allow us to clearly separate the $\chi(3415):\chi(3510):\chi(3555)$ states, although our fit indicates the higher mass is preferred. We note that a recent gluon fusion model[2] predicts production cross sections for these states in the ratio 3:4 for $\chi(3415):\chi(3555)$. Production of the $\chi(3510)$ by fusion of two gluons is forbidden. Folding in the measured[10] branching ratios for $\chi \to \psi\gamma$, we would expect to see ψ-γ's in the ratio 1:6.5 for $\chi(3415):\chi(3555)$. Our data are consistent with this ratio.

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Backbending in ^{22}Ne

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The yrast line in ^{22}Ne has been investigated by the reaction ^{11}B+^{13}C up to the 10^+ state which is found at 15.46-MeV excitation energy. A backbending in ^{22}Ne shows up around spin 8. The Strutinsky method is applied to interpret the ^{22}Ne rotational motion.

The investigation of yrast lines of light nuclei ($A<30$) at high excitation energy is of great importance because here, in contrast to heavier nuclei, very reliable nuclear-structure calculations are available.[1-3] Therefore, phenomena like backbending, etc., can possibly be related to particular microscopic mechanisms in a more unique way than in heavy nuclei. Moreover, in this mass region purely microscopic (shell model) and macroscopic (Strutinsky) methods both can be applied to the same phenomena and thus can be compared with each other.

The ^{22}Ne nucleus lying between the two best known light nuclei ^{20}Ne (Refs. 4 and 5) and ^{24}Mg (Ref. 6) is one of the most highly deformed light nuclei. The yrast line in ^{22}Ne is at present clearly identified only up to the 6^+ state at 6.305 MeV,[7] a member of the $K^\pi=0^+$ band built on the ^{22}Ne ground state. Broude *et al.*[8] suggested a candidate for the 8^+ yrast state at 11.00-MeV excitation energy. Almost no information exists for levels above this energy. This is mainly due to the low threshold for particle emission that limits the applicability of particle-γ correlation studies to excitation energies of ~10 MeV in ^{22}Ne. For higher excitation energies, however, a powerful method is particle spectroscopy by heavy-ion compound reactions.[6, 9-11]

The ^{20}Ne nucleus is the only light nucleus which showed experimental evidence for a backbending at relatively low excitation energies.[4] This effect has been successfully reproduced by shell-model calculations using the full s-d shell basis.[1] This model has been applied in the prediction of rotational bands in ^{22}Ne.[3] Using the SU(3) group to truncate the shell-model space, Arima, Sakakura, and Sebe[1] predicted an irregularity in the yrast line of ^{22}Ne (backbending) around spin 8 and the position of the 10^+ yrast state at 15.8 MeV.

Only very recently an alternative method, the Strutinsky procedure for rotating nuclei,[12] has been applied to light nuclei in the mass range $A \approx 20-50$.[13] This method works on the basis of a deformed single-particle model and is therefore capable of describing also states with spins higher than those accessible in shell-model calculations. Even though it is presently not directly applicable to the calculation of low-spin states ($I \lesssim 8$), because of its neglect of residual interactions, it nevertheless yields useful qualitative information on shapes and moments of inertia of these states. Details on the general procedure of the calculations presented in this paper are given in Ref. 13.

In the present Letter an investigation of the ^{22}Ne yrast line up to ~19-MeV excitation is reported. A backbending of the yrast line is found at $I = 8-10$. The reactions[14] ^{11}B(^{13}C,d)^{22}Ne and ^{13}C(^{11}B,d)^{22}Ne at $E_{\text{c.m.}} = 19$ MeV were used to select high-spin states in the final nucleus. The experiment was performed at the Heidelberg MP-tanden Van de Graaff accelerator using a multigap magnetic spectrograph for detection of the reaction products. A typical spectrum is shown in Fig. 1. Angular distributions were measured for 82 states in ^{22}Ne in the range $\theta_{\text{c.m.}} = 7°-90°$ in steps of $4°-7°$. A resolution of ~60–80 keV full width at half maximum (FWHM) was achieved using ~25-μg cm^{-1} self-supporting targets. At the bombarding energy used in the present experiment the grazing angular momentum in the entrance channel is ~$14\hbar$.

Experimental cross sections were obtained by use of the least-squares peak-fitting program JASPER based on symmetric Gaussian peak shapes and by a second-order polynomial for background definition in small-excitation-energy regions.[6] The FWHM was assumed to be equal for neighboring peaks in the spectra. The ambiguity in the definition of the background is reflected in the uncertainty attributed to the differential cross section.

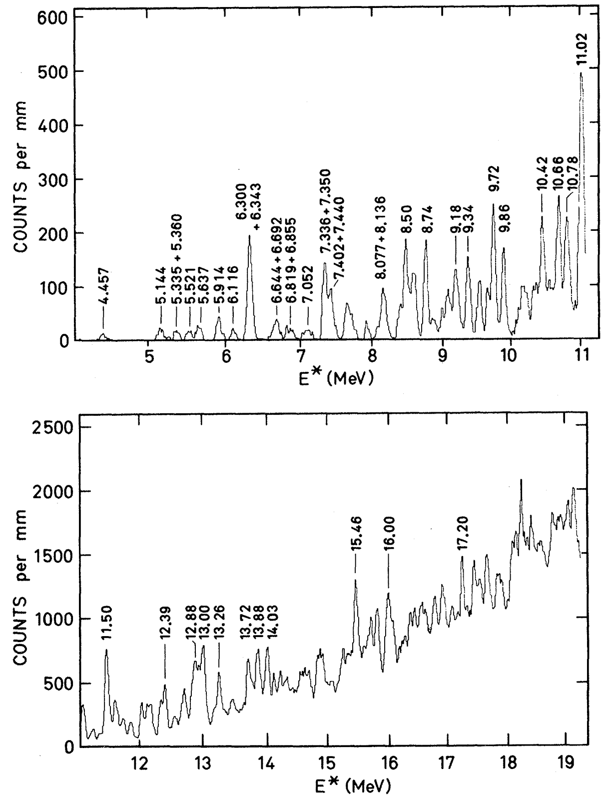

FIG. 1. Spectrum of the reaction ^{11}B(^{13}C,d)^{22}Ne measured at $E_{\text{lab}} = 41.4$ MeV and $\theta_{\text{lab}} = 13°$.

The measured angular distributions were analyzed within the statistical model using the computer code STATIS.[15] The reaction ^{11}B(^{13}C,d)^{22}Ne shows a damping of statistical fluctuations allowing for an average fluctuation of ~15% for the total cross section of a transition leading to a 10^+ state in ^{22}Ne.

By simultaneous least-squares fit to all *relative* angular distributions of transitions to states of known spin as a function of the angular momentum cutoff ($J_{\max}$) in the Hauser-Feshbach expression (see, e.g., Refs. 6, 9), the critical angular momentum in the ^{24}Na compound nucleus at the excitation energy of 39.17 MeV was determined. The value $J_{\max} = 12$ was obtained independently by both reactions using a wide range of level-density parameters a ($A/9.5 < a < A/5.3$) [Fig. 2(a)]. This value is much lower than the yrast spin expected for ^{24}Na at 39-MeV excitation energy under the assumption of a rigid rotor and is thus probably reflecting an entrance-channel limitation. An average level density $A/a = 6.5 \pm 0.1$ reproduces the *absolute* experimental angular dis-

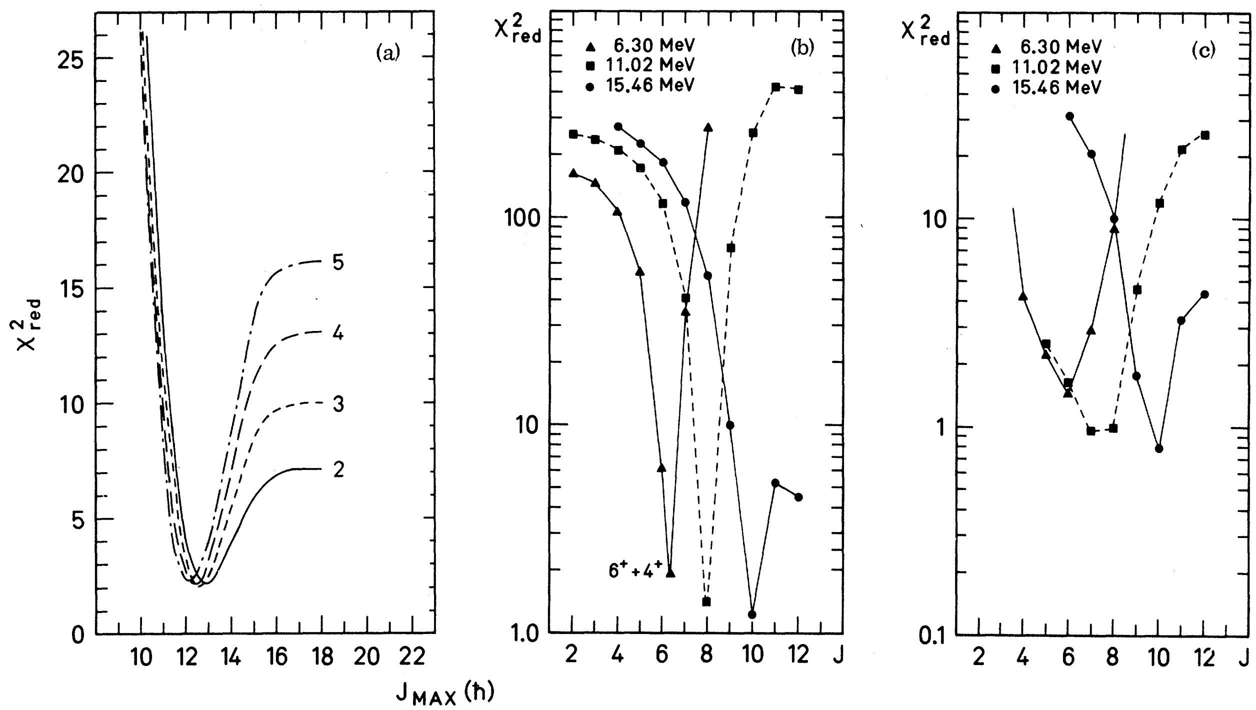

FIG. 2. (a) χ^2 values of a fit to relative angular distributions of states of known spin as a function of J_{max}. Level densities used are $a/A = 0.125$ (curve 2), 0.135 (curve 3), 0.145 (curve 4), and 0.155 (curve 5). (b) χ^2 of fits to the absolute angular distributions by statistical-model calculations as a function of the spin of the final state (assuming singlets). The 6^+ yrast state at 6.305 MeV has been fitted also together with the unresolved 4^+ state at 6.34 MeV. (c) χ^2 of fits to the shape of the angular distributions by statistical-model calculations as a function of the spin of the final state.

tributions.

Good agreement is obtained between experimental and theoretical angular distributions for states of known spin. In the present Letter only the ^{22}Ne yrast states will be discussed. A detailed description of all results will be given elsewhere.

For peaks at high excitation energies ($E^* > 10$ MeV), where the level density is higher, the possibility of a cluster of low-spin states simulating a high-spin state cannot be ruled out completely[6,11] by a fit to the *absolute* angular distributions [Fig. 2(b)]. However, since the shape of the angular distributions is given mainly by the highest-spin state of a supposed cluster (due to its higher cross section), a cluster built up by low spins should display a very anisotropic angular distribution (~ $1/\sin\theta$) while the high-spin states will have a flatter distribution. Therefore by a χ^2 fit to the shape of the angular distribution (anisotropy), as proposed by Szanto de Toledo *et al.*,[10] a high-spin state can be distinguished from a cluster of low-spin states [Fig. 2(c)]. This method has the highest sensitivity for final spins a few units below J_{max}. Figures 2(b) and 2(c) show that best χ^2 fits of the shape are obtained for spin-8^+

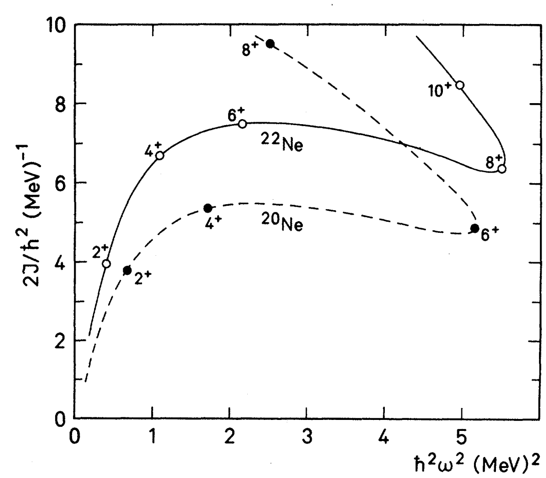

FIG. 3. Effective moments of inertia plotted as a function of the square of the effective rotational frequencies for ^{20}Ne and ^{22}Ne.

and -10^+ for the states at 11.02 and 15.46 MeV, respectively. The high-spin selectivity of the reaction is such that, in the case of a transition to a state at 16 MeV of excitation, the differential cross section varies ~ 30% when a spin of 9^- or 10^+ is attributed. The χ^2 values of the fits for the assignments given above are within the 97% confidence level. Fits for several possible doublets show, however, that the possibility of one unit lower in $\hbar$ for these yrast states cannot be completely ruled out.

The plot of the effective moment of inertia of ^{22}Ne as a function of the effective rotational frequency is shown in Fig. 3, and displays clearly a backbending phenomenon at spin 8. For comparison the backbending of ^{20}Ne is also shown.

The existence of these backbends is due to a rotational alignment effect: The particles in the sd shell align their angular momenta along the axis of rotation.[16] Thus the physical explanation for the backbending is identical with that in heavy nuclei[17] with the simplification here that only four or six particles are treated explicitly.

As can be seen from Fig. 3, there are two important differences between ^{20}Ne and ^{22}Ne. First, the moment of inertia for the 4^+ and 6^+ states is larger in ^{22}Ne than in ^{20}Ne by much more than can be accounted for by a simple $A^{5/3}$ scaling of the moments of inertia (for the 6^+ state in ^{22}Ne this would give a value of $2I/\hbar^2 \approx 6$ MeV^{-1}). Second, the backbending occurs in ^{22}Ne two units of angular momentum later than in ^{20}Ne. Both effects can be understood qualitatively with the help of Strutinsky-type calculations shown in Fig. 4. For the 6^+ state these calculations yield a smaller deformation for ^{20}Ne than for ^{22}Ne. This difference is correlated with the later approach to $\gamma = -60°$ in the ^{22}Ne case, corresponding to an oblate nucleus rotating around its symmetry axis. In this state all particles in the open sd shell are aligned along the rotation axis. Naturally, this alignment takes place later in ^{22}Ne because of the two extra nucleons.

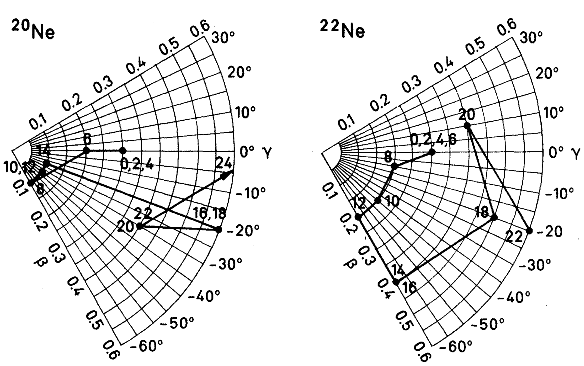

FIG. 4. Trajectories in the β-γ deformation-energy surfaces for yrast states in ^{20}Ne and ^{22}Ne.

The sharp minima with respect to β deformations in the β-γ deformation-energy surface show a drastic "antistretching" effect mainly in ^{20}Ne up to spin 14, simultaneous with the trend towards triaxiality. On the other hand, the softness of the minima in the β-γ plane with respect to the γ deformation, in contrast to the case of "good" heavy rotors, explains the experimental difficulties in defining excited rotational bands in ^{22}Ne.

In conclusion, the observation of a 10^+ yrast state at 15.46-MeV excitation in ^{22}Ne confirms some of the shape effects expected in fast rotating light nuclei.

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Total Angular Momentum Determinations from the (t_{pol},d) Reaction on ^{58,64}Ni

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The (t_{pol}, d) reaction at 16 MeV has been used to determine the total angular momentum of levels in ^{59}Ni and ^{65}Ni. This represents the first reported results of this reaction using a polarized triton beam. The data indicate distinct differences and advantages over (d_{pol},p) data at similar bombarding energies. The (t_{pol},d) reaction is used on ^{58}Ni to compare data with distorted-wave Bron-approximation predictions for known spin states and on ^{64}Ni to resolve an important controversy over spin values in ^{65}Ni.

The development of a polarized triton source[1] has permitted a number of direct-reaction experiments not previously possible. In particular, the (t_{pol},α) reaction was shown to be an excellent tool for spin determinations of proton-hole states in both sperhical[2] and deformed[3] nuclei. The neutron stripping reaction (t,d) is also known to be an excellent spectroscopic tool with the data being well suited to analysis by distorted-wave Born-approximation (DWBA) techniques, which yield consistent spectroscopic factors.[4] This feature arises from the strong-absorption characteristics of both reaction particles, which produce a strongly peaked surface reaction relatively independent of the choice of optical potentials. This strong absorption in the (t,d) reaction also produces a more definitive diffractive structure in the angular distributions which, under some circumstances, leads to a more reliable determination of the transferred orbital angular momentum than is possible with (d,p) reactions. A further difference between the (t,d) and (d,p) reactions is the higher angular momentum transfer favored by the former reaction over the latter, usually by 2–3$\hbar$.

The present Letter describes the (t_{pol},d) reaction, which has been performed for the first time. This study combines the attributes of the (t,d) reaction discussed above with analyzing-power (A_y) measurements, which permit the assignment of total angular momentum and parity (J^π) to nuclear states. In the medium-mass region discussed here, the A_y angular distributions, when considered along with the differential cross sections, are sufficiently definitive to assign reliable J^π values and spectroscopic factors. In addition, these new results show that the (t,d) measurements have a more definitive diffractive structure over a smaller angular range than (d,p) results at comparable energies. This permits a better determination of J^π values. The (t_{pol}, d) reaction also shows distinctive A_y patterns for $\frac{9}{2}^+$ states, whereas (d_{pol},p) does not.

We investigate here the (t_{pol},d) reaction on ^{58}Ni and ^{64}Ni targets. The residual nucleus ^{59}Ni has been extensively studied,[5,6] and the low-lying levels have well-established spin values. It thus serves as an excellent calibration nucleus to obtain emperical A_y angular distributions and as a point of comparison with DWBA predictions of A_y values. The study of ^{65}Ni using this technique was made to resolve a conflict in spin assign-

