coefficients of absorption in large fields apparently describes the anisotropy of electric conductivity in a magnetic field.

[1] H. E. Bömmel, Phys. Rev. **100**, 758 (1955).
[2] H. E. Bömmel, Proc. Fifth International Conference on Low Temperature Physics and Chemistry, Madison, Wis., Aug. 26-31 (1957).
[3] Morse, Bohm, and Gavenda, Phys. Rev. **109**, 1394 (1958).
[4] R. W. Morse and H. V. Bohm. Proc. Fifth International Conference on Low Temperature Physics and Chemistry, Madison, Wis., August 26-31, 1957.
[5] S. Ya. Sokolov, Usp. Fiz. Nauk **40**, 3 (1950).
[6] A. B. Pippard, Phil. Mag. **2**, 1147 (1957).

Translated by J. G. Adashko
245

RANGES OF MU-MESIC ATOMS IN HYDROGEN CHAMBERS

S. S. GERSHTEĬN

Leningrad Physico-Technical Institute, Academy of Science, U.S.S.R.

Submitted to JETP editor December 15, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 1309-1311 (April, 1959)

IN the experiments of Alvarez et al.,[1] who observed nuclear reactions catalyzed by μ^- mesons in a hydrogen chamber, the origin of the track of a μ^- meson that had carried off energy from a nuclear reaction was often separated from the point at which the μ^- meson was stopped by a "fissure" on the order of 1 mm in size. The same kind of fissure not infrequently separates the point at which the μ^- meson was stopped from the beginning of the track of the electron generated in the μ^- meson decay. Alvarez et al.[1] attribute the appearance of the fissure to the recoil energy (of the order of $\frac{1}{3} \times 135$ ev $\simeq 45$ ev) of the mesic deuterium atom during the capture of the μ^- meson from the proton by the deuteron. They believe that this energy creates a gap equal to the fissure. This view is confirmed by the effective cross sections for $d_\mu + p$ and $d_\mu + d$ scattering computed by Cohen et al.[2] The effective $d_\mu + p$ cross section is small, and, as calculations have shown, a d_μ mesic atom with an energy of 45 ev actually does travel a distance on the order of 1 mm in hydrogen. Therefore, for a slight increase in the concentration of deuterium, the fissure is observed more often, because then a greater number of μ^- mesons are captured by the deuterons. When the deuterium concentration is increased still more (to about 4.3%[1]), the d_μ track becomes very short (on the order of a few hundredths of a millimeter) because of $d_\mu + d$ collisions (whose effective cross section are computed to be large[2]), and the fissure is not observed. (Here the essential thing is that in collisions of d_μ atoms with protons at rest the d_μ atoms are not deflected into angles exceeding 30°, while in $d_\mu - d$ scattering the angle of deflection may be as great as 90°.)

In $p_\mu - p$ scattering, transitions may occur between levels of the hyperfine structure of the mesic atom. For energies considerably exceeding that of hyperfine dissociation ($\Delta\epsilon \approx 0.183$ ev) an analytic expression can easily be provided for the $p_\mu + p \rightarrow p_\mu + p$ cross section calculated by Cohen et al.[2] The cross section for p_μ scattering by protons is

$$\sigma = 2\pi\left(\frac{1}{4}\,\frac{\lambda_g^2}{1+k^2\lambda_g^2} + \frac{3}{4}\,\frac{\lambda_u^2}{1+k^2\lambda_u^2}\right), \qquad (1)$$

where* $k^2 = (M_p\epsilon)^{1/2}/\hbar$, ϵ is the energy of the relative motion of p_μ and p in the center-of-mass system, and λ_g and λ_u are the scattering lengths of protons by the mesic molecular potentials $E_q(R)$ and $E_u(R)$, which correspond respectively to symmetric and antisymmetric wave functions (in the proton coordinates) for the 1s σ_g and the 2p σ_μ system (in the first the total spin of both protons is equal to zero and in the second, equal to 1). The potentials $E_g(R)$ and $E_u(R)$ which include a correction for the influence of μ meson motion,[4] accurate to order m_μ/M_p, can be approximated accurately by a Morse potential and an exponential.[5] The scattering lengths λ_g and λ_u are easily expressed in terms of the parameters of these functions.[6] However, the approximation given formerly by this author[6] is too rough; more exact values have been obtained for these parameters by Zel'dovich et al.[5] (in their Fig. 2 the value of α has been rounded off to 0.67 from 0.673). If the more accurate values are employed, then $\lambda_g \approx -17.3$ and $\lambda_u \approx 5.25$ (in mesic atom units). When $kR_0 < 1$, the pp_μ mesic molecular level and cross section (1) are in good agreement with the computations published by Cohen et al.[2] The rather large value for λ_g can be attributed to the presence of a virtual level near zero[6,7] in

the system. Because of this condition, cross section (1) has a resonance character for low energies.

For energies comparable to the energy $\Delta\epsilon$ of the hyperfine structure the scattering cross section varies according to which of the hyperfine states in p_μ is occupied. As was shown earlier,[6] the scattering cross section for a $F = 1 \rightarrow F = 0$ transition is very large (the transition probability for the more exact parametric values is $W \approx 5 \times 10^9$ sec^{-1}). Therefore, p_μ mesic atoms pass to the state $F = 0$ in a time $t \simeq 2 \times 10^{-10}$ sec and acquire an energy $\frac{1}{2}\Delta\epsilon \approx 0.1$ ev. The elastic scattering cross section of p_μ in the $F = 0$ state can be obtained in a way analogous to that reported earlier,[6]

$$\sigma_{el} = 2\pi \left| \frac{(\lambda_g + 3\lambda_u) + 4ik_2\lambda_u\lambda_g}{4 + ik_1(\lambda_g + 3\lambda_u) + ik_2(3\lambda_g + \lambda_u) - 4k_1k_2\lambda_u\lambda_g} \right|^2, \quad (2)$$

where $k_1 = \sqrt{M_p\epsilon}$, $k_2 = \sqrt{M_p(\epsilon - \Delta\epsilon)}$, and ϵ is the energy in the center-of-mass system. It is important to note that the value of $\lambda_g + 3\lambda_u$, which with the values of λ_g and λ_u given above determines the elastic cross section, is very small (while the value of $\lambda_g - \lambda_u$ entering into the inelastic cross section is large). Therefore, the elastic scattering cross section is very small:† for $\epsilon = 0$, $\sigma_{el} \approx 1.7 \times 10^{-22}$, and for $\epsilon = \frac{1}{4}\Delta\epsilon$, $\sigma_{el} \approx 2.2 \times 10^{-22}$ cm^2.

For $\epsilon = \frac{1}{4}\Delta\epsilon$, the inelastic cross section for the process by which pp_μ mesic molecules are formed is[5] $\sigma_{inel} = W_{pp\mu}/Nv \approx 2.4 \times 10^{-22}$ cm^2. Thus, the mean free path of a mesic atom that has passed from $F = 1$ to $F = 0$ is $\lambda \approx 1/N\sigma_{tot} \approx 0.5$ mm, i.e., a noticeable "fissure" can be observed even in pure hydrogen.

The $d_\mu + d$ cross section for energies greater than the hyperfine structure level is analogous to Eq. (1):

$$\sigma = 2\pi \left(\frac{2}{3} \frac{\lambda_g^2}{1 + k^2\lambda_g^2} + \frac{1}{3} \frac{\lambda_u^2}{1 + k^2\lambda_u^2} \right); \quad \lambda_g = 6.7; \quad \lambda_u = 5.7.$$

This cross section is two times smaller than the one obtained by Cohen et al.[2] We note that in the case of $d_\mu + d$ collisions a transition to a lower state of the d_μ ($F = \frac{1}{2}$) hyperfine structure is also possible (although the probability of this is considerably less than for the resonance transition in p_μ). This circumstance could, roughly speaking, triple the probability of $\mu^- + d \rightarrow n + n + \nu$ capture in comparison to the value computed by A. Rudik,[8] if it is assumed that the capture of a μ^- meson from the $F = \frac{3}{2}$ state is very much suppressed. However, the formation of dd_μ molecules causes the blending of the $F = \frac{1}{2}$ and $F = \frac{3}{2}$ states, and subsequent catalysis of the $d + d$ reaction would appear to make experiments for the study of the $\mu^- + d \rightarrow n + n + \nu$ reaction in deuterium impracticable.

*Assuming that $kR_0 \ll 1$ [R_0 is the interaction radius of the potentials $E_g(R)$ and $E_u(R)$].

†It should be noted that actually the cross section may be quite different from these values because of the sensitivity of the resonance value for λ_g on the exact form of the potential.

[1] Alvarez, Bradner, Crawford, et al., Phys. Rev. **105**, 1127 (1957).

[2] Cohen, Judd, and Riddel Jr., Phys. Rev. **110**, 1471 (1958).

[3] V. B. Belyaev and B. N. Zakhar'ev, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 996 (1958), Soviet Phys. JETP **8**, 699, (1959).

[4] Bates, Ledsham, and Stewart, Phil. Trans. Roy. Soc. **A246**, 215 (1953); A. Dalgarno and R. McCarrol, Proc. Roy. Soc. **237**, 383 (1956).

[5] Ya. B. Zel'dovich and S. S. Gershteĭn, J. Exptl. Theoret. Phys. (U.S.S.R.) **35**, 649 (1958), Soviet Phys. JETP **8**, 453 (1959).

[6] S. S. Gershteĭn, J. Exptl. Theoret. Phys. (U.S.S.R.) **34**, 463 (1958), Soviet Phys. JETP **7**, 318 (1958).

[7] Ya. B. Zel'dovich, Dokl. Akad. Nauk SSSR **95**, 493 (1954).

[8] A. Rudik, Dokl. Akad. Nauk SSSR **92**, 739 (1953).

Translated by A. Skumanich
246

FLUCTUATIONS OF ATOMIC STRUCTURE IN LIQUID HELIUM

V. K. PROKHORENKO and I. Z. FISHER

Belorussian State University

Submitted to JETP editor December 18, 1958

J. Exptl. Theoret. Phys. (U.S.S.R.) **36**, 1311-1312 (April, 1959)

A detailed investigation of the atomic structure of liquid helium was carried out[1] by studying the scattering of slow neutrons. It was found that the packing of the atoms is quite dense, with an average coordination number of approximately eight units. However, the average distance between nearest atoms exceeded considerably the distance to the minimum on the curve of potential energy