Soviet Scientific Reviews, Section A

PHYSICS REVIEWS

Volume 4 (1982)

Edited by

I. M. KHALATNIKOV

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PREFACE TO THE SERIES

In the last few years many important developments have taken place in Soviet science which may have not received as much attention as deserved among the international community of scientists because of language and circulation problems.

In launching this series of *Soviet Scientific Reviews* we were motivated by the desire to make accounts of recent scientific advances in the USSR more readily and rapidly accessible to scientists who do not read Russian. The articles in these volumes are meant to be in the nature of reviews of recent developments and are written by Soviet experts in the fields covered. Most of the manuscripts are translated from Russian. In the interest of speedy publication neither the authors nor the volume editors have an opportunity to see the translations or to read proofs. They are therefore absolved of any responsibility for inaccuracies in the English texts.

Soviet Scientific Reviews periodically publishes volumes in Physics, Chemistry, Physico-Chemical Biology, Mathematical Physics and Astrophysics and Space Physics.

We are much indebted to the volume editors and individual authors for their splendid cooperation in getting these volumes put together and sent to press under considerable time pressure.

The success of this series depends, of course, on how well it meets the readers' needs and desires. We therefore earnestly solicit readers' comments and particularly suggestions for topics and authors for future volumes.

By taking this initiative we hope to contribute to the development of scientific cooperation and a better understanding among scientists.

FOREWORD

In this volume there is an article by V. A. Lyubimov, who reaches a conclusion of great impact to elementary particle physics and astrophysics. In "Does the Neutrino have a Rest Mass?" he discusses in detail the characteristics of the endpoint β-spectrum of tritium, and comes to the widely acclaimed conclusion that the electron neutrino has a nonzero mass.

The paper by B. P. Zakharchenya and V. G. Fleisher is devoted to the experiments on optical cooling and polarization by a weak magnetic field of an electron–nucleus spin system in semiconductors. Of particular interest are the phenomena of auto-oscillations and collective motion of spins under these conditions.

K. O. Keshishev, A. Ya. Parshin, and A. I. Shal'nikov describe their pioneer investigations of surface phenomena in quantum crystals. The boundary between the quantum liquid, i.e., superfluid helium, and quantum crystal, i.e., solid helium, is a new quantum object possessing quite specific properties. This boundary is a certain type of two-dimensional quantum liquid that can undergo weakly attenuating oscillations due to periodic melting and recrystallization.

Yu. A. Osip'yan contributes a review of experimental research on the interaction of electrons with dislocations in semiconductors (germanium and silicon). The physical picture of the energy spectrum of a semiconductor crystal with dislocations is deduced from the analysis of the experimental data on electroconductivity, paramagnetic resonance, etc.

We hope that this collection of reviews by Soviet physicists will be welcomed by experts.

I. M. Khalatnikov
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of Theoretical Physics,
Moscow

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ON THE INFLUENCE OF MATTER AND PHYSICAL FIELDS UPON THE NATURE OF COSMOLOGICAL SINGULARITIES

V. A. BELINSKII and I. M. KHALATNIKOV, *L. D. Landau Institute for Theoretical Physics, USSR Academy of Sciences, Moscow*

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The articles for this series are each written in Russian by a Soviet expert in the field, then rapidly translated into, and published in, the English language. The aim of the series is to make accounts of recent scientific advances in the USSR readily and rapidly available to other scientists.

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DOES THE NEUTRINO HAVE A REST MASS? (ITEP EXPERIMENT ON THE MEASUREMENT OF THE β SPECTRUM OF TRITIUM)

V. A. LYUBIMOV

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Contents

The ITEP experiment, in which precision measurements of the β spectrum of tritium were made near the end point, is discussed. The measurements were made with a new type iron-free β spectrometer with a toroidal magnetic field. The results indicate that the neutrino (at least one of either of its types) has a nonzero rest mass.

I Introduction

1 The Discovery of the Neutrino

In 1930 there sprung "from the tip of the pen" of Wolfgang Pauli one of the most puzzling particles in the strange yet charming and beautiful family of elementary particles, the neutrino. Experiments have shown that the electrons emitted in the radioactive decay of nuclei, called β decay, had a continuous spectrum. This was surprising, since the β-decay energy, equal to the mass difference between the parent and daughter nuclei, had a definite value. The energy conservation law seemed to be violated in β decay. Debye's comment on this vexing circumstance was: "It is best not to think of it . . . just as of new taxes." Yet Pauli got to thinking . . . . By postulating that besides the electron there is produced in addition to the electron also a neutrino–a neutral fermion (particle with spin-$\frac{1}{2}$) and with vanishingly small (perhaps zero) mass, Pauli saved the energy conservation law. The neutrino was invented from the very outset as an elusive particle. Pauli could hardly suggest at that time, however, that it would take 25 years to observe this particle in experiment. Only in the Fifties did Reines and Cowan [1] succeed in recording an antineutrino from a reactor in a process inverse to β decay. The reason was that the neutrino interacts extremely weakly with matter. The main Puzzle of the neutrino, however, is its rest mass. Are the neutrinos doomed to "perpetual motion" at the speed of light, or can they "take a rest"? The answer depends on whether the neutrino rest mass is zero or not.

2 *Does the Neutrino Have Mass? (Theoretical Premises)*

We note first that there are no rigorous theoretical grounds for the neutrino to be massless. Let us trace the changes in the opinions held in their time, based on model representations, concerning the existence of a neutrino mass.

In 1929 the year before the Pauli neutrino was born, Weyl has shown that a massless neutral fermion is described by a two-component wave function. Weyl's equations, however, were noninvariant to space inversion. Under these conditions, by the way, it would be natural to consider the neutrino as a massive particle. In 1957, experiment [2] has confirmed the hypothesis of Lee and Yang, that spatial parity is violated in weak interactions. Thus Weyl's equations were justified. Landau, Salam, Lee, and Yang formulated a two-component neutrino theory, in which the neutrino was regarded as a Weyl particle. Yet precision measurements of the β-electron polarization have shown that the polarization is a maximum and its value is $-v/c$, meaning that the electron is involved in the β interaction only through two components [3] (the remaining components are suppressed in a ratio $(1-\beta^2)/\beta^2=(M_e/P)^2$). In the V–A theory of universal weak interaction, developed shortly after by Feynman, Gell-Mann, Marshak, and Sudarshan, all four fermions participate already in the weak interaction through two components. A two-component neutrino is thus possible, being a Weyl particle with $M_\nu = 0$, or else $M_\nu \neq 0$, but by virtue of the V–A interaction the neutrino is "two-component" and has then a polarization equal to v/c. The first possibility seemed esthetically more attractive. The neutrino is then 100% polarized against the direction of motion, and the antineutrino along its motion. Other components of the neutrino wave function (right-hand neutrino and left-hand antineutrino) do not interact in our world and can be regarded as nonexistent, or can be sent off "through the looking glass" to the "next world" [4]. A most economical neutrino scheme was thus obtained. At the start of the Sixties hardly anyone (with the possible exception of Pontecorvo [5]) doubted that the neutrino mass is zero.

Now another subject, a question topical in its time: Why did nature need to create two particles, the muon and the electron, differing by virtue of the universality of the weak interaction in nothing but their mass? At least a partial answer was found in 1962, when experiment revealed a neutrino of another sort—the muonic neutrino. This discovery was not quite unexpected. The absence of a $\mu \to e + \gamma$ decay (at a level lower by a factor $\sim 10^3$ than might be expected if there were only one sort of neutrino) suggested the existence of the muonic neutrino, and an experiment aimed at its observation was quite deliberately planned (at Pontecorvo's suggestion [8]). The detection of the muonic neutrino has shown that the muon and electron have different lepton charges, e^- and ν_e having an electronic lepton charge, and μ^- and ν_μ a muonic lepton charge. After the discovery in 1975 of a third charged lepton, τ, the existence also of a τ neutrino could be expected. There are thus at least three pairs of leptons. The charged leptons (e, μ, τ) have different masses. It would be natural to assume that neutrinos having different lepton charges have also different masses. But to this end the neutrino mass would have to differ from zero. At nonzero neutrino mass, mutual transitions of the neutrinos into one another (oscillations) are possible [5, 9]. This beautiful effect (whose analog is the situation with K^0 mesons) was predicted by Pontecorvo [5] long before the experimental discovery of different sorts of neutrinos ($\nu \leftrightarrow \bar{\nu}$ transitions).

A last and final circumstance. The success of the theory of electroweak interaction has stimulated attempts at further unification, that of the strong and electro-weak interactions (the "Grand Unified Theory"). This theory is based on the symmetry between the quarks, which are responsible for the strong interaction, and the leptons. Some versions of this theory predict a neutrino with nonzero rest mass.

A "referendum" on the question of the neutrino mass was held at the "Neutrino-80" Conference. Approximately 80% of those queried were in favor of a nonzero mass. Thus, the opinion of the scientific community now favors a massive neutrino, but the very fact of "solving" this problem by voting returns to the initial situation—we have no rigorous theoretical grounds for assuming the neutrino to be massless or to have a mass different from zero. Thus, the problem of the neutrino mass has to be solved experimentally.

3 *Experimental Estimates of the Neutrino Mass*

Attempts to estimate the neutrino rest mass by experiment were undertaken already long ago. A direct method of determining the neutrino mass is to investigate the form of the β spectrum. If the neutrino has a finite mass, the shape of the spectrum changes: the β spectrum bends at the end point and is shortened by exactly an amount equal to the neutrino mass. The shorter the β spectrum itself, the larger the mass effect on the spectrum, and the smaller the distortion introduced in the measurements by instrumental errors. Therefore the β decay of tritium with an end-point energy 18.6 keV has become the classical research object for the estimate of the neutrino mass. One of the first studies was that of Hanna and Pontecorvo in the late Forties [10]. This was a very simple experiment: a proportional counter was filled with tritium gas and from the counter pulse heights it was possible to obtain directly the spectrum of the tritium, its shape, and its end-point energy, and impose accordingly a limit on the neutrino mass. The limit was determined by the resolution. In that experiment the upper bound obtained for the neutrino mass was about one kiloelectron volt. Further advances in the determination of the neutrino mass limit were determined by improvement of the resolution. The most convenient experimental method for this purpose was the use of magnetic beta-spectrometers, which made possible a substantial improvement of the resolution. The record was set in 1972 by Bergkvist [11]. With a magnetic spectrometer of ~50 eV resolution at the end point of the β spectrum, an upper bound of 55 eV was obtained for the neutrino mass, with a 90% confidence level.

In all these studies, however, only an upper limit for the neutrino mass was obtained. The question whether the neutrino mass is finite or zero remained open. But recently in 1980 V. A. Lyubimov, E. G. Novikov, V. Z. Nozik, E. F. Tret'yakov, and V. S. Kozik have completed at ITEP a cycle of precision measurements of the β spectrum of tritium contained in a valine molecule [12]. The analysis of the experimental data points to a nonzero neutrino mass.

II Experimental Setup Used in the ITEP Experiment

1 Spectrometer Optics

The ITEP spectrometer is of a new type, iron-free, with a toroidal magnetic field [13]. The principle of toroidal focusing systems, whose magnetic field is produced inside the body of revolution made up of current turns of special shape, was proposed by Vladimirskii et al. in the Fifties [14]. Tret'yakov pointed out [15] that a system of straight current-carrying conductors arranged on the generatrices of a cylinder is capable of focusing particles emitted perpendicular to the revolution axis. The structure of the focusing in such a system is periodic (Fig. 1). The ITEP spectrometer is based on this principle.

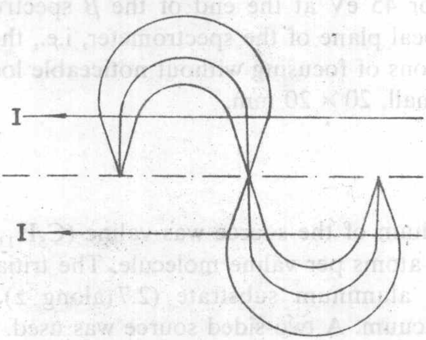

Figure 1 Focusing in the magnetic field of straight current conductors.