The results of this integration are shown in Fig. 2. At $\varepsilon \ll 1$ the amplitude has an exponential growth in accord with the linear theory ($\varepsilon \sim \exp(0.683\tau)$). When $\varepsilon \sim 1$, amplitude oscillations are produced by the capture of the beam in the potential well of the wave. In this case there is no noticeable damping of the oscillations as a result of phase "mixing" of the captured particles. The energy of the wave excited by the monoenergetic beam is quite appreciable

$$\frac{E^2}{4\pi} = \varepsilon^2 n_1 m v_0^2 \left(\frac{n_1}{n_0}\right)^{1/3} \tag{11}$$

where $\varepsilon$ ranges from 1.5 to 0.5.

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[1] R.Mazitov, Prikl. Mat. Teor. Fiz. No. 1, 25 (1965).
[2] Th. O'Neil. Phys. Fluids 8, 2255 (1965).
[3] A.V. Gurevich, Zh. Eksp. Teor. Fiz. 54, 522 (1968) [Sov. Phys.-JETP 27, 282 (1968)].
[4] V.D. Shapiro and V.I. Shevchenko, Ukr. Fiz. zh. 13, 1989 (1968).

## ENERGY SPECTRA OF PARTICLES OBSERVED IN REACTIONS PROCEEDING VIA A COMPOUND NUCLEUS

B.A. Rumyantsev
Nuclear Physics Institute, USSR Academy of Sciences, Siberian Division
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The energy distribution of the nucleons emitted by a compound nucleus is satisfactorily described by the Maxwellian distribution $\sigma(E_f) \sim \exp(-E_f/T)$, with a temperature $T \sim 0.5 - 2.0$ MeV [1]. The only exception is the hard part of the spectrum with energy $E_f \lesssim E_i$ ($E_i$ is the energy of the incident particle), where $\sigma(E_f)$ is a nonmonotonic function [2]. We consider here an effect that makes it possible to explain qualitatively the difference between the observed spectrum and the evaporation spectrum.

It is easy to verify that a compound nucleus is a normal Fermi system, since the temperature of the phase transition from the superfluid state into the normal state, $T_e \simeq 0.57\Delta$ ($2\Delta$ is the energy gap and is of the order of 0.5 - 1.5 MeV in even-even nuclei), is as a rule smaller than T. If the particle leaves the nucleus with a velocity $v \gg R\Delta$ (i.e., within times much shorter than the pairing relaxation time $\sim 1/\Delta$), then the ensuing cooling of the nucleus can be regarded as instantaneous. The normal state $|i\rangle$ that is produced thereby is metastable with a width $\Gamma = \Delta$, and represents a superposition of the ground and excited states of the superfluid nucleus $|f\rangle$[1)].

1) We note that the competing process, i.e., the emission of a nucleon from a superfluid nucleus, is less probable in our case, since the normal state lies higher in energy: $\delta E = E_N - E_S = (\rho\Delta)(\Delta/2) > 0$ ($\rho$ is the density of the single-particle levels at the Fermi boundary) and $\exp[-(E_f - E_N)/T] > \exp[-(E_f - E_S)/T]$.

In the sudden-perturbation approximation, it is easy to calculate the populations of the different states of the superfluid nucleus

$$w_{i\to f} = |\langle f|i\rangle|^2. \tag{1}$$

The energy difference $\delta E$ between the normal and superfluid phases is of the order of several MeV. Therefore, being interested in the inelastic spectrum in the region $E_i - \delta E < E_f < E_i$, we can assume approximately that the metastable state $|i\rangle$ is described by the wave function of the ground state of the Fermi gas, i.e.,

$$|i\rangle = \prod_{\nu=1}^{N/2} (\mathring{u}_\nu + \mathring{v}_\nu a_\nu^+ a_{\tilde{\nu}}^+)|0\rangle, \tag{2}$$

where

$$\mathring{u}_\nu = \theta(\epsilon_\nu - \epsilon_F); \quad \mathring{v}_\nu = \theta(\epsilon_F - \epsilon_\nu), \quad a_\nu|0\rangle = 0,$$

and $\nu$ and $\tilde{\nu}$ are states conjugate in time[2].

We shall describe the superfluid nucleus in the ground state $|0)$ by means of the wave function

$$|0) = \prod_\nu (u_\nu + v_\nu a_\nu^+ a_{\tilde{\nu}}^+)|0\rangle, \tag{3}$$

where

$$2u_\nu v_\nu = \Delta/E_\nu; \quad u_\nu^2 - v_\nu^2 = \epsilon_\nu/E_\nu; \quad E_\nu = \sqrt{\epsilon_\nu^2 + \Delta^2},$$

and the energy $\varepsilon_\nu$ of the single-particle levels is reckoned from the Fermi boundary $\varepsilon_F$ (the difference between the values of $\varepsilon_F$ in the superfluid and normal nuclei is neglected). For the two-quasiparticle and phonon excited states $|\lambda\lambda')$ and $|\omega)$ we have, respectively

$$|\lambda\lambda') = \alpha_\lambda^+ \alpha_{\lambda'}^+|0),$$
$$|\omega) = \sum_{\lambda\lambda'} A_{\lambda\lambda'} \alpha_\lambda^+ \alpha_{\lambda'}^+|0). \tag{4}$$

Here $A_{\lambda\lambda'}$ are the coefficients of expansion of the phonon operator in terms of the two-quasiparticle operators in the Tamm-Dancoff approximation ($\alpha_\lambda|0) = 0$).

Using (2), (3), and (4) we can easily find the probabilities of the transitions to different states of the superfluid nucleus

$$w_{i\to 0} = \prod_\nu (u_\nu \mathring{u}_\nu + v_\nu \mathring{v}_\nu)^2 = \Big(\prod_{\nu>\nu_F} u_\nu^2\Big)\Big(\prod_{\nu<\nu_F} v_\nu^2\Big), \tag{5a}$$

$$w_{i\to\lambda\lambda} = w_{i\to 0}\left(\frac{\mathring{u}_\lambda v_\lambda - \mathring{v}_\lambda u_\lambda}{\mathring{u}_\lambda u_\lambda + \mathring{v}_\lambda v_\lambda}\right)^2, \tag{5b}$$

$$w_{i\to\omega} = w_{i\to 0}\left(\sum_\lambda A_{\lambda\lambda} \frac{\mathring{u}_\lambda v_\lambda - \mathring{v}_\lambda u_\lambda}{\mathring{u}_\lambda u_\lambda + v_\lambda v_\lambda}\right)^2. \tag{5c}$$

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[2] For simplicity, we consider here only even-even nuclei with $I^\pi = 0^+$.

Changing from summation over $\nu$ in $\ln w_{i\to 0}$ to integration with respect to the energy $\varepsilon_\nu$, we readily get the estimate

$$w_{i\to 0} \approx \exp[-\rho\Delta(\pi - 2)]. \qquad (6)$$

It is seen from (5c) that the phonon transition probability contains the factor $\overset{\circ}{u}_\lambda v_\lambda - \overset{\circ}{v}_\lambda u_\lambda$, which is odd with respect to the Fermi boundary. Therefore $w_{i\to\omega}$ will be very small if the coefficients $A_{\lambda\lambda}$ do not contain an analogous factor. Out of all the known vibrational excitations, this property is possessed only by the coefficients $A_{\lambda\lambda}$ of the pair-oscillation phonon [3]. Estimates show that in this case $w_{i\to\omega}$ is of the order of the transition to the ground state (5a).

Thus, it follows from our results that the energy spectrum of the particles emitted by a compound nucleus should have a maximum in the region $E_f \sim E_i - (\rho\Delta/2)\Delta$, with a width $\Gamma \sim \Delta$. The "fine structure" of this resonance is described by formulas (5). The experimental data are in qualitative agreement with these predictions. However, the quantitative comparison with experiments requires a clear-cut separation of the contribution of the direct processes, and more detailed assumptions concerning the form of the wave function of the intermediate state $|i\rangle$.

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[1] I.H. Towle and R.O. Owens. Nucl. Phys. A100, 257 (1967); K. Tsukada and T.I. Lee. Nucl. Phys. 83, 274 (1966).
[2] E.R. Flynn and L. Rosen. Phys. Rev. 153 1228 (1967).
[3] D.R. Bes and R.A. Borglia. Nucl. Phys. 80, 289 (1966).

## SELF-SIMILAR THERMAL WAVE IN A TWO-TEMPERATURE PLASMA HEATED BY A LASER PULSE

S.I. Anisimov
L.D. Landau Institute of Theoretical Physics, USSR Academy of Sciences
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When a plasma is heated by a powerful laser pulse, an important role is played by the electronic thermal conductivity. For the case of ultrashort pulses, the thermal wave connected with the electronic thermal conductivity is the main mechanism of energy transfer to the interior of the target during the initial stage of the process [1, 2]. Then, as the electrons become cooled, the thermal wave attenuates rapidly and the principal role is assumed by energy transfer connected with the hydrodynamic motion.

In the case of longer pulses one can no longer expect, in general, such a separation of the process into a thermal-wave stage and a mass-motion stage. An analysis of the process of plasma heating entails considerable difficulties in this case, and has not yet been performed completely.

It is shown in this paper that the problem of heating and motion of a two-temperature plasma with allowance for the electron-ion relaxation and the electronic thermal conductivity admits of a self-similar solution in the case when the energy flux absorbed by the plasma increases linearly in time. Since a linear function is a reasonable approximation for the initial part of a real laser pulse, this self-similar solution can be used in an analysis of plasma