen, which can easily penetrate neighboring atoms because its total charge is zero, this criterion leads to the result

$$\sigma = \tfrac{1}{2}\pi \left[\frac{3e^2 a_\mu \hbar v_0}{(\Delta E)^2}\right]^{2/3},$$

which is about $\pi a_0^{\,2}$. In mesonic atoms of higher Z the $2p-2s$ collision de-excitation cross section will be even smaller since the now non-neutral mesonic atom no longer can penetrate neighboring atoms.

The foregoing observations justify the following conclusions: (*i*) In light elements, $Z \leq 5$, $2p-2s$ collisional de-excitation probably is not rapid enough to explain Stearns and Stearns[1] K-series data, but is not negligible compared to radiative or (usual estimates of) Auger transition rates, and assuredly is much more rapid than any collisional de-excitation process between levels of different principal quantum number. (*ii*) Collisional excitation and de-excitation between levels of the same principal quantum number n is even more probable in higher shells $n \geq 3$, where ΔE is much smaller. There are no metastable levels in these shells, but the collisions will tend to statistically distribute the μ meson among levels of the same n, thereby modifying previous estimates[2] of the transition rates from $n \geq 3$ and of the percentages of μ-mesonic atoms ultimately reaching the $2p$ and $2s$ states. (*iii*) The effect (*ii*), and the effect (*i*) if large enough, will depend on the immediate environment of the μ-mesonic atoms. Thus in the light elements, where the radiative rates do not dominate collisional and Auger de-excitation rates, the radiative yields using chemical compounds should differ from the yields in pure elements, due account being taken of the possibility of meson charge transfer.

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ERRATA

THEORY OF SOLID He^3. Newton Bernardes and Henry Primakoff [Phys. Rev. Letters 2, 290 (1958)].

This Letter presented a theory of the properties of solid He^3 on the basis of a Heitler-London model of a solid. Our calculations indicated that (1) solid He^3 should behave as a nuclear antiferromagnet with a paramagnetic Curie temperature $T_C \cong 0.3°K$ at $p \cong 30$ atmos, and (2) the melting curve of He^3 should have a minimum near 0.35°K and a maximum below 0.1°K.

Our calculations have been revised and a numerical mistake was discovered. As a consequence we now find a value $T_C \cong 0.1°K$ for the Curie temperature at $p \cong 30$ atmos which is in better agreement with the experimental results of Fairbank and Walters.[1] In order to obtain a revised melting curve in a self-consistent way we recalculated the entropy of the solid using the value $T_C = 0.1°K$. The change in volume, $V_{liq} - V_{sol}$, was again taken equal to 1 cm^3/mole and independent of temperature. The entropy of the liquid was obtained by extrapolating the experimental values of Brewer and Daunt[2] to appropriate pressures. In a first approximation we used values of the entropy of the liquid extrapolated to 30 atmos, and a melting curve was obtained in first approximation by using the equation of Clapeyron, and taking $p = 29.3$ atmos as the melting pressure at $T = 0.37°K$ (the temperature where our theoretical curve for the entropy of the solid crosses the extrapolated experimental curve[2] for the entropy of the liquid). A second approximation for the melting curve was obtained by using, in the Clapeyron equation, extrapolated values of the entropy of the liquid corresponding to the melting pressure as given by our results in first approximation; on the other hand, we neglected the variation of the entropy of the solid with varying melting pressure. The resulting melting curve was found to lie lower than the one obtained in first approximation, and much lower than the melting curve obtained on basis of the assumption made by Pomeranchuk,[3] i.e., that spin alignment in the solid only occurs below 10^{-7} °K.

Our results for the melting curve are shown in Fig. 1 together with smoothed experimental values of Baum, Brewer, Daunt, and Edwards[4] who, avoiding the usual blocked capillary method, succeeded for the first time in observing the melting curve of He^3 below the temperature of the minimum.

Experiments at lower temperatures would be of great interest since a further distinction be-

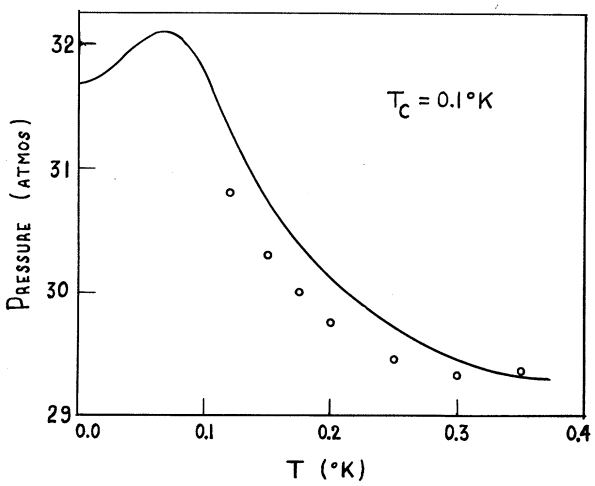

FIG. 1. Melting curve of He^3: solid line calculated as described in the text; the circles correspond to experimental points.[4]