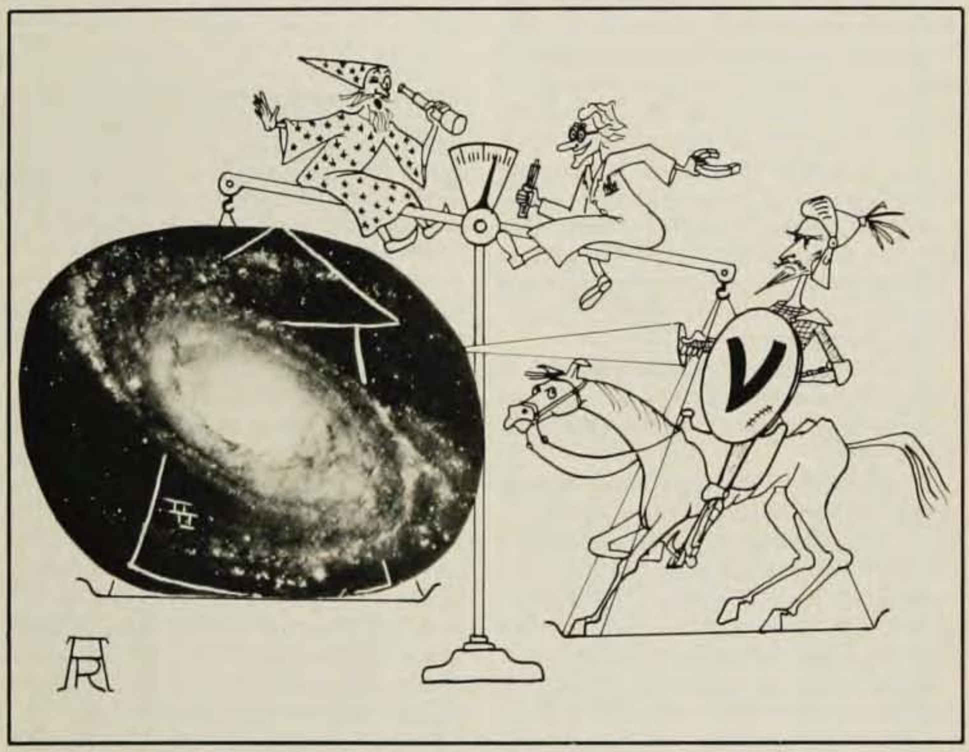
Experiments set limits and a value for neutrino mass



Neutrinos may outweigh the visible mass in the Universe, to the amazement of physicists and astrophysicists alike. Cartoon is by Alvaro De Rújula, who is trying to weigh the electron neutrino by looking at the capture of orbital electrons in a heavy atom—Ho^{163} or Pt^{193}.

Over thirty years ago the first real attempt to search experimentally for the electron neutrino mass was made by Geoffrey C. Hanna and Bruno Pontecorvo at Chalk River and by S. C. Curran and his collaborators at the University of Glasgow. They studied the end point of the tritium beta-decay spectrum. Since then a number of experimenters have established upper limits on the mass of ν_e from this spectrum.

Until last year the best limit was by Karl-Erik Bergkvist (Research Institute of Physics in Stockholm), who found in 1972 an upper limit of 55 eV at the 90% confidence level. There was a more recent limit reported in 1976 (at the International Neutrino Conference in Aachen) by a group from the Institute for Theoretical and Experimental Physics in Moscow; they found the upper limit was 35 eV at the 90% confidence level.

Last year essentially the same group at ITEP, continuing their previous experiment, reported, instead of a limit, a nonzero result for the ν_e mass. They said it was in the range 14–46 eV at the 99% confidence level. Since the new Soviet report no compelling arguments have appeared that would invalidate their experimental results. But no report of experimental confirmation has appeared.

Meanwhile another tritium beta-decay experiment, which used tritium implanted in silicon crystals, has reported still another upper limit—65 eV.

Upper limits on the electron neutrino mass from neutrino-less nuclear double-beta decay and tritium beta decay correspond to a range of 15–40 eV.

Now groups at CERN and Princeton are trying a new approach for measuring M_ν—looking at the capture of orbital electrons in a heavy atom such as holmium-163 or platinum-193.

The search also continues for neutrino oscillations from one type to another; such oscillations imply that the mass of at least one neutrino type is nonzero. Last year a group from the University of California at Irvine reported[1] (PHYSICS TODAY, July 1980, page 17) finding evidence for ν_e changing its type as it traveled from the Savannah River reactor to a detector. At a session on neutrino mass at the American Physical Society meeting in Baltimore this April, Felix Boehm (Caltech) reported that he and his collaborators from Caltech, the Technical University of Munich and the French Institute for Nuclear Science, using the Grenoble reactor, find their "results clearly exclude the results from the Irvine group." On the other hand, Dennis Silverman (Irvine) and Amarjit Soni (UCLA) have analyzed all of the reactor experiments performed at various distances and report[2] that these experiments are not consistent with the no-oscillation hypothesis and do favor neutrino oscillations. Experiments at accelerators have not produced evidence for neutrino oscillations.

Tritium beta decay. In the mid 1960's, Bergkvist started looking into the tritium beta-spectrum endpoint, with the goal of doing high-resolution spectrometry. He observed that the relevant counting rate typically varies as $M_\nu^{5.5}$, so that there is rapid change in experimental feasibility over a small interval of neutrino mass. By combining electrostatic and magnetic methods, he had earlier improved the luminosity (product of source area and transmission) in beta spectroscopy by a factor of 300 over that of conventional methods. Using the new technique, his result[3] for M_ν was less than or equal to 55 eV at the 90% confidence level.

At the neutrino-mass session in Baltimore in April, Bergkvist compared his 1972 experiment with that of the ITEP group,[4] which consists of V. A. Lyubimov, E. G. Novikov, V. Z. Nozik, E. F. Tretyakov and V. S. Kosik. The ITEP background at the endpoint is 12 times smaller than Bergkvist's. However the ITEP luminosity, while partly relying on Bergkvist's methods, is $\frac{1}{20}$th as great as in his experiment.

The ITEP experimenters made their tritium source by evaporating a tritium compound onto a backing, rather than by implanting low-energy tritium ions in the surface layer of a foil, as was done by Bergkvist. The ITEP procedure, Bergkvist stresses, allowed a more accurate procedure for determining the experimental response function. The data acquisition time in the Bergkvist experi-

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ment was 90 hours. He says the ITEP acquisition time was about 3200 hours.

Bergkvist notes that both his and the ITEP experiment have the following problem: The sudden change in charge of the beta-decaying nucleus causes excitations of the surrounding atomic electrons, which causes a diffuseness in the beta-decay spectrum, an effect he calls "atomic interplay." The ITEP group used Bergkvist's 1972 calculation of these effects, worked out for the free tritium atom and the free T–H or T–T molecule. In an actual source, there are inevitably uncertainties in the precise magnitude of these atomic and molecular effects. The neutrino mass derived decreases when the assumed spread in endpoint energy is decreased. However, in the assignment of the lower limit for the mass, the ITEP group assumed the atomic final-state energy spread to be zero, that is, effectively no atomic interplay. With this extreme assumption the neutrino mass value inferred is still nonzero, "the most striking feature of the ITEP result," Bergkvist told us.

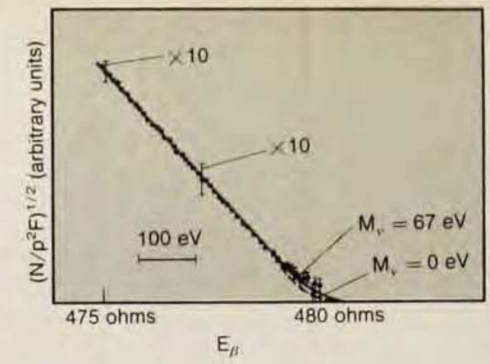
The ITEP group reports that M_ν is greater than or equal to 14 eV and less than or equal to 46 eV at the 99% confidence level.

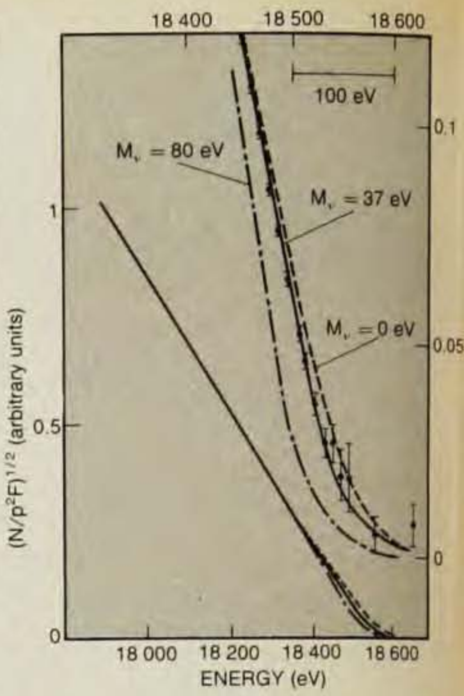
Bergkvist has already started experiments in Stockholm to explore the feasibility of combining the high luminosity of his 1972 experiment with the more favorable background of the ITEP experiment. He feels he can improve his background by at least a factor of two.

Other tritium experiments. John J. Simpson at the University of Guelph in Ontario has recently measured[5] the beta-energy spectrum of tritium implanted at high energy into a Si(Li) x-ray detector. He reports M_ν less than 65 eV with 95% confidence and a best value of 20 eV, which he notes is only 0.2 standard deviations from zero mass. Simpson feels that the accuracy imposed by atomic effects is better in his type of experiment than in those done with a magnetic spectrometer and that his main uncertainty is statistical; so he is concentrating on an experiment with a higher count rate and better control of the response function of the detector.

Thomas J. Bowles of Los Alamos and Hamish Robertson of Michigan State University and their collaborators are developing a source of free tritium atoms to overcome the problem with the atomic final-state energy spread. Richard N. Boyd and his collaborators at Ohio State University are setting up an experiment to examine the endpoint region in tritium decay. To do this they will decelerate the electrons and measure their time of flight by detecting them in coincidence with prompt atomic photons.

Neutrino-less double beta decay. Limits on the electron neutrino mass, assuming that ν_e is a Majorana particle and therefore basically identical with its antiparticle, can also be set from a combination of theoretical and experimental considerations on neutrino-less double beta decay. From geochemical measurements, one can compare the lifetimes for double beta decay in Te^{128} and Te^{130}. Various workers have used the ratio of the lifetimes to estimate what fraction of the decays produce two neutrinos and what fraction produce zero. Such considerations have been used by M. Doi, T. Kotani, H. Nishiura, K. Okuda and T. Takasugi (Osaka University) to cancel out nuclear-structure effects; they obtain a limit on M_ν = 30–40 eV.





Tritium beta-decay endpoint spectra (Kurie plots) obtained by Bergkvist[3] (above) and the ITEP group[4] (right) indicate the difference between the expected spectra for different values of M_ν. Bergkvist found $M_\nu \leq 55$ eV (90% confidence level); the ITEP group found M_ν to be 14–46 eV (99% confidence level).

From instrumented searches one can study double beta decay of $Se^{82} \rightarrow Kr^{82}$. Such an experiment, by Bruce T. Cleveland (Brookhaven), William Leo (University of Geneva), Chien-Shiung Wu (Columbia University), Leonard Kasday (Bell Labs), A. Rushton (Irvine), Peter Gollon (Brookhaven) and Jack Ullman (Lehman College) yielded[6] a lower limit of $10^{21.5}$ years on the lifetime of the neutrino-less component in this double beta decay. More recently Michael K. Moe and Dennis Lowenthal (Irvine) found[7] a value of $10^{19.0\pm0.1}$ years for the lifetime associated with the two-neutrino component, indicating that the great majority (perhaps all) of the double-beta decays in $Se^{82} \rightarrow Kr^{82}$ are two neutrinos. The Irvine measurement yields a lifetime 27 times shorter than geochemical measurements of the same process (by B. Srinivasan and his collaborators in 1973).

Henry Primakoff (University of Pennsylvania) and S. Peter Rosen (Purdue University) have collaborated over the years in several analyses[8] of double beta decay. Rosen told us that the experiments by Cleveland and collaborators and by Moe and Lowenthal translate into a neutrino mass limit of 16 eV, according to a recent calculation of nuclear matrix elements by Wick Haxton (Purdue), G. J. Stephenson (Los Alamos) and Dan Strottman (Los Alamos).

When you look at mechanisms operating in neutrino-less double beta decay, M_ν is not the only key parameter. It's also possible that the neutrino couples to the electron in both a left-handed and right-handed way, a feature of some gauge theories. To separate the effects of the neutrino mass from those of the right-handed current, one can study transitions from the ground state of the parent nucleus with spin 0 (even–even) to an excited state of the daughter with nonzero spin. It turns out that these transitions are generated only by right-handed currents and have no contributions from the mass, as was pointed out by Rosen. Ettore Fiorini (University of Milan), following a suggestion by A. Molina and Peter Pascual (University of Barcelona) had looked for transitions from the ground state of Ge^{76} to an excited state of Se^{76} with spin 2. Then, if $0^+ \rightarrow 2^+$ decays are seen to have comparable rates to $0^+ \rightarrow 0^+$ decays, one would know that right-handed currents are also involved. Such an experiment is now being done at Guelph by Simpson and J. L. Campbell and is being proposed by Frank Avignone (University of South Carolina).

Wu told us that the most important experiment to do now with germanium, selenium or tellurium is to look at the single spectral line indicating maximum energy output when no neutrinos are emitted.

In a forthcoming review paper, Rosen and Primakoff also work out the implications for neutrino-less double-beta decay of an extremely massive neutrino, as has been postulated by theorists such as Sheldon Glashow (Harvard University) and by Robert Marshak (Virginia Polytechnic Institute and State University); Rosen and Primakoff estimate that its mass must be greater than or equal to 10 GeV (or possibly even much greater if the double-beta decay transition takes place among quarks in that part of the nuclear wave function in which nucleons have lost their identity). In discussing all the bits of evidence for nonvanishing neutrino mass, Primakoff told us "the exciting thing is that the various numbers for the electron neutrino mass—values and limits—obtained from different kinds of experiments are all in the range 10–50 eV."

Capture of orbital electrons. In the process of capturing an orbital electron, the transition $Z \rightarrow (Z-1) + \gamma + \nu_e$ occurs. By measuring the shape near the endpoint of the photon spectrum, one can hope to determine the neutrino mass. If the number of these photons in the x-ray range is sufficiently large, their energies can be measured very accurately by Bragg reflection from crystals. For typical nuclides, which capture electrons from the K shell, the photon emission rates are too low. However, Alvaro De Rújula (CERN) noted[9] that in electron-capturing isotopes in which capture from the K or L shell is forbidden, the fractional counting rate at the endpoint is enhanced by several orders of magnitude. The probability for emission of photons in bremsstrahlung capture from the angular-momentum-one orbital is very high when the photon energy is below or close to the energy of the subsequently emitted characteristic x ray. By a search of isotope tables, De Rújula found that Nature has provided six isotopes where the photon endpoint energy is below the x-ray energy. Two in particular, are very good: $Pt^{193} \rightarrow Os^{193}$ has an endpoint of about 45 keV. The optimal electron-capturing isotope, De Rújula found, was $Ho^{163} \rightarrow Dy^{163}$. In this case, both the lifetime and the photon energy end point are not well determined; the latter probably lies in the range 2–10 keV.

Now theorist De Rújula is participating in an experiment at the on-line isotope separator at CERN, which is known as ISOLDE. His collaborators are J. U. Andersen (University of Aarhus, Denmark), P. Gregers Hansen (Aarhus), Bjorn Johnsen (CERN), E. Laegsgaard (Aarhus) and Helge Ravn (Aarhus). In their first round of experiments, the group expects to use relatively low resolution photon detectors made of Ge–Li. They are doing coincidence measurements between bremsstrahlung and Auger electrons or x rays.

Experiments using photon emission in electron orbital capture (in other words, internal bremsstrahlung electron capture) have essentially no problems with atomic interplay. The high Z and the retained total charge in the inner region of the atom cooperate to produce negligible shake-up in the outer shells. The CERN–Aarhus collaboration believes its experiment will have a sensitivity to a neutrino mass in the region 10–200 eV.

At Princeton, a group is also working on Ho^{163}, but not looking at internal bremsstrahlung electron capture. Charles Bennett explained that he and his collaborators are measuring the decay rates for capture of 3s, 3p, 4s and higher electrons. Because the 3s electrons are bound with 2 keV, if the mass difference between Ho^{163} and Dy^{163} is 2.5 keV, only 0.5 keV is left for the neutrino, and as a result, the 3s capture rate is strongly suppressed by a neutrino mass. The 4s electrons, on the other hand, are bound by only 0.4 keV and are less strongly affected. The relative capture rates, 3p/3s and 4s/3s, can therefore be used in combination to determine both the neutrino mass and the Ho^{163}–Dy^{163} mass difference. Decay rates also depend on the details of atomic structure. But the atomic-physics effects are essentially identical in Ho^{162} and Ho^{161}, and similarly for Ho^{163}. The mass difference between Ho^{161} and Dy^{161} is 850 keV; so the neutrino mass is totally irrelevant and the atomic-physics effects can be extracted, he said.

Last fall the group, consisting of Aksel L. Hallin, Bennett, Robert A. Naumann, Paul Springer, Mike Witherell, Frank Calaprice (all at Princeton), Robert Chrien (Brookhaven), Patricia Baisden, and David Sisson (Livermore) sent an Er^{162} sample to the High-Flux Beam Reactor at Brookhaven and now has 3 mg of Ho^{163}; experiments are under way, and x rays from 3s capture have already been seen. Bennett notes that although the quoted value of its halflife is (33 ± 23) years, the halflife could easily be considerably longer, indicative of a higher sensitivity to neutrino mass effects. Also, as has been discussed above, there is a big uncertainty in the mass difference. If it is small and favorable, M_ν of 50 eV will introduce a 10% correction to the 3s capture rate. If the mass difference is larger, the sensitivity of the relative capture rates to neutrino mass effects rapidly decreases.

Astrophysicists are continuing to investigate enthusiastically the ramifications of neutrinos with mass. It is widely believed now that neutrinos with masses in the range of a few eV would provide most of the mass of the universe. Massive neutrinos might be responsible for the invisible mass in galactic halos and for the missing mass of the universe. Clearly the study of neutrino mass continues to be a weighty subject. —GBL

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Fractionally charged solitons

Move over, quarks. Make room for solitons with fractional charges. These newcomers have surfaced in theories from two distinct branches of physics—relativistic field theory and condensed-matter physics. The appearance of solitons (solitary wave solutions to nonlinear problems) in a wide range of physics problems is increasingly common, but their association with non-integer quantum numbers is a new feature. The analogous mathematical structure of the theories that show this feature is especially appealing to particle theorists because the predictions of the condensed-matter model are more amenable to experimental verification than are those of the more abstract field theories.

The emergence of fractional fermion numbers in relativistic field theory was noted[1] several years ago by Roman Jackiw (MIT) and Claudio Rebbi (now at Brookhaven) in their mathematical investigations of various relativistic field theories. Independently several condensed-matter physicists were working on a soliton theory of the linear organic polymeric chain, polyacetylene. Recently J. Robert Schrieffer (Institute for Theoretical Physics, Santa Barbara) has carried this model far enough to show the emergence of fractional quantum numbers. Jackiw and Schrieffer realized[2] the convergence of their two approaches when Jackiw visited the Institute for Theoretical Physics, whose purpose is to promote just such interactions across physics disciplines. In one of the field theories investigated by Jackiw and in the condensed-matter model, the presence of a soliton produces degenerate, zero-energy solutions for the fermion field, each with a quantum number of $\pm\frac{1}{2}$.

Schrieffer's recent work is based on a model he developed[3] at the University of Pennsylvania with Wu-Pei Su (now at the Institute for Theoretical Physics) and Alan J. Heeger. Almost concurrently Michael J. Rice (Xerox Webster Research Center) proposed[4] a similar theory. Hajime Takayama (Hokkaido University, Sapporo, Japan), Y. R. Lin-Liu (now at