notation would be $\langle m^{\mathrm{Maj}}\rangle_\nu$ which is constrained to be less than 10 eV, with 90% CL, by our data. The limiting half-life reported here, when considered with the shell-model calculations of Ref. 5 and the direct mass measurement of Ref. 4, strongly implies that the electron neutrino is not a Majorana mass eigenstate. This conclusion was reached earlier in Ref. 5 on much weaker experimental constraints.

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Complete Particle-Core Multiplets Populated in ^{99}Ru by the (^{3}He, $2n\gamma$) Reaction

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Extensive sets of yrast and nonyrast states in ^{99}Ru have been populated by the reaction ^{98}Mo(^{3}He, $2n\gamma$)^{99}Ru. The population of nonyrast states is attributable to the characteristics of the reaction rather than the specifics of the nuclear structure involved. Several complete particle-core multiplets have been successfully interpreted with a particle-rotor model.

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(HI, $xn\gamma$) reactions have been used extensively to study the band structure of nuclei. These reactions, however, preferentially populate states of maximum angular momentum at a given energy (yrast states). In an odd-A nucleus these frequently correspond to the most aligned coupling of the core and odd-particle angular momenta. Conceptually different nuclear models frequently give similar predictions for yrast states; hence differentiation of disparate models requires the population of a more complete set of nuclear states. Light-particle–induced reactions have traditionally been used to populate nonyrast states. Standard reactions generally populate their own subsets of the complete structure, limited by angular momentum transfer and/or spectroscopic selection rules, so that the criterion of completeness is not satisfied. If only low-spin states are of interest, complete sets can be populated by the average-resonance-capture (n, γ) reactions. In order to investigate different particle-core coupling schemes, a means of bridging the angular momentum gap between (n, γ) and (HI, $xn\gamma$) reactions is required. This Letter reports a new approach which is remarkably successful in populating complete multiplets of states.

Compound-nucleus reactions clearly average over the nuclear structure in the incident channel, and the initial angular momentum in the residual nucleus can be controlled by varying the mass of the projectile and its energy relative to the Coulomb barrier. If, however, the goal is to populate the widest possible range of nonyrast states, the excitation energy relative to the yrast line, $E_y{}^*$, is critical. The nonyrast states of interest lie in a range ΔE above the yrast states. As long as ΔE is small compared to $E_y{}^*$, the transition rates to all these states can be similar. Thus, a high $E_y{}^*$ substantially increases the possibility of populating complete sets of nonyrast states. $E_y{}^*$ is basically controlled by the Q value of the reaction, so that large positive Q values are desirable. A ^{3}He projectile is ideal because of its large mass excess.

States in ^{99}Ru have been populated by the reaction ^{98}Mo(^{3}He, $2n\gamma$)^{99}Ru. The 13-MeV ^{3}He beam was obtained from Purdue University's model FN tandem Van de Graaff accelerator. γ-ray angular distributions, γ-γ coincidences, γ-γ directional correlation, and γ-ray linear polarization measurements were performed. The normal angular-momentum analysis (angular distributions and measurements of directional correlation from oriented nuclei) used to establish spins in (HI, $xn\gamma$) reactions is complicated in the (^{3}He, $2n\gamma$) experiment because the system is relatively deoriented. As a result, many A_{44}'s from angular distributions were statistically unmeasurable. However, combining the linear polarization and the A_{22} allows a definite spin assignment. Firm spin assignment could be made for essentially all the low-lying states of the resultant decay scheme shown in Fig. 1. Asterisks indicate near yrast states which constitute three bands built on $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{11}{2}^-$ states. These states, and a few others, have been observed previously.[1,2] The nonyrast states observed here exhibit a wide range of angular momenta from $\frac{1}{2}$ to $\frac{17}{2}$.

The question of completeness can be qualitative-

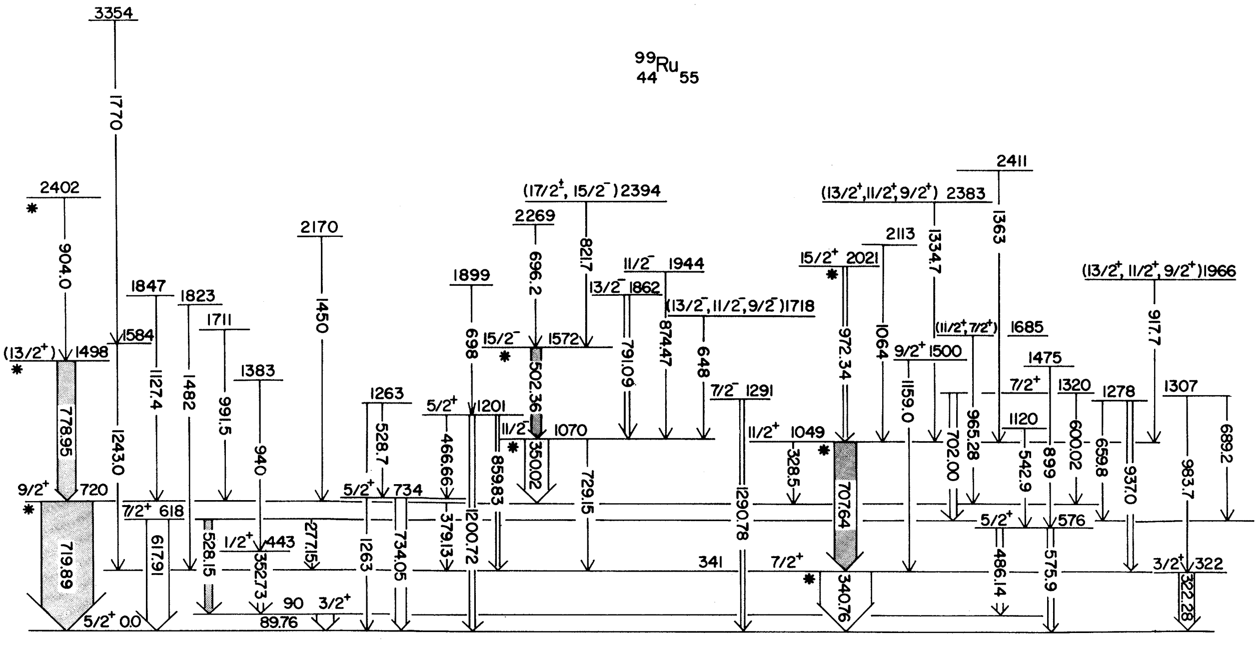

FIG. 1. Decay scheme of ^{99}Ru. The spin and parity assignments enclosed in parentheses are not uniquely determined by the data. Arrow widths are proportional to observed intensities and the shaded arrows indicate $\Delta I = 2$ transitions.

ly evaluated in a model-independent way. A complete set of states can be constructed by coupling each available particle to the ground and excited states of the core. Each of these multiplets will be spread over an energy range centered about the sum of the particle and core energies. The lowest positive-parity states of ^{99}Ru would thus reflect the coupling of $\frac{5}{2}^+$ and $\frac{7}{2}^+$ particles to the ground state and the first 2^+ state, and the lowest negative-parity states the coupling of an $\frac{11}{2}^-$ particle to the same core states. States with all of the spins this counting scheme requires have been observed in the present work. This comparison is obviously over-simplified, but it is consistent with complete $|2+j; I\rangle$ multiplets. A more specific evaluation requires the use of a nuclear model.

Ideally, the best model would be one in which any particle could be coupled to all states of the core, and relevant energies and transition properties calculated. The interacting boson approximation (IBA) model provides the possibility of treating the core completely.[3] However, for odd-A nuclei multi-j shell, and $M1$ transition, calculations cannot be performed at present. Hence, this model cannot be used in the present context. Particle-rotor models cannot by their nature include core states which are patently nonrotational (the second 2^+ state, for example). However, multi-j shell calculations are tractable, and electromagnetic transition probability calculations follow from the established work of Nilsson.[4] Thus, a particle-rotor model has been used in an attempt to identify multiplets based on the first 2^+ state (assumed to be rotational) of the core.

By consideration of the nucleus as a slightly deformed, symmetric rotor, bands such as those mentioned above have been successfully interpreted in many transitional nuclei.[5,6-8] This particular model utilizes the strong-coupling limit of the rotational Hamiltonian[4] with the Coriolis interaction treated to all orders.[9] The model has few free parameters, and these are completely determined by the systematic structure observed with (HI, $xn\gamma$) reactions. No additional parameters are required to predict the complete multiplet structure. Calculated multiplets based on rotational core states depend primarily on the position of the Fermi surface in the Nilsson basis and the form of the Coriolis interaction.

As evidenced in Fig. 1, there are many states of similar spins and energies, making unique identification of states solely on the basis of energies impossible. As the transition properties are a more direct measure of the wave functions, branching ratios provide a characteristic signature for the states. Correspondence of branching ratios means that not only does the observed state decay as predicted, but it is fed as predicted. It is, therefore, not just the decay properties of a single state which suggest the identification; it is the decay pattern of all the states together which determine the identification of individual states.

Although the core angular momentum, R, is not a good quantum number in the strong-coupling limit, each calculated wave function exhibits a dominant R value. Three of the states observed correspond to the $R\simeq 0$ band heads of the $\frac{5}{2}^+$, $\frac{7}{2}^+$, and $\frac{11}{2}^-$ bands. Fifteen other low-lying states correspond to three complete $R\simeq 2$ multiplets of $d_{5/2}$, $g_{7/2}$, and $h_{11/2}$ parentage. In Fig. 2, dashed curves connecting the calculated energies are shown with the experimental energy levels. The identification of various members of the three multiplets is quite specific according to the criteria discussed above. Consider as an example the decay of the state at 1686 keV. For either possible spin assignment ($\frac{7}{2}^+$ or $\frac{11}{2}^+$) several possible decay paths would seem to be energetically

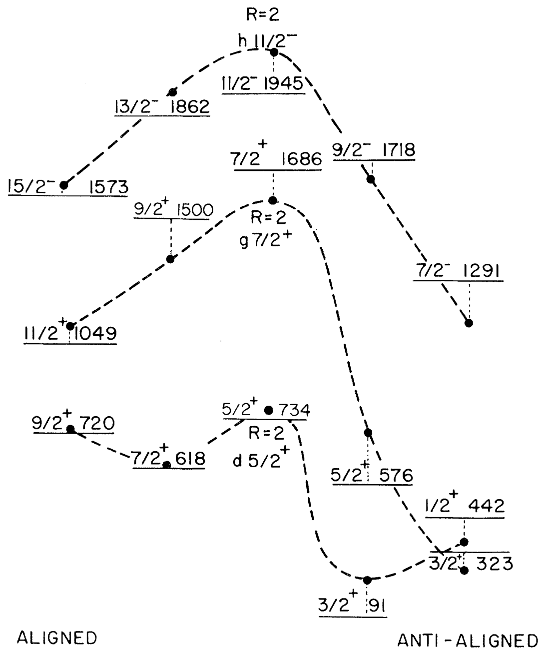

FIG. 2. States identified as members of the $R\simeq 2$ multiplets based on $d_{5/2^+}$, $g_{7/2^+}$, and $h_{11/2^-}$ particles. The dashed curves connect the energies calculated from the rotational model with the deformation parameter, δ, equal to 0.12.

favored over the one observed. The calculation predicts that the $|2^+\frac{7}{2},\frac{7}{2}\rangle$ state will decay only to the $|2^+\frac{5}{2},\frac{9}{2}\rangle$ state. Since the 1686 state has this decay pattern and the energy predicted by the calculation, it is identified as the $|2^+\frac{7}{2},\frac{7}{2}\rangle$ state.

The shape of the calculated curves in Fig. 2 is governed by the effect of the Coriolis interaction, which reduces the energy of the states in proportion to the alignment of the total angular momentum, I, and the particle angular momentum, j.[9] I and j are aligned when R and j are aligned, or antialigned. An arch curve is expected when the Fermi surface is near the low-lying states of given parentage. A flatter curve is expected when the Fermi surface is near the higher states of a given parentage, as less alignment is possible. These are the same conditions which produce $\Delta I = 2$ or $\Delta I = 1$ yrast bands. In ^{99}Ru the Fermi surface satisfies the former condition for the $g_{7/2}$ and $h_{11/2}$ multiplets and the latter condition for the $d_{5/2}$ multiplet as shown in Fig. 2.

In addition to the $R \simeq 2$ multiplets, states from the 4^+ and second 2^+ multiplets are expected. States having the energies and transition properties calculated for $R \simeq 4$ multiplets have been observed. Unfortunately, the spins of many states at higher excitation energies could not be determined in the present work because of poor statistics. Thus, no reliable measure of completeness for $R \simeq 4$ multiplets has been attempted. Other states are observed which do not fit into the pattern of the particle-rotor model. Thus the reaction may be more complete than has been demonstrated for the $R \simeq 2$ multiplets.

As evidenced by the presented results, the (^{3}He, $2n\gamma$) reaction is a powerful tool for populating nonyrast states in a wide range of angular momenta. In fact, three complete particle-core multiplets have been observed experimentally and successfully interpreted with a particle-rotor model. The empirical results are actually more complete than the model. This completeness allows a more rigorous test of various models than has previously been possible.

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Velocity-Modulated Infrared Laser Spectroscopy of Molecular Ions: The ν_1 Band of HCO$^+$

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The first observation of vibration-rotation transitions in HCO$^+$ is reported. The ν_1 absorption band was measured with a color-center laser by modulating the drift velocity of the ion in an ac discharge and detecting the Doppler-shifted absorptions with lock-in techniques. The ν_1 frequency is determined as 3088.727 ± 0.003 cm^{-1}.

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Vibration-rotation spectroscopy of charged molecules has become experimentally realizable only within the last decade, principally through the pioneering efforts of Wing and co-workers[1] and Oka[2]. Wing and co-workers have observed vibrational spectra of HD$^+$, HeH$^+$, and D$_3^+$ in fast ion beams by monitoring the changes in charge-transfer cross sections that result when vibration-rotation transitions of these ions are velocity tuned into coincidence with a CO laser.