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# ON THE QUANTUM THEORY OF UNSTABLE ELEMENTARY PARTICLES

PHYSICS

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**Abstract**

**Full Text**

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**PHYSICS**

**L. A. KHALFIN**

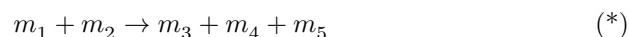
## **ON THE QUANTUM THEORY OF UNSTABLE ELEMENTARY PARTICLES**

*(Presented by Academician V. A. Fock on 5 IV 1965)*

1. As in <sup>(1)</sup>, the initial fundamental point of departure of the entire work is the natural assumption (in fact accepted by everyone)\* that unstable particles are elementary to the same extent as stable ones, in the sense that the properties of unstable elementary particles (and, in particular, their law of decay) do not depend on the method of their preparation. At the same time, the consequences of an alternative assumption will be investigated.

In contrast to <sup>(1)</sup>, the main attention will be devoted not to decay, but to the reaction of production of unstable particles, for example, according to the scheme  $m_1 + m_2 \rightarrow m_3 + m$ ,  $m \rightarrow m_4 + m_5$ ,  $m \rightarrow m_6 + m_7$  (let, for definiteness,  $m_4 + m_5 < m_6 + m_7^{**}$ ), where  $m$  is an unstable particle, and  $m_1, m_2, m_3, m_4, m_5, m_6, m_7$  are stable.

2. In reactions of formation of stable particles, for example, according to the scheme



the application of the law of conservation of energy-momentum in the usual form is natural\*\*\*:

$$p_1 + p_2 = p_3 + p_4 + p_5, \quad (1)$$

which, as is well known, leads to the existence of an energy threshold for the reaction under consideration (\*), determined by the rest masses of the particles  $m_3, m_4, m_5$ .

In reactions of production of unstable particles, however, for example, according to the scheme



application of the conservation law in the form

$$p_1 + p_2 = p_3 + p \quad (2)$$

and, as a consequence, the existence of an energy threshold determined by the masses of the particles  $m_3$  and  $m$ , does not follow a priori from anywhere, since the unstable particle  $m$  does not have a definite value of mass (energy). Moreover, the energy distribution  $W_{E_0}(E)$  of the reaction products (\*\*\*) at a fixed energy  $E_0$  of the colliding particles  $m_1$  and  $m_2$  will be

$$W_{E_0}(E) = \int \omega_{m_3}(E')c(E'; E_0)\omega_m(E - E'; E') dE', \quad (3)$$

where  $\omega_{m_3}(E')$  is the distribution density (obviously, kinematic <sup>(1)</sup>) of the energy of the particle  $m_3$ ,  $\int c(E'; E_0)dE'$  is the probability of the reaction (\*\*\*) at fixed—

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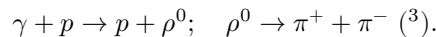
\* It is not difficult to trace that all experimental methods of studying and determining the properties (quantum numbers) of unstable particles are essentially based on the assumed a priori validity of this supposition.

\*\* In what follows, where necessary,  $m_i$  will mean the rest mass of the  $i$ -th particle.

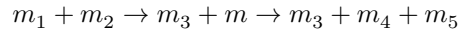
\*\*\* By  $p_i$ , as usual, is meant the four-momentum of the particle  $m_i$ .

fixed energy  $E_0$ ,  $\omega_m(E; E')$  is the energy-distribution density of particle  $m$  for fixed energy  $E'$  of particle  $m_3$ .

3. If the hypothesis of the elementarity of unstable particles is valid, then in  $\omega_m(E; E')$  there is only a kinematic (see (1)) dependence on  $E'$ , and, consequently,  $W_{E_0}(E) \neq \delta(E - E_0)$ , i.e., the conservation law in its usual form is explicitly violated\*. It is clear that, for a violation of order  $\Gamma$ , and, consequently, for ordinary unstable particles with lifetimes  $\sim 10^{-10}$  sec, the available experimental data do not contradict the consequence obtained from the hypothesis of elementarity. Obviously, direct experimental observation of this effect for ordinary particles is practically impossible. In the case of resonance particles\*\*, however, the situation is more favorable—especially at the “threshold” for the production of resonance particles, i.e., when the energy of the colliding particles is such that it is above the threshold of reaction (\*) and the maximum energy  $E_{m_4} + E_m$  allowed by the usual energy-conservation law (1) lies in the neighborhood of  $E_m$  ( $E_m$  is the energy (“mass” (2)) of the unstable particle  $m$ ). An experiment of this type can at present be carried out using, for example, the reaction

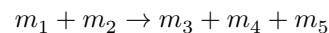


4. The experiment proposed above on the production of a resonance particle at “threshold” can give an explicit resolution of the alternative: do the properties (in particular, their decay law, or equivalently <sup>4,5</sup>, the mass distribution) of unstable particles depend on the preparation or not? If the experiment shows an explicit dependence of the properties of unstable particles on the preparation, so that the conservation law (1) in the reaction

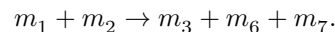


is explicitly fulfilled<sup>\*\*\*</sup>, then this will force us completely to reconsider our ideas about the concept and properties of elementary particles, which are now generally accepted.

5. A very good criterion for resolving the alternative is the possible use of the principle of indistinguishability of identical particles and its consequence—the symmetrization principle (the Pauli principle) (6). Thus, by studying pair production of resonance particles<sup>\*\*\*\*</sup> and, in particular, angular correlations, one can obtain explicit experimental consequences of the symmetrization principle if the properties of unstable particles do not depend on the preparation, or its explicit violation if the properties of unstable particles do depend on the preparation.
6. In connection with the experiment proposed above on the production of particles at “threshold,” it is necessary to reconsider the problem of the possibility of several decay channels for one and the same unstable particle. Indeed, if the experiment shows that the properties of unstable particles depend on the preparation, so that the energy-conservation law is valid in its usual form, then it immediately follows from this that, in fact, different decay channels are decay channels of different particles. To prove this, let us consider an experiment (a thought experiment for ordinary unstable particles and a real one for resonance particles) on the production of an unstable particle in reaction (\*\*). Namely, let the energy  $E_0$  of the colliding particles  $m_1, m_2$  be such that it is above the threshold of the reaction



and below the threshold of the reaction



If the properties of unstable

\* Violation of the conservation law is predicted in a nonstationary experiment with the formation of an unstable particle. This in no way contradicts the fact that, in a stationary experiment on resonance scattering  $m_4 + m_5 \rightarrow m \rightarrow m_4 + m_5$ , the energy-conservation law will, of course, be fulfilled in its usual form.

\*\* Usually resonance particles are observed in selected, according to the usual energy-conservation law for the final reaction products, multiparticle reactions.

It can be shown that, if the hypothesis of the elementarity of resonance particles is valid, such a method of selecting observations in no way contradicts the assumed elementarity of resonance particles and imposes no special restrictions.

\*\*\* In this case unstable particles will have a finite mass (energy) distribution, the specific properties of the decay law of which have been studied in (2, 5).

\*\*\*\* Experiments on pair production at the “threshold” of resonance particles in the present state are clearly possible.

particles depend on the preparation, so that the conservation law is satisfied, then, obviously, in this experiment the formation of the particle  $m \rightarrow m_4 + m_5$  is possible (i.e.  $m_1 + m_2 \rightarrow m_3 + m \rightarrow m_3 + m_4 + m_5$ ), but the formation of a particle  $m$  with two decay channels is impossible (i.e.  $m_1 + m_2 \rightarrow m_3 + m$ ;  $m \rightarrow m_4 + m_5$ ,  $m \rightarrow m_6 + m_7$ ). If, however, the properties of unstable particles do not depend on the preparation, then in this experiment it is possible to produce a particle  $m$  with two different decay channels, and, as a consequence, to observe the second channel  $m_1 + m_2 \rightarrow m_3 + m \rightarrow m_3 + m_6 + m_7$  against a zero background of direct production of  $m_6, m_7$ ,  $m_1 + m_2 \rightarrow m_3 + m_6 + m_7$ , since this latter reaction is forbidden.

Thus, if the properties of unstable particles do not depend on the preparation, then the usually assumed existence of an unstable particle with different channels is not contradictory. If, however, the properties of unstable particles depend on the preparation, then the different decay channels are in fact decay channels of different particles having the same “mass,” lifetime, and other usual quantum numbers. However, since experimentally a different probability of formation of different “channels” is observed, it is necessary to assume that different particles having the same “mass,” lifetime, and other usual quantum numbers possess some new quantum numbers, distinguishing them, which are essential for their production.

7. An ideal method for solving the problem—whether different decay channels are decay channels of different particles or whether they are indeed different decay channels of one and the same particle—would be the investigation of nonexponential terms in the decay law (2, 5, 7–9). Let the unstable particle  $m$  have two decay channels  $m \rightarrow m_4 + m_5$  and  $m \rightarrow m_6 + m_7$ . Then the energy distribution (mass distribution)  $\omega_m(E)$  of the unstable particle  $m$  is

$$\omega_m(E) = c_1 \tilde{\omega}_m(E) + c_2 \tilde{\omega}_m(E), \quad (4)$$

where  $c_1, c_2$  are the intensities of the corresponding channels\*;

$$\tilde{\omega}_m(E) \equiv \begin{cases} 0, & E < (m_4 + m_5)c^2, \\ \bar{\omega}_m(E), & E \geq (m_4 + m_5)c^2, \end{cases} \quad (5a)$$

$$\tilde{\omega}_m(E) \equiv \begin{cases} 0, & E < (m_6 + m_7)c^2, \\ \bar{\omega}_m(E), & E \geq (m_6 + m_7)c^2. \end{cases} \quad (5b)$$

As is not difficult to see from <sup>(2, 5)</sup>, the nonexponential terms are explicitly determined by the values of the threshold energies  $E_1 \equiv (m_4 + m_5)c^2$  and  $E_2 \equiv (m_6 + m_7)c^2$ , so that, by studying the decay law  $m \rightarrow m_4 + m_5$ , one can detect a nonexponential term determined by  $E_2 = (m_6 + m_7)c^2$ , if  $m$  really has two different channels, or fail to detect it, if the different decay channels are in fact decay channels of different particles. The principal exponential term in the decay law, according to (5), will be the same in the different alternatives. The effect indicated above, of the influence of one channel on the other in the decay law, is essentially an analogue of the Wigner–Baz threshold effect <sup>(10–12)</sup>.

8. As we have seen, the following alternative arises: a) the properties of unstable particles do not depend on the preparation (i.e. they are elementary), and then the energy conservation law in its usual form is violated\*\*, while the existence of several different channels for one unstable elementary particle is not contradictory; b) the properties of unstable particles clearly depend

\* Here the specific form of  $\bar{\omega}_m(E)$  is immaterial to us, so that  $\bar{\omega}_m(E)$  need not necessarily be dispersive <sup>(2)</sup>.

\*\* The violation of the conservation law in its usual form in no way contradicts its validity for ordinary stationary experiments, in particular for resonance-scattering experiments.

from the preparation (i.e., they are not elementary)\*, and the law of conservation of energy is valid in the usual form, then the different decay channels are in fact decays of different particles, whose ordinary quantum numbers and “mass” and lifetime coincide, but whose new quantum numbers differ. Both alternatives lead to most interesting consequences.

If alternative b) is valid, then this would mean the necessity of a complete revision of our notions of elementary particles, of the theory of decay interaction—in particular, of the theory of weak interaction—a completely new approach to the experimental determination of the quantum numbers of unstable particles and, as a consequence, the necessity of new methods for proving violations of conservation laws in decay interactions (a good example of this is the problem of  $k_2^0 \rightarrow \pi^+ + \pi^-$  decay <sup>(13)</sup>). The consequences of alternative a) are no less striking.

Which alternative is valid, and for which unstable particles (systems), is a question for nature.

I express my gratitude to Academician V. A. Fock for his attention and interesting discussion, and to the participants of the seminar of the Department of Theoretical Physics of Leningrad University for interesting discussions.

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\* This is certainly so for unstable excited levels of complex systems—atoms and nuclei (see in more detail in <sup>(1)</sup>).

*Note: Figure translations are in progress. See original paper for figures.*

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