EXTENSIVE ROTATIONAL STRUCTURE IN THE ODD-ODD DEFORMED NUCLEUS Ho^{166}†

Gordon Lee Struble, Neil Shelton, and Raymond K. Sheline
Florida State University, Tallahassee, Florida

(Received 6 August 1962)

Odd-odd deformed nuclei are difficult to study in detail by conventional beta- and gamma-ray spectroscopy. Investigations using these methods lead to a sparsity of data because of the systematics of the mass-energy surfaces of the appropriate odd-odd and even-even nuclei and because only the low-spin states of the odd-odd nuclei can be populated by the 0^+ ground states of the even-even parents. Using (d,p) reaction spectroscopy, we have been able to observe 31 states below 818 keV in Ho^{166}. Twenty-two of the states fit into four rotational bands, and three of these bands result from the two lowest energy Nilsson configurations.[1] Thus, extensive rotational structure has been observed in an odd-odd nucleus for the first time.

The observation of relatively complete and interpretable level structure below 818 keV has led us to the following conclusions: (1) Moments of inertia of the two rotational bands derived from the same configuration, with Ω_p and Ω_n parallel for one band and Ω_p and Ω_n antiparallel for the other, are identical within our experimental error. However, in different configurations the moments of inertia vary. (2) The energy displacement between the odd and even members of the $K=0$ band, which was first described by Asaro et al.,[2] continues systematically to high spins. The moments of inertia for these members are identical. (3) The coupling rules of Gallagher and Moszkowski,[3] which describe the spin of the ground state, are on rare occasions in error, but the nature of the error can be understood in terms of the rotational contribution to the two states involved. (4) The Nilsson levels of neighboring odd-A nuclei can be used to predict the lowest energy configurations in Ho^{166}.[1] Thus, the Nilsson level systematics which have been so successful in predicting odd-A nuclei seem to be equally useful in interpreting not only ground states but also other low-lying configurations in odd-odd nuclei.

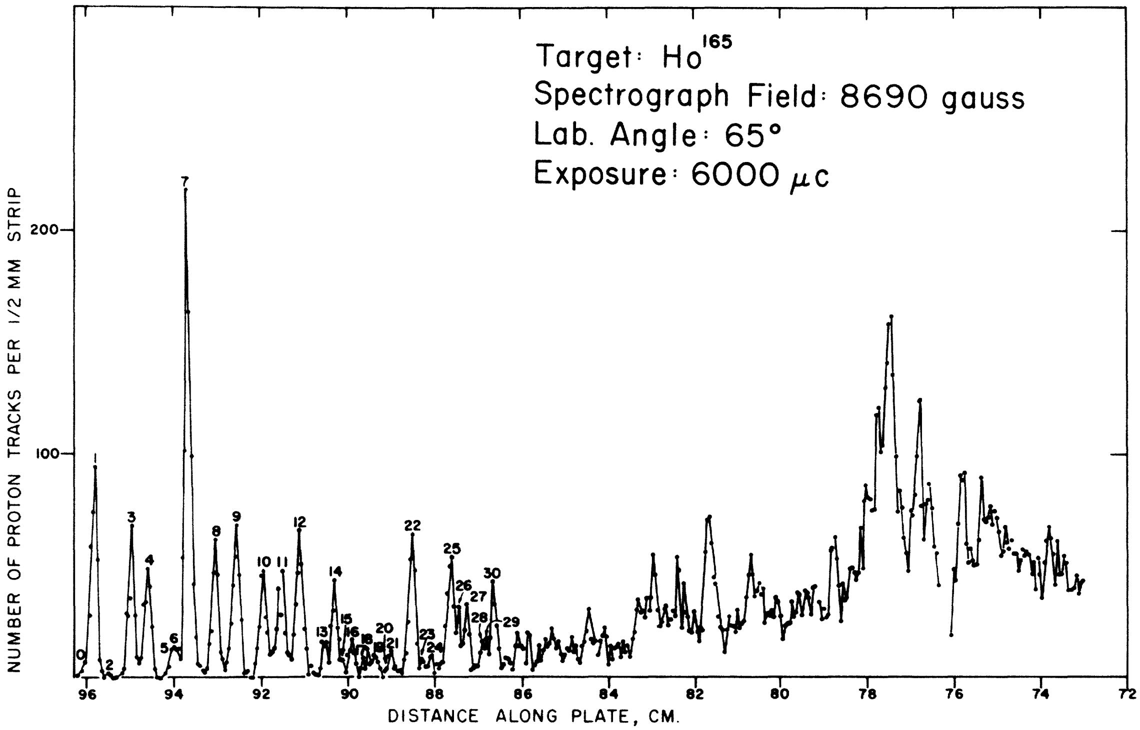

FIG. 1. Experimentally determined levels in Ho^{166}. A proton spectrum is shown of the reaction Ho$^{165}(d,p)$Ho^{166} run at an angle of 65° with respect to the 12-MeV deuteron beam. The number of proton tracks per $\frac{1}{2}$-mm strip is plotted versus plate distance. The large full widths at half-maxima observed in the levels labeled 6 and 12 do not change appreciably with angle, suggesting that they both may be unresolved doublet states.

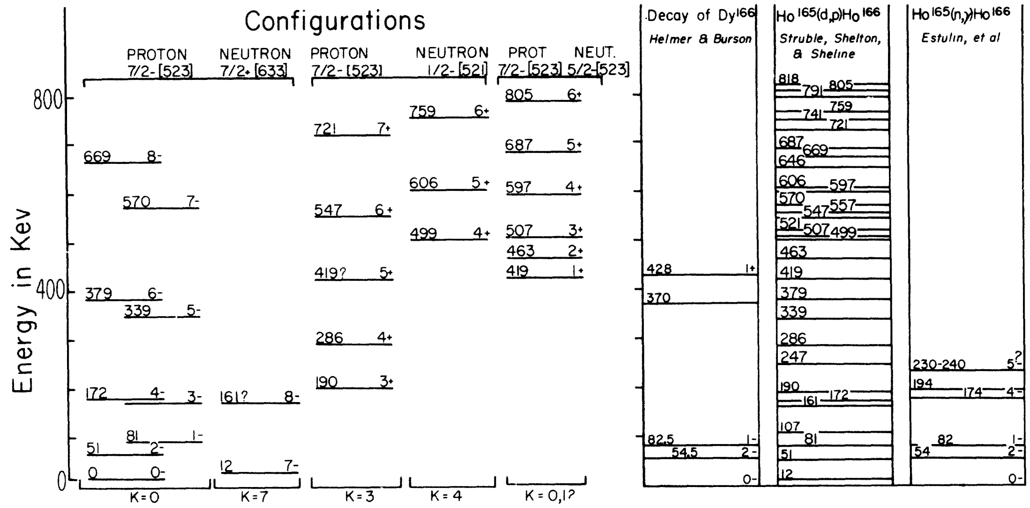

FIG. 2. Rotational structure observed in Ho^{166}. On the right-hand side the 31 levels that have been identified are compared with those found by Helmer and Burson through the decay of Dy^{166} and by Estulin et al. by (n,γ) reaction spectroscopy.[5,6] On the left-hand side the states are grouped into five rotational bands under the Nilsson configurations which are coupled to form the band head. The numbers are the experimentally determined energies. A question mark on a level indicates that at the calculated energy a previously assigned level appears but that there is evidence for unresolved doublet structure. Choosing a single value of $\hbar^2/2\mathfrak{J}$ of 9.2 keV for the $K=0^-$ and $K=7^-$ bands and 12.0 keV for the $K=3^+$ and $K=4^+$ bands, comparisons between the theoretically expected band and the experimentally observed band are made. In the $K=0$ band the average value of the absolute difference between the levels calculated and the experimentally determined states is 4 keV. For the $K=7$ band this difference is 2 keV, while for both the $K=3$ and $K=4$ bands it is 7 keV. This is within the experimental accuracy of this method. The anomalous energies in the band built on the 1^+ state indicate an admixture of a $K=0$ configuration with the $K=1$ intrinsic configuration.

The experimental data for this paper were obtained using a Browne-Buechner type spectrograph coupled with the Florida State University Tandem Van de Graaff accelerator.[4] A spectrum obtained for the reaction $\mathrm{Ho}^{165}(d,p)\mathrm{Ho}^{166}$ is shown in Fig. 1 where the number of proton tracks per $\frac{1}{2}$-mm strip is plotted versus plate distance. Q values are generally determined to ±10 keV with differences in Q values corresponding to energy of excitation in Ho^{166} being somewhat more accurately determined.

An attempt has been made to analyze these levels into intrinsic states with associated rotational bands from energy considerations alone. The spins and parities determined by previous investigators for seven of the states have been a valuable assistance in our analysis.[5,6]

On the right-hand side of Fig. 2 a comparison is made between previous experimental data and the data of this research. On the left-hand side the levels have been grouped into several rotational bands to show our analysis more clearly. A question mark indicates that at the calculated energy, although a previously assigned level appears, there is evidence for a doublet structure (see Fig. 1).

The 67th proton has been successfully assigned the Nilsson asymptotic quantum numbers $\frac{7}{2}^-$ [523], and the 99th neutron has been assigned $\frac{7}{2}^+$ [633].[5] According to the rules of Gallagher and Moszkowski, the coupling of these odd nucleons in Ho^{166} should lead to a ground state of spin 7^- with its associated rotational band and a 0^- state with associated rotational states. In fact, by these and previous data, the ground state of Ho^{166} seems to be 0^-.[7] This violates the coupling rules of Gallagher and Moszkowski but can be understood by considering the difference in rotational contribution to the energy of the intrinsic states formed by the coupling of the odd nucleons. This has the general form $\Delta W_{\mathrm{rot}} = (\hbar^2/\mathfrak{J})\Omega_l$, where $\mathfrak{J}$ is the moment of inertia and Ω_l is the smaller value of Ω_p and Ω_n. When Ω_l is large as it is in Ho^{166}, the rotational effect will be sufficient to reverse the sense of the coupling rules. Therefore, it is not surprising to find a 0^- ground state. It is important to emphasize that the energy displacements between the odd and even members of the $K=0$ bands continue systematically to high spins and the moments of inertia are identical. The $K=7^-$ band head representing the recoupling of the odd proton and odd neutron is assigned to the 12-keV level. This is in agreement with those investigators who have observed by decay scheme measurements an approximate degeneracy in the 0^- and 7^- isomeric states.[7,8]

The 3^+ state probably results from the intrinsic configuration in which the $\frac{7}{2}^-$ proton state couples with the low-lying $\frac{1}{2}^-$ [521] neutron state which is seen as the first excited intrinsic state in both Dy^{165} and Er^{167}.[9] This spin assignment agrees with Gallagher and Moszkowski's coupling rules. One then expects another intrinsic state due to the coupling of the same single-particle states but in the opposite sense. We have assigned this state to the 4^+ level at 499 keV. The rotational band built on the 4^+ level has the same moment of inertia as the 3^+ band.

Some element of doubt remains about the exact nature of the 1^+ intrinsic state. Helmer and Burson suggest from transition intensities that $K \neq 1$, but their data is not conclusive.[5] Since the moments of inertia are identical, it seems likely that this level is the 1^+ $(K = 1^+)$ state seen as the Ho^{162} ground state.[10] In this configuration, the $\frac{7}{2}^-$ proton state couples with $\frac{5}{2}^-$ [523] neutron state. The energy alternation of the even-odd states observed in this band and the data of Helmer and Burson suggest an admixture of an octopole vibration $(K = 0^+)$ built on the $K = 0^-$ ground state or possibly an intrinsic configuration with $K = 0^+$.

This analysis is, for the most part, based on purely energy systematics. In spite of this, the configurations, the intrinsic states, the associated rotational bands, and the agreements of the moments of inertia of the same configuration give us confidence in the general structure of the analysis.

[†] This work was supported by the U. S. Atomic Energy Commission Contract AT-(40-1)-2434.

[1] S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Medd. 29, 16 (1955).

[2] F. Asaro, I. Perlman, J. O. Rasmussen, and S. G. Thompson, Phys. Rev. 120, 934 (1960).

[3] C. J. Gallagher, Jr., and S. A. Moszkowski, Phys. Rev. 111, 1282 (1958).

[4] C. P. Browne and W. W. Buechner, Rev. Sci. Instr. 27, 899 (1956).

[5] R. G. Helmer and S. B. Burson, Phys. Rev. 119, 788 (1960).

[6] I. V. Estulin, A. S. Melioransky, and L. F. Kalinkin, Nucl. Phys. 24, 118 (1961).

[7] O. B. Nielsen (private communication).

[8] J. S. Geiger, R. L. Graham, and G. T. Ewan, Nucl. Phys. 30, 409 (1962).

[9] B. R. Mottelson and S. G. Nilsson, Kgl. Danske Videnskab. Selskab, Mat. Fys. Skrifter 1, 8 (1959).

[10] I. Perlman, Proceedings of the International Conference on Nuclear Structure, 1960, edited by D. A. Bromley and E. W. Vogt (University of Toronto Press, Toronto, Canada, 1960), p. 547.

ANNIHILATION OF ANTIBARYONS[*]

Y. Eisenberg[†]
Laboratory for Nuclear Science and Department of Physics, Massachusetts Institute of Technology,
Cambridge, Massachusetts

(Received 17 December 1962)

The purpose of the present note is to draw attention to some simple consequences which follow from the asymmetry of the "strange"-mesonic cloud surrounding baryons and antibaryons.

Let us consider first the nucleon-antinucleon annihilation into two mesons. Our point is then the following: the π-mesonic cloud around a nucleon or an antinucleon may contain, in general, pions of all charges [e.g., $\bar{p} \to \pi^- \bar{n}$, $\pi^0 \bar{p}$, or π^+-$(\bar{N}^*)^{--}$; a similar situation exists for $\bar{n}$, p, and n]. However, the "strange"-meson cloud surrounding antinucleons can contain (in a dissociation to single mesons) only $\bar{K}^0$ and K^- mesons, and that surrounding nucleons only K^+ and K^0 mesons (i.e., $\bar{p} \to \bar{K} + \bar{Y}$ and $p \to K + Y$, where Y represents all possible hyperons and excited hyperons, with $S = 1$).[1] In the c.m. system, in the annihilation process into two mesons, one can imagine the $\bar{p}$ dissociating into meson + $\bar{B}$, with the meson continuing in the direction of the $\bar{p}$ and the $\bar{B}$ annihilating the other nucleon to give the second meson. Thus if we have, for example, $\bar{p} + p \to \pi^- + \pi^+$, the π^- or π^+ meson could be emitted from the $\bar{p}$ cloud. However, if we have annihilation into strange mesons, $\bar{p} + p \to K^- + K^+$, the K^- will always be emitted from the $\bar{p}$ cloud, whereas the K^+ will come from the p cloud. The simplest diagrams representing this situation are shown in Fig. 1. If this represents the main mechanism for $\bar{p}p$ annihilation at high energies into two mesons, one should expect to observe experimentally a more symmetric c.m. angular distribution for the π^- mesons and a strong peak-