of the stability criterion for a liquid of S. V. Tiablikov, which statement was based on a misunderstanding of what was contained in reference 3.

The author thanks N. N. Bogoliubov and S. V. Tiablikov for their discussion of the question and for pointing out the error.

[1] I. Fisher, J. Exper. Theoret. Phys. USSR 28, 171 (1955); Soviet Phys. JETP 1, 171 (1955)

[2] S. Tiablikov, J. Exper. Theoret. Phys. USSR 17, 386 (1947)

[3] I. Fisher, J. Exper. Theoret. Phys. USSR 28, 437 (1955); Soviet Phys. JETP 1, 273 (1955)

[4] I. Fisher, J. Exper. Theoret. Phys. USSR 28, 447 (1955); Soviet Phys. 1, 289 (1955)

Translated by R. T. Beyer
294

Capture of Thermal Neutrons by Isotopes of Lead

A. V. SHUT'KO AND D. F. ZARETSKII

(Submitted to JETP editor August 31, 1955)
J. Exper. Theoret. Phys. USSR 29, 866-868
(December, 1955)

1. CHARACTERISTIC of the capture of thermal neutrons by a natural mixture of lead isotopes is a gamma-ray spectrum consisting of only two lines[1]. The gamma quanta appear as quanta of the electric dipole type, the energies (E_{γ_1} = 7.380 ± 0.008 mev and E_{γ_2} = 6.734 ± 0.008 mev) being equal to the binding energies of a neutron in Pb^{208} and Pb^{207}, respectively. This simplicity of the spectrum represents the exception among the spectra of heavy elements and is associated with the "magic" attribute of Pb^{208}. An analysis of levels Pb^{208} and Pb^{207} shows that the simplicity of the spectrum can be explained if one assumes that an intermediate nucleus is not created during the capture, but that the process consists of an immediate transition of a neutron from a continuous spectrum into bound states. This same mechanism also specifies the correct magnitude of the cross section for capture of thermal neutrons by lead.

2. Having investigated gamma rays accompanied by beta decay of Tl^{208}, Elliott[2] et al obtained the energy level scheme of Pb^{208} (Fig. 1), from which it is seen that for capture of thermal neutrons by Pb^{207} transitions to excited levels of Pb^{208} are possible for only a high multipolarity. It is necessary to note also that these levels apparently correspond to an excited proton since: 1, spins and parity, shown in Fig. 1, can be obtained from the shell model, assuming that a proton from the filled shell (82 protons) is shifted to the succeeding unfilled shell; 2, lower levels (E = 2.6 mev and E = 3.2 mev) are not excited in the reaction Pb^{207} (dp) Pb^{208}* (energy of deuteron is 14 mev[3]); 3, these levels arise from beta decay of Tl^{208}, i.e., it can be assumed that radiation results from the transition of a proton from its excited state, arising from the conversion of a neutron into a proton, to its low-lying state.

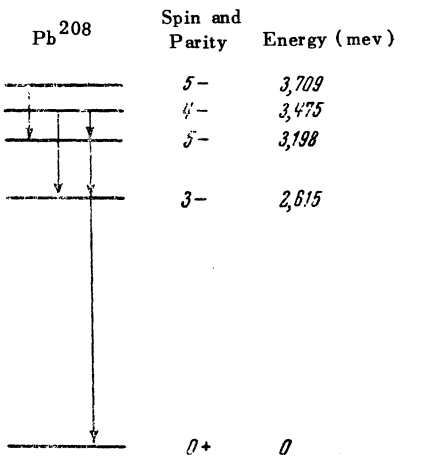

Fig. 1

The first two levels excited in the reaction[3] Pb^{207} (dp) Pb^{208}* have energies respectively equal to 3.37 mev and 3.60 mev. It is assumed that these levels have spins of 4 and 5, and parity opposite to the parity of the ground state of Pb^{208} (spins and parities of levels in (dp) experiments have been identified in accordance with the shell model). The next levels lie near the energy 5-6 mev. Thus it is seen that electric dipole capture must dominate for the ground state of Pb^{208}.

Let us consider Pb^{207}. The scheme of low-lying energy levels of odd nuclei can be divided into three classes[4]: "consecutive" system of levels, "hole" system and mixed system. The excitation of "consecutive" and "hole" levels in nuclei corresponds to the excitation of optical and x-ray terms in an atom. Now one can count it as an established fact[4] that the lower excited levels of Pb^{207} appear "hole like" (Fig. 2). As the figure shows, the spins and parities allow electric dipole transitions to the ground state $p_{1/2}$, and also to the excited state $p_{3/2}$ (E_{level} = 0.870 mev). If one assumes that the shell model holds for higher levels, then their spins and parities exclude dipole transitions.

Transitions between levels of a continuous spectrum, which evidently have the appearance of "consecutive", and the "hole" level $p_{3/2}$ appear forbidden compared with the transitions to level $p_{1/2}$, since the "cross-over" transitions appear particle-like. From the point of view of the intermediate nucleus, which we ordinarily understand as many-particle excitation, transitions to levels $p_{3/2}$ and $p_{1/2}$ are equally proper, and the absence of a transition to the $p_{3/2}$ level is difficult to explain.

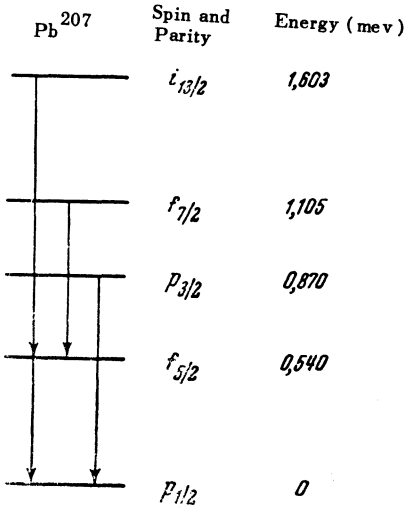

Fig. 2

3. Let us evaluate the magnitude of the cross section for capture of thermal neutrons by Pb^{207}. Taking into account the preceding, we assume that during capture only a single neutron, which is moving in a field described by a certain effective potential, $U(r)$, changes state. The total cross section of the electric dipole capture is equal to

$$\sigma_c = \frac{16\pi\,\mu\omega^3}{9h^2k_nc^4}\,Q_{10}^2, \tag{1}$$

$$Q_{10} = -\frac{Ze}{A}\sqrt{\frac{3}{4\pi}}\int \varphi_b^*(\mathbf{r})\, z\, \varphi_a(\mathbf{r})\, d\mathbf{r},$$

where φ_a and φ_b are the wave functions of the neutron in the initial and final states, k_n is the wave number of the incident neutron. Assuming that the potential changes sharply enough on the surface of the nucleus, we obtain (see, for example, reference 5)

$$Q_{10} \approx -(ZeU_0R^2/A\mu\cdot\omega^2)\,L_{k_n0}(R)\,R_{E1}(R), \tag{2}$$

where U_0 is the magnitude of the effective potential inside the nucleus; $L_{k_n0}(r)$ and $R_{E1}(r)$ are the radial wave functions corresponding to the incident (l=0) and the bound neutron (l=0). In the limit where $k_n \to 0$ the value of the wave function $L_{k_n0}(R)$ is expressed in terms of the scattering amplitude and radius of the nucleus:

$$\lim_{k_n\to 0} L_{k_n0}(R) = (R-a)/R, \tag{3}$$

where a is the experimentally determined scattering amplitude of thermal neutrons in Pb^{207}. In addition if $(2\mu E/h)^{1/2}R \gg 1$ and $U_0^{1/2} \gg E^{1/2}$ (E is the order of magnitude of the binding energy of neutrons in Pb^{208}), one can find that

$$R_{E1}(R) \approx R^{-3/2}. \tag{4}$$

From Eqs. (1)-(4) it follows

$$\sigma_c = \frac{32\pi}{9}\left(\frac{Z}{A}\right)^2\frac{e^2}{hc}\,\frac{(R-a)^2}{k_nR}\,\frac{U_0^2}{\mu c^2E}. \tag{5}$$

For $U_0 = 42$ mev, $R = 7.8\times10^{-13}$ cm, $a = 9.6\times10^{-13}$ cm,[6] the incident energy of thermal neutron $E_n = 0.025$ ev, and $E = 7$ mev, we obtain $\sigma_c \approx 0.42$ barn, which agrees with the experimentally determined value of 0.7 barn. Above we compared the theoretical evaluation of the cross section with data on the capture of thermal neutrons by Pb^{207}. Experiments[7] show that the cross section for capture of neutrons by Pb^{206} is within an order smaller than the cross section for capture by heavier isotopes. This diminution can be attributed to the fact that capture of neutrons by Pb^{206} is accompanied by a certain deformation of the self-consistent field, but in the case of Pb^{207} this deformation has practically no significance. One can say that capture by Pb^{206} appears less "single-particle-like" than in the case of Pb^{207}. Thus, the anomalous character of the capture radiation in isotopes of lead apparently is explained if it originates from a single-particle picture of capture. Obviously, such a consideration under no circumstances is applicable to heavy nuclei which are far from closed shells. These nuclei have great density of levels for the intermediate nucleus, and thus single-particle capture cannot compete with collective capture.

The authors thank Prof. A. S. Davydov for his discussion as well as B. F. Turchin for his valuable comments.

[1] B. B. Kinsey, G. A. Bartholomew, and W. H. Walker, Phys Rev. 82, 380 (1951).

[2] L. G. Elliott, R. L. Graham, J. Walker, and J. L. Wolfson, Phys. Rev. 93, 356 (1954).

[3] J. A. Harvey, Canad. J. Phys. 31, 278 (1953).

[4] L. K. Peker and L. A. Sliv, Izv. Akad SSSR, Ser. Fiz. 17, 411 (1953).

[5] E. D. Courant, Phys. Rev. 82, 703 (1951).

[6] C. G. Shull and E. O. Wollan, Phys. Rev. 81, 527 (1951).

[7] H. Pomerance, Phys. Rev. 88, 412 (1952).

Translated by B. G. Saunders
284

Crystalline Anisotropy of the Intermediate State

IU. V. SHARVIN AND V. L. SEDOV
Institute of Physical Problems, Academy of Sciences, USSR

(Submitted to JETP editor July 18, 1955)
J. Exper. Theoret. Phys. USSR **29**, 897 (December, 1955)

WE have undertaken experiments on the investigation of the moments of forces which act through the agency of a magnetic field on a monocrystalline sphere of lead of high purity (99.998%), placed in the intermediate state. The specimen was mounted on a torsion suspension so that the [010] axis could be vertical and was placed (at a temperature of 3.65 °K) in a magnetic field whose direction could be changed in the horizontal plane. In addition, we superimposed a small (1-2 oersteds) magnetic field, which changed its sign with a period of 30 sec. Under these conditions we could observe the moments, which evidently have a reversible equilibrium character, and which arise as a consequence of the dependence of the surface tension at the boundary of the superconducting and normal phases on the orientation of this boundary with respect to the lattice. The great scatter of the results of various experiments, which is connected with the imperfections of the lattice of the specimens, does not permit a completely reliable quantitative check. However, qualitatively speaking, the two samples that we investigated gave results in agreement, namely, that the free energy of the specimen, as a function of the angle between the field and the tetragonal axis has maxima in the [100] and [001] directions. The intermediate minimum is located approximately at an angle of 25-35° with respect to the tetragonal axis. The height of the maxima for our samples (diameter 12.6 mm, 50% superconducting phase) was of the order of 10^{-3} erg. These results are evidently in qualitative agreement with the anisotropies of the penetration depth found by Pippard [1].

We express our thanks to A. I. Shal'nikov for his interest in this work.

[1] A. B. Pippard, Proc. Roy. Soc. (London) **203**, 195 (1950).

Translated by R. T. Beyer
303

Heat of Vaporization of Oxygen in the Temperature Range 80-106°K

R. A. ALIKHANOV
Institute of Physical Problems, Academy of Sciences, USSR

(Submitted to JETP editor July 21, 1955)
J. Exper. Theoret. Phys. USSR **29**, 902-903 (December, 1955)

UP to the present time the heats of vaporization of condensable gases as a function of temperature have been little studied, although they are of both practical and theoretical interest. The basic theoretical methods of calculating heats of vaporization require the knowledge of a great number of other quantities. Experimental determinations have been few and insufficiently reliable.

We have undertaken to investigate the heat of vaporization of oxygen from 80° to 106°K by a precision method which we have developed, carried out as follows. A calorimeter contains an evaporator filled with the liquid, and a measured amount of power is applied. The vapor which forms is collected by condensation in a light tank and weighed at room temperature on an analytical balance. During the weighing period the evaporation process goes on in another similar flask.

The apparatus which has been constructed for this purpose includes:

(1) a vacuum adiabatic calorimeter, similar to the one described previously [1], with a number of changes and improvements;

(2) a system of two capillaries leading out of the calorimeter; one is used during filling and evaporation, and the other is connected to a mercury manometer;

(3) a gas system consisting of two thin-walled stainless steel tanks, closed by vents of original construction, a Bourdon manometer, and operating valves used during the period of evaporation.

Thirty-five measurements were made of the heat of evaporation at seven different temperatures. The