A major purpose of the Technical Information Center is to provide the broadest dissemination possible of information contained in DOE's Research and Development Reports to business, industry, the academic community, and federal, state and local governments.

Although a small portion of this report is not reproducible, it is being made available to expedite the availability of information on the research discussed herein.

1

LA-UR -89-2010

CONF-8906190--2

Los Alamos National Laboratory is operated by the University of California for the United States Department of Energy under contract W-7405-ENG-36

LA-UR--89-2010

DE89 014035

TITLE "Improved Limit on the Mass of ν_e from the Beta Decay of Molecular Tritium"

AUTHOR(S) T. J. Bowles, J. L. Friar, R. G. H. Robertson, G. J. Stephenson, Jr., D. L. Wark, and J. F. Wilkerson
Los Alamos National Laboratory
Los Alamos, NM 87545
D. A. Knapp
Livermore National Laboratory
Livermore, CA 94550

SUBMITTED TO XXIII Yamada Conference on Nuclear Weak Process and Nuclear Structure
June 12-15, 1989

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

By acceptance of this article, the publisher recognizes that the U.S. Government retains a nonexclusive, royalty-free license to publish or reproduce the published form of this contribution, or to allow others to do so, for U.S. Government purposes.

The Los Alamos National Laboratory requests that the publisher identify this article as work performed under the auspices of the U.S. Department of Energy.

Los Alamos National Laboratory
Los Alamos, New Mexico 87545

FORM NO 836 R4
ST NO 2629 5/81

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

Improved Limit on the Mass of ν_e from the Beta Decay of Molecular Tritium

T. J. Bowles[a], J. L. Friar[b], R. G. H. Robertson[a],
G. J. Stephenson, Jr.[a], D. L. Wark[a], and J. F. Wilkerson[a]
Los Alamos National Laboratory,
Los Alamos, NM 87545.
and
D. A. Knapp,
Physics Division, Lawrence Livermore National Laboratory,
Livermore, CA 94550.
(Presented by D. L. Wark)

ABSTRACT

We report a new upper limit of 13.4 eV (95% confidence level) on the mass of the electron antineutrino from a study of the shape of the beta spectrum of free molecular tritium. This result appears to be inconsistent with a reported value for the mass of 26(5) eV. The electron neutrino is evidently not massive enough to close the universe by itself.

That the mass of the electron neutrino (or antineutrino; we make no distinction here) could be determined from the shape of beta spectra has been known since Fermi's formulation of the theory of beta decay. In 1981, a group at the Institute for Theoretical and Experimental Physics (ITEP) in Moscow reported[1] from their study of the tritium spectrum that ν_e had a mass of 35 eV, with revolutionary implications for particle physics and cosmology. More recent ITEP work[2] has reduced this value slightly to 26(5) eV, with a "model-independent" range of 17 to 40 eV. Fritschi et al.[3] found in a similar type of experiment at the University of Zürich an upper limit of 18 eV, and other measurements have neither confirmed nor contradicted these works.[4,5] Both the Zürich and ITEP experiments have very high statistical accuracy, and the difference between the two results must be a consequence of systematic effects. A probable origin for such effects is the solid source materials used, for which molecular structure calculations are difficult to carry out to the necessary precision.

Unlike other experiments presently in operation, our experiment at the Los Alamos National Laboratory makes use of a gaseous source of T_2 to capitalize on the simplicity of the two-electron system. When a triton decays to ^3He, the orbital electrons are no longer in an eigenstate and distribute themselves over the set of eigenstates of the residual molecule. The resulting energy spread impressed on the outgoing beta must be very precisely calculated (at the 1% level) if serious errors in interpreting the data are to be avoided. Such calculations can be carried out with some confidence for atomic and molecular tritium, but with less certainty for solid sources like those used by ITEP and Zürich. Use of a gaseous source also confers the advantages of minimal and well understood energy-loss corrections, and no backscatter corrections. Thus the gaseous source minimizes systematic uncertainties, but it is technically more difficult, and statistical accuracy can be hard to obtain.

In an earlier paper[5] we described our apparatus briefly and reported the initial result obtained with it: $\nu_e < 27$ eV at 95% confidence level (CL). Sensitivity to neutrino mass increases extremely slowly with data acquisition time, roughly as the fifth root, so it was clear that significant improvement in the limit could only transpire through an increase in the data rates. To this end, we have made a number of improvements, the principal one being the replacement of the simple single-element proportional counter in the spectrometer with a 96-pad Si microstrip detector array.

The new detector is an octagonal array of 300-μm-thick planar passivated Si wafers (n-type) each with a sensitive area of 7 x 10 mm^2. The sensitive area is subdivided into 12 strips on 0.83-mm centers by readout pads. There are thus 96 microstrips tiling the surface of a 2-cm diameter cylinder. The wafers, manufactured by Hamamatsu Photonics KK, are mounted on 1-mm thick sapphire substrates (Saphikon Inc.) clamped at one end to water-cooled copper braids. Sapphire is not only an excellent conductor of heat (there are thermal radiation loads from the nearby spectrometer conductors) but is also quite radiopure. The wafers are water-cooled to 13 C; further cooling was considered unwise in view of the possible pumping of tritiated condensate onto the surfaces of the detectors. For electron spectroscopy, the customary Au layer on the entry surface of the wafers has been omitted and only the thin (less than 0.5 μm) ion-implanted contact intervenes. For 23-keV electrons, resolutions of 2.5 to 4.0 keV FWHM are observed.

Signals from the hybrid preamplifiers are each amplified, shaped, and passed through a biased amplifier to remove the baseline noise before being summed in groups of 12. A multichannel analog-to-digital converter records the 8 multiplexed analog signals, and majority logic units register 96-bit patterns describing the locations and multiplicities of the events. Valid events have a multiplicity of one. Events are processed and written on two disks by a 12-MHz computer in 400 μs.

Numerous other improvements have been made. An axial gradient has been superimposed on the magnetic field of the source to eliminate the trapping of electrons, which previously necessitated a large and complex correction. Baffles were installed in the spectrometer, and the acceptance reduced by half, to improve the lineshape. A getter pump was added to remove atmospheric gases that caused extra energy loss when Kr was being recirculated. The stability and background of the Si detector that monitors the source strength was improved, and the source density was stabilized with the addition of a servo regulator. Notwithstanding the loss in spectrometer acceptance, the gross data rate is 8 times higher than previously, and the signal-to-background about the same. Of the 96 channels, 9 are at present either non-functional or excessively noisy, and are not used.

The beta spectrum is formed by setting the spectrometer to analyze a fixed momentum (equivalent to an energy of 23 keV) and scanning the accelerating voltage on the source. A typical data acquisition interval at a particular voltage is 35 seconds, at the end of which a 1024-channel spectrum from the Si monitor detector and the contents of scalers used in dead-time correction are written to disk after the event-mode data. After every 5 data points, a calibration measurement at the voltage farthest from the endpoint (i.e. the highest voltage) is taken to monitor stability. Data voltages are repeated in random order with a frequency that reflects the parts of the spectrum most significant in determining the neutrino mass. Data are recorded in sets of 6700 measurements, including calibration points, at 800 voltages. Before and after a tritium data set, the 17820-eV K-conversion line of $^{83}Kr^m$ is recorded two or three times to determine the instrumental resolution and energy scale.

Analysis of the data begins with manual creation of a set of 87 "windows" on the energy spectra from the individual pads. The windows include most of the counts from 23-keV electrons from the source, and exclude the bulk of the background counts from tritium in the spectrometer.

Each pad receives counts corresponding to a slightly different momentum, the total range being about 100 eV in energy from one end of the detector to the other. The data is thus organized by summing counts from the same pad numbers on each wafer to form 12 spectra, each independently calibrated by a $^{83}Kr^m$ spectrum similarly formed. The "raw" tritium spectra can be compared to the theoretical spectrum modified by corrections for energy loss, instrumental resolution, apparatus efficiency, and the final-state spectrum. The neutrino mass and its variance is then estimated[5] from a plot of the sum of Ξ^2 for all pads against m_ν^2.

Electrons lose energy by inelastic scattering as they spiral through the source gas. The cross section differential in energy has been constructed from various data, as described previously.[5] The total inelastic cross section is very tightly constrained by the Liu sum rule[6] to be $\sigma_0 = 3.474(11) \times 10^{-18}$ cm^2 at 18.5 keV.

The gas-density profile in the source is determined by kinetic theory from the measured throughput of gas scavenged by pumps into a calibrated volume, given the dimensions and temperature (130K) of the source tube. For each element of phase space (θ, z) in the source, a mean superficial density $n(\theta,z)$ can be computed by Monte Carlo methods. Plural interactions have a Poisson distribution appropriate to the elementary mean densities. The energy-loss spectrum becomes

$$G(E) = \int_{z_1}^{z_2}\int_{-C}^{C}\sum_j \frac{[n(\theta,z)\sigma_0]^j \exp[-n(\theta,z)\sigma_0]}{(1-C)\ j!} \ F^j(E)\ dz\ d(\cos\theta) \ ,$$

where $F^j(E)$ is the j-fold convolution of the unit normalized differential cross section ($j=1,20$). The angular integration includes only angles between 32 and 148 degrees, to comply with Monte Carlo calculations of the initial angle spectrum accepted by the spectrometer. The probability of an electron interacting is 8.5 %, and the number of interactions per decay is 9.1 %, an indication of the generally small scattering probability and the very minor role played by plural interactions. The stopping power computed with our differential cross section (which satisfies the Liu sum rule) is 0.44×10^{-16} eV-cm per atom, 18% below the Bethe stopping power.[7] This difference represents the major uncertainty in the energy-loss estimates.

Measurement of the instrumental resolution is accomplished by circulating $^{83}Kr^m$ (from the decay of ^{83}Rb) through the source and recording the nominally monoenergetic K-conversion line at 17820(3) eV. This single calibration is sufficient becsuse, in our apparatus, the spectrometer is always set to analyze the same momentum, and spectra are obtained simply by scanning the acceleration voltage applied to the source. Conversion lines are accompanied by shakeup and shakeoff satellites, and, rather than rely on calculations for their positions and intensities, we have carried out a K-shell photoionization measurement on Kr at the Stanford Synchrotron Radiation Laboratory.[8] Excellent agreement between the shapes of the spectra is obtained when the slightly better-resolution photoionization spectrum is convoluted with a Gaussian to match the internal-conversion data. Most important, a long tail (2×10^{-4} eV^{-1}) observed in the data but not predicted by theory is shown to be a part of the Kr spectrum (and not instrumental). A more detailed description of this work is given elsewhere.[8,9] A spectrum of thermal electrons from the source region accelerated to 19 keV showed evidence for a weak tail of 7 x 10^{-6} eV^{-1}, and the Kr data also shows evidence of marginal statistical significance for a residual tail at about this level. This residual tail being presumably of instrumental origin, we take the instrumental resolution to be given by a Gaussian with an added flat tail of 7 x 10^{-6} eV^{-1} extending to 350 eV, and extract the Gaussian parameters by fitting to the diagram line and first satellites of the Kr spectrum, for which the theoretical description appears to be good. The Gaussian variances for the 12 spectra averaged about 120 eV^2. The instrumental linewidth is sufficiently narrow that details of its shape have only a small influence on the results. The effect of the added tail on m_ν^2 is 15 eV^2, and we associate a 15 eV^2 uncertainty with it.

There are contributions to the tritium linewidth not contained in the Kr calibration. The partition of recoil energy between internal and translational degrees of freedom of the THe^+ ion contributes[10] a variance of 9 x 10^{-2} eV^2. Zero-point vibrational motion in the T_2 molecule[11] and thermal motion create Doppler broadenings of variance 4 x 10^{-4} and 4 x 10^{-2} eV^2, respectively. These contributions are negligible.

The small variation of apparatus efficiency with acceleration voltage introduces a spectral distortion that can influence the neutrino mass derived. It is customary to parametrize this with empirically determined linear and quadratic correction terms α_1 and α_2 in the spectrum. In our apparatus both the spectrometric data and the monitor data are subject to efficiency corrections. The monitor efficiency function may easily be measured by plotting its rate, corrected for source pressure, against acceleration voltage, but there is no comparable method for the spectrometric data. However, it is possible, although very computer-intensive, to calculate the efficiency directly by Monte Carlo methods. We find that the spectrometric efficiency is strictly linear, with $\alpha_1 = -2.0(3) \times 10^{-5}$ eV^{-1}, in reasonable agreement with the value $-2.6(2) \times 10^{-5}$ derived by fitting the spectrum to a linear term only. (Our earlier opinion[5] that optimization of the transmission at the endpoint would produce only even order terms is incorrect because the optimization applies to total electron energy, not acceleration voltage.) As a test, we also calculated the variation of count rate with focus-coil current and found qualitative agreement with data but some quantitative discrepancies. For that reason, and because linear and quadratic corrections produce different neutrino masses, we consider both linear and quadratic terms in the fit separately, adopt a mean value and treat the total spread in neutrino mass squared (105 eV^2) as a systematic uncertainty.

Experimental tests of a number of possible sources of systematic error were conducted. Low-pressure T_2 gas in magnetic and electric fields suggests the production of T^+, $T_2{}^+$, and $T_3{}^+$ ions, and T^* and $T_2{}^*$ metastables, in the source region. Positive ions are trapped in the source by the arrangement of fields and can escape only by migrating across field lines through scattering and charge exchange. Trapped ions were sought in two different experiments, one[12] in which $^{83}Kr^m$ and T_2 were introduced simultaneously into the source, and the second in which T_2 was introduced directly into the acceleration-gap region rather than the source midpoint. In neither case were trapped ions seen, and the second experiment sets a limit of 5×10^{-4} on the ratio of ions to neutrals, corresponding to an excess variance of order 0.2 eV^2. The cross sections for the production of metastables is lower than for ions, and their lifetimes in the source are shorter, owing to wall collisions.

Another test was to search for electrons scattered into the beam from the walls (which are highly contaminated with tritium). The apparatus was designed with a guard region between the wall and the part of the gas visible to the spectrometer equal to two or more electron radii, so that two consecutive scatters would be needed for an electron to enter the beam. Helium gas was introduced into the apparatus (hydrogen would have exchanged with the tritium) after tritium had been pumped away, and scattered electrons were sought in the spectrometer. As expected, none was seen, at a level of 10^{-4} of the source strength.

The final-state spectrum (of the THe^+ ion) has the most important influence on the tritium spectrum. Calculations have been reported for the decay of T_2 in the sudden approximation. The Martin-

Cohen (MC) calculation[13] is truncated at 94 eV excitation, the Quantum Theory Project (QTP) calculation[10,14] is truncated at 164 eV and the Ågren-Carravetta calculation[15] at 90 eV. The last calculation has not yet been utilized in the analysis of our data. The MC and QTP calculations are in very good accord, the latter (the one we adopt) giving m_ν^2 8 eV^2 larger owing to its greater range. The MC calculation omits 1.3% of the strength, while the QTP one omits 0.5%, and the distribution of this strength is responsible for the difference between the variances, 545 eV^2 and 617 eV^2, respectively, and the sum-rule result of Kaplan and Smelov,[16] 1110 eV^2. Despite this alarming discrepancy, the effect on neutrino mass is actually rather small, as we have found by simulating the missing 0.5 % of strength with discrete and continuous distributions that satisfy the sum rule. An upward correction to m_ν^2 of 20(10) eV^2 for the strength missing in the QTP calculation results.

The validity of the sudden approximation, on which all these calculations rest, has not seriously been questioned, largely because of the work of Williams and Koonin[17] (WK), who claimed that the rescattering contributions (i.e., the interaction of the beta directly with orbital electrons) were less than 10^{-3} in the case of the atom. WK, however, treated only s-wave final states, arguing that other partial waves would each contribute of order $(1/pa_0)^2 - (1/36)^2$, where p is the beta momentum, and a_0 the Bohr radius. They then invoked Intemann's argument[18] that the highest partial wave of interest would have an ℓ of order pa_0, but erroneously found this quantity to be 1/36, whereas it is actually 36. A complete calculation appears to be very difficult, but Friar[19] has obtained a closed-form expression for the p-wave bound and continuum strengths. We double this contribution to make an estimate for the T_2 molecule, and find m_ν^2 shifts upward by 6 eV^2. Friar also shows that higher ℓ contributions fall off very rapidly for bound states, and we find from a semiclassical model that this is true for the continuum as well. We estimate the total effect to be not more than about 3 times the p-wave, but the need for a complete continuum calculation for the T_2 molecule is manifest.

The tritium data set obtained (13400 measurements) spanned an interval of about 9 days and led to spectra totalling 8000 counts in the last 100 eV, of which 1400 were background. The spectra covered the range 16500 - 19200 eV. The maximum-likelihood procedure described earlier[5] was used to obtain values for m_ν^2, E_0, amplitude, background, α_1 and α_2. These results, and their 1-σ statistical uncertainties, are listed in Table I.

Table I. Results from analysis of August, 1988 data; uncertainties are one standard deviation statistical.

	α_1 only	α_2 only	
m_ν^2	-250(90)	-145(90)	eV^2
E_0	18567.2	18569.2	eV
α_1	$-2.6(2) \times 10^{-5}$	--	eV^{-1}
α_2	--	$-8.8(5) \times 10^{-9}$	eV^{-2}
Ξ^2 (av.)	945.8	945.1	(892 D.O.F)

In Table II we list the estimated uncertainties (1-σ) in m_ν^2 from all sources. We have not at this time considered all relevant contributions to the uncertainty in the endpoint energy, E_0. In principle, a useful test of the reliability of tritium beta decay experiments is the value obtained for the ^3H - ^3He mass difference. Our present endpoint energy is in good agreement with the one we obtained previously, and with some other experiments, but independent experimental information on the mass difference is not decisive yet.[12]

We take the conservative viewpoint that we do not know which is the correct description of the curvature, and that the two choices are but a selection from a large variety of possible efficiency functions. Our best estimate is then the average of the α_1 and α_2 fits, and the uncertainty associated with efficiency correction is the difference between them.

In Figure 1, we plot the residuals for the fit near the endpoint for $m_\nu = 0$ and 30 eV, from which it may be seen qualitatively that a 30-eV mass is rejected. That conclusion is borne out quantitatively

Table II. Contributions (eV^2) to the uncertainty in $m_\nu{}^2$ at one standard deviation.

Analysis:	
Statistics	90
Beta monitor statistics, dead time	5
Energy Loss:	
18% in theoretical spectrum shape:	15
5% Uncertainty in source density	4
Resolution	
Width	12
Skewness	6
Tail	15
Final States	
Differences between theories	8
Region above truncation point	10
Rescattering	20
Apparatus Efficiency	
Linear vs Quadratic	105
Total	143

when all uncertainty components are considered. As discussed elsewhere,[20] setting confidence levels on quantities physically forbidden from having negative values is a complex issue, especially when the measured value (through normal statistical fluctuations) falls in the non-physical regime. Our result (from the average of the fits with α_1 and α_2 separately) is $m_\nu{}^2 = -198(143)$ eV^2, which would have arisen in less than 8% of trials from a neutrino mass greater than 0 eV. To derive a confidence level on the mass is less straightforward. The Particle Data Group sets forth[21] a Bayesian prescription that is at least well-defined, if not rigorously

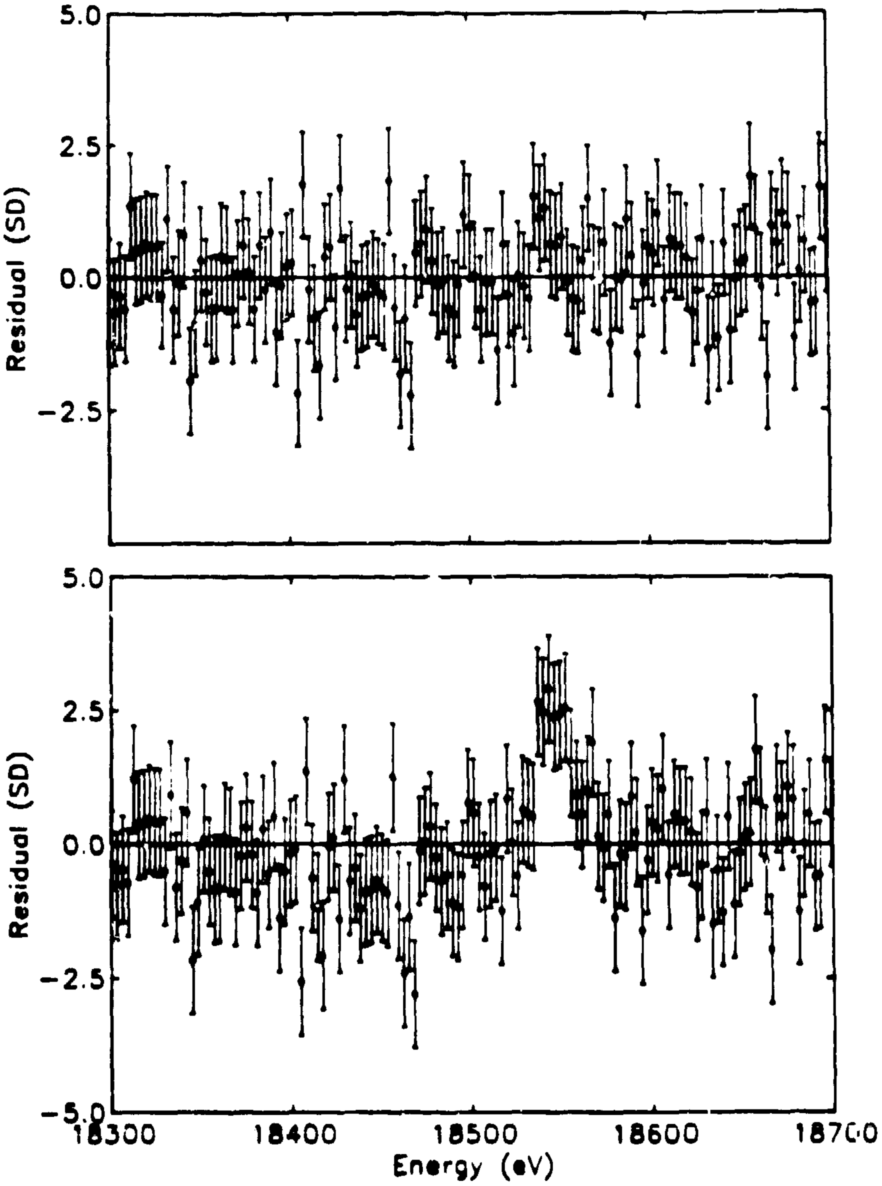

Fig.1. Residuals in fits to neutrino masses of 0 (top) and 30 eV (bottom). All other parameters including α_1 and α_2 have been allowed to vary.

justified. On that basis, we find a 95% confidence level upper limit on the neutrino mass of 13.4 eV.

Negative apparent values of m_ν^2 can arise in two physical models of which we are aware, neither of which can be accommodated in the standard framework of particle physics and cosmology. One mechanism is neutrino capture from an ultra-dense sea of relic neutrinos[22] (10^{17} cm^{-3} are needed in order to be observable in our experiment), and the other is tachyonic neutrinos[23] There is no compelling need at present to invoke either of these exotic concepts.

The results of our experiment are entirely inconsistent with the ITEP result, 17 to 40 eV. We are not able to speculate usefully on the exact source of this disagreement, but we have noted how demanding this type of experiment is on the precision of all correction factors. Uncertainties in energy loss, backscattering, and final-state effects are presumably substantially larger for solid sources than for free molecular T_2. We note, finally, that this low limit on the mass of ν_e should permit a new analysis of the neutrino data from the supernova SN1987a largely free of the time-dispersive effects introduced by neutrino mass, and that ν_e is incapable of closing the universe by itself.

We gratefully acknowledge the assistance of M. Anaya in this work.

REFERENCES

a Physics Division

b Theoretical Division

1. Lubimov, V. A., Novikov, E. G., Nozik, V. Z., Tret'yakov, E. F., Kozik, V. S., Phys. Lett. **94B**, 266 (1980).

2. Boris, S., et al., Phys. Rev. Lett. **58**, 2019 (1987); Boris, S. D., et al., Pis'ma Zh. Eksp. Teor. Fiz. **45**, 267 (1987) [Sov. Phys. JETP Lett. **45**, 333 (1987)].

3. Fritschi, M., et al., Phys. Lett **173B**, 485 (1986).

4. Kawakami, H., Nisimura, K., Ohshima, T., Shibata, S., Shoji, Y., et al. Phys. Lett. **187B**, 198 (1987).

5. Wilkerson, J. F., et al., Phys. Rev. Lett. **58**, 2023 (1987).

6. Liu, J. W., Phys. Rev. A **7**, 103 (1973).

7. Inokuti, M., Rev. Mod. Phys. **43**, 297 (1971).

8. Bartlett, R. J., Brown, G. S., Bowles, T. J., Crasemann, B., Henderson, J., Knapp, D. A., Robertson, R. G. H., Schaphorst, S.

Sorenson, S. L., Trela, W. J, Wark, D. L., and Wilkerson, J. F. (unpublished).

9. Robertson, R. G. H., et al., Proceedings of the VIIth Moriond Workshop, Les Arcs, France, January 1989 (to be published).

10. Kolos, W., et al., Phys. Rev. A **31**, 551 (1985).

11. Cohen, J. S., private communication.

12. Staggs, S. T., et al., Phys. Rev. C **39**, 1503 (1989).

13. Martin, R. L. and Cohen, J. S., Phys. Lett. **110A**, 95 (1985).

14. Fackler, O. et al., Phys. Rev. Lett. **55**, 1388 (1985).

15. Ågren, H. and Carravetta, V., Phys. Rev. A **38**, 2707 (1988).

16. Kaplan, I. G. and Smelov, G. V., in Proceedings of the International Symposium on Nuclear Beta Decays and Neutrino, edited by T.Kotani, H. Ejiri and E. Takasugi (World Scientific, Singapore 1986), p. 347.

17. Williams, R. D. and Koonin, S. E., Phys. Rev. C **27**, 1815 (1983)

18. Intemann, R. L., Phys. Rev. A **26**, 3012 (1982).

19. Friar, J. L. private communication.

20. Robertson, R. G. H. and Knapp, D. A., Ann. Rev. Nucl. Part. Sci **38**, 185 (1988).

21. Particle Data Group, Phys. Lett. **170B**, 1 (1986).

22. Irvine, J. M., and Humphreys, R., J. Phys. G: Nucl. Phys. **9**, 847 (1983).

23. Chodos, A., Hauser, A. I., and Kostelecky, V. A., Phys. Lett. **150B**, 431, (1985).