High-spin states in doubly odd ^{158}Ho

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High-spin states in ^{158}Ho have been studied through the ^{152}Sm(^{11}B,5n)^{158}Ho reaction at a beam energy of 60 MeV. In addition to the previously known yrast band, three new rotational bands, namely, the $\{p7/2^-[523]\otimes n3/2^-[521]\}K^\pi=5^+$ ground-state band, the $\{p7/2^+[404]\otimes n3/2^+[651]\}K^\pi=5^+$ band, and the $\{p7/2^-[523]\otimes n11/2^-[505]\}K^\pi=9^+$ band, are proposed. The yrast band is connected to the ground-state band, and its configuration is reassigned as the $\{p7/2^-[523]\otimes n3/2^+[651]\}K^\pi=5^-$ rather than the $\{p7/2^-[523]\otimes n5/2^+[642]\}K^\pi=6^-$. On the basis of the present experimental study, the spin values of the member states of the yrast band turn out to be larger by three units with respect to the earlier tentative spin assignments and in agreement with the latest spin assignments based on the arguments of the level energy systematics and the alignment additivity. [S0556-2813(99)04006-6]

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High-spin states in ^{158}Ho have previously been studied through ^{159}Tb(α,5n) ^{158}Ho and ^{160}Dy(p,3n)^{158}Ho reactions, and only the yrast band was reported [1]. The state fed by 100.6 and 215.7 keV γ rays was assigned as the head with $I^\pi=6^-$ of the yrast band in [1], and later it was reassigned as $I^\pi=7^-$ in [2,3]. In the systematic study of the signature inversion of odd-odd nuclei in the mass region of $A\sim160$, it was suggested that the I^π of the same state should be reassigned as 9^- on the basis of the level energy systematics and the alignment additivity rule [4]. The purpose of the present experimental study is to clarify these discrepancies and to obtain more information on the high-spin level scheme of the doubly odd deformed nucleus ^{158}Ho.

In the present study, high-spin states in ^{158}Ho were populated through the ^{152}Sm(^{11}B,5n) reaction at the beam energy of 60 MeV. The ^{11}B beam was provided by the HI-13 tandem accelerator at CIAE in Beijing. A self-supporting target composed of two stacked 0.5 mg/cm^2 metallic foils, enriched to 98.4%, was used. γ-γ coincidence measurements were performed using the detecting system [5] consisting of eight Compton-suppressed HPGe detectors and one planar HPGe detector. The γ-γ coincidence matrix and DCO matrix have been constructed and, in total, about 120×10^6 coincidence events were collected. Relative excitation functions of the emitted γ rays were measured to determine the optimum beam energy and to make isotopic assignments of observed γ rays.

Figure 1 is the level scheme of ^{158}Ho proposed by the present study. In addition to the $ph11/2\otimes ni13/2$ yrast band (band 3), three new rotational bands are observed. The placements of gamma rays in the yrast band are in agreement with those of [1] except that six more levels have been added. The connections between band 1 and 2, as well as between band 2 and 3, have been established. Figure 2 shows examples of spectra which were used to construct the level scheme of Fig. 1. The DCO ratios of the stronger and cleaner linking γ rays have been determined by gating at intraband crossover transitions. DCO ratios of the 134, 246, 303, and 356 keV linking transitions are plotted in Fig. 3 together with those of the transitions of the yrast band.

Configurations which are expected to be observed in ^{158}Ho, as listed in Table I, can be constructed from the orbitals observed in neighboring odd-Z nuclei (^{157}Ho [6], ^{159}Ho [7]) and odd-N nuclei (^{157}Dy [8], ^{159}Er [9]). Quantities, such as the rotational parameter $A(\hbar^2/2\theta)$ and gyromagnetic factor G^{kk} (as defined in [10]) of bands based on these expected configurations can be predicted from the rel-

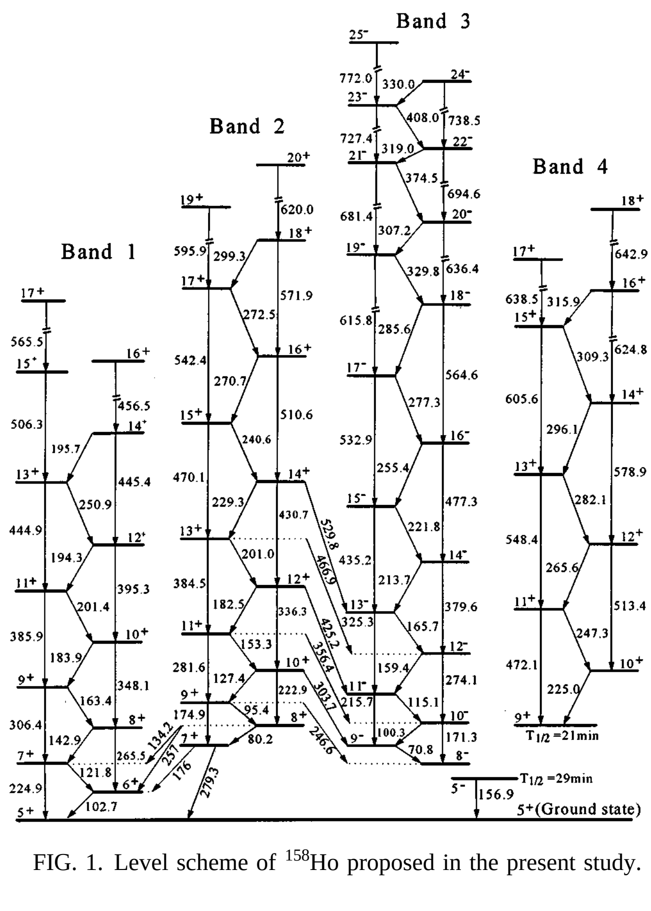

FIG. 1. Level scheme of ^{158}Ho proposed in the present study.

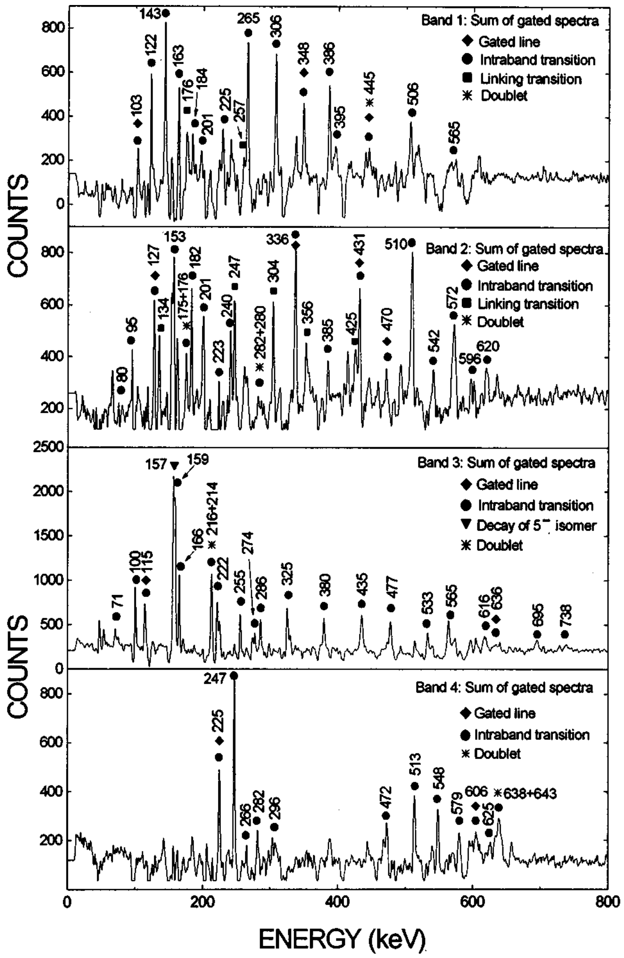

FIG. 2. Examples of γ-γ coincidence spectra.

evant quantities of the corresponding proton and neutron bands in neighboring odd-A nuclei. The comparison between these predicted quantities of the expected configurations and the experimental ones extracted from the observed bands is of great help for identifying the configurations of the observed bands, especially in the cases where the observed bands are short and information on band crossing cannot be obtained. The predicted A values of the bands built on the expected configurations and experimental ones of the observed bands are listed in Table I, where the bandhead energies $\overline{Epn}$'s which were obtained approximately by summing up $\overline{Ep}$ and $\overline{En}$ (see Table II) are also given. The parameters A of proton and neutron bands as well as the bandhead energy relative to the ground state in the neighboring odd-A

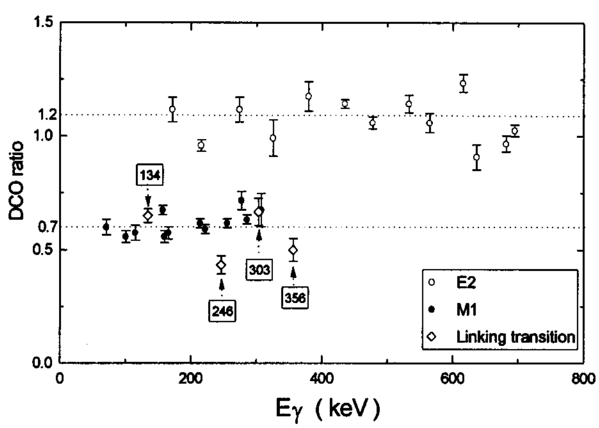

FIG. 3. DCO ratios of some linking transitions (open diamonds) together with those of $\Delta I=1$ cascade transitions (solid circles) and $\Delta I=2$ crossover transitions (open circles) of the yrast band. The DCO ratios were obtained by setting gate on crossover quadrupole transitions, and they were normalized so that the DCO ratio of 370 keV quadrupole transition in ^{159}Ho equals 1.2.

TABLE I. Comparison between experimental and predicted rotational parameter $A(\hbar^2/2\theta)$.

Configuration candidates	K^π	Prediction Epn (keV)	Prediction A (keV)	Experiment A (keV)
$\pi 7/2^-[523]\otimes\nu 3/2^-[521]$	$5^+,2^+$	0	8.6	8.8 (0.3)
$\pi 7/2^-[523]\otimes\nu 3/2^+[651]$	$5^-,2^-$	267	6.2	6.0 (0.2)
$\pi 7/2^-[523]\otimes\nu 11/2^-[505]$	$9^+,2^+$	250	10.0	11.6 (0.1)
$\pi 7/2^-[523]\otimes\nu 5/2^-[523]$	$6^+,1^+$	281	8.6	
$\pi 7/2^-[523]\otimes\nu 3/2^-[532]$	$5^+,2^+$	400	10.9	
$\pi 7/2^+[404]\otimes\nu 3/2^-[521]$	$5^-,2^-$	116	11.1	
$\pi 7/2^+[404]\otimes\nu 3/2^+[651]$	$5^+,2^+$	383	7.4	5.2 (0.4)
$\pi 7/2^+[404]\otimes\nu 11/2^-[505]$	$9^-,2^-$	366	13.7	
$\pi 7/2^+[404]\otimes\nu 5/2^-[523]$	$6^-,1^-$	397	11.1	
$\pi 7/2^+[404]\otimes\nu 3/2^-[532]$	$5^-,2^-$	516	15.3	
$\pi 5/2^+[402]\otimes\nu 3/2^-[521]$	$4^-,1^-$	153	12.3	
$\pi 5/2^+[402]\otimes\nu 3/2^+[651]$	$4^+,1^+$	420	7.9	
$\pi 5/2^+[402]\otimes\nu 11/2^-[505]$	$8^-,3^-$	403	15.5	
$\pi 5/2^+[402]\otimes\nu 5/2^-[523]$	$5^-,0^-$	434	12.3	
$\pi 5/2^+[402]\otimes\nu 3/2^-[532]$	$4^-,1^-$	553	17.7	
⋮	⋮	⋮	⋮	

TABLE II. Bandhead energies and rotational parameters of relevant rotational bands in neighboring odd-Z, odd-N, and even-even nuclei.

	^{157}Ho		^{159}Ho		Average	
Proton orbitals	Ep (keV)	A (keV)	Ep (keV)	A (keV)	$\overline{Ep}$ (keV)	$\overline{A}$ (keV)
$7/2^-[523]$	0	10.5	0	11.2	0	10.9
$7/2^+[404]$	66.9	16.6	165.9	14.2	116	15.4
$5/2^+[402]$	53.1	19.6	252.6	15.9	153	17.8
	^{157}Dy		^{159}Er		Average	
Neutron orbitals	En (keV)	A (keV)	En (keV)	A (keV)	$\overline{En}$ (keV)	$\overline{A}$ (keV)
$3/2^-[521]$	0	12.3	0	11.7	0	12.0
$3/2^+[651]$	308	6.2	226	9.4	267	7.8
$11/2^-[505]$	199.4	13.6	300	16.5	250	15.0
$5/2^-[523]$	341.1	11.5	220.2	12.4	281	12.0
$3/2^-[532]$	350	15.3	287	7.4	400	17.0

Even-even nuclei

^{156}Dy: $A=15.8$ keV, ^{160}Er: $A=18.4$ keV, Average: $\overline{A}=17.1$ keV

TABLE III. Comparison between experimental and predicted G^{kk}.

Configuration	K^{π}	g_R^{00}	$G_{\rm pred}^{KK}$	$\|G_{\rm expt}^{KK}\|$
$\pi 7/2^-[523]\otimes\nu 3/2^-[521]$	5^+	0.48(9)	1.9(2)	1.6(2)
$\pi 7/2^-[523]\otimes\nu 5/2^-[523]$	6^+	0.48(8)	2.5(3)	
$\pi 7/2^-[523]\otimes\nu 3/2^+[651]$	5^-	0.39(6)	2.3(4)	2.7(2)
$\pi 7/2^+[404]\otimes\nu 3/2^+[651]$	5^+	0.23(8)	0.97(8)	1.3(1)
$\pi 5/2^+[404]\otimes\nu 3/2^+[651]$	4^+	0.13(2)	2.3(4)	
$\pi 7/2^-[523]\otimes\nu 11/2^-[505]$	9^+	0.55(6)	−0.45(4)	0.54(18)
$\pi 7/2^+[404]\otimes\nu 11/2^-[505]$	9^-	0.38(7)	−2.4(5)	

nuclei, are listed in Table II. The predicted and experimental G^{kk} are listed in Table III, and the relevant parameters which were used in obtaining the predicted and experimental G^{kk} of Table III are listed in Table IV. The methods and formulas, which were used to calculate the predicted values and to extract the experimental values of A and G^{kk}, have been described in detail by Drissi *et al.* [10], and we will not repeat them here. Spins and configurations of the observed bands are discussed as follows.

The configuration $\{p7/2^-[523]\otimes n3/2^-[521]\}K^{\pi}=5^+$ has been assigned to the ground state of ^{158}Ho [11–13]. The relative energy position of band 1 in the level scheme of Fig. 1 suggests that band 1 is probably the ground-state band. Assuming that the lowest observed state is the bandhead with $K^{\pi}=5^+$, the extracted experimental values of A and G^{kk} from band 1 are in agreement with the predicted ones as shown in Tables I and III. These comparisons between the experimental and predicted quantities consistently support the assumption that band 1 is the ground-state band with configuration $\{p7/2^-[523]\otimes n3/2^-[521]\}K^{\pi}=5^+$ and the lowest observed state is the bandhead. A similar situation has also occurred in ^{160}Ho [10].

Figure 3 shows that the DCO ratios of the 134, 246, 303, and 356 keV linking transitions fall into the $\Delta I=1$ group with DCO ratio of ~0.7. The observation of the two accompanying linking transitions 134 and 258 keV suggests that the multipolarity of the 134 keV linking transition is most probably $M1$. Under this assumption the spin and parity of the member states of band 2 are fixed as shown in Fig. 1. The spins of the member states in band 3 are also fixed by the 246, 303, and 356 keV linking transitions with $\Delta I=1$ between band 2 and 3. It was previously known that band 3 is the negative parity yrast band with the configuration $ph11/2\otimes ni13/2$. The multipolarities of the 246, 303, and 356 keV linking transitions are limited to be $E1$ by the different parties of bands 2 and 3. This is consistent with the fact that none of the linking transitions between bands 2 and 3 is accompanied by another linking transition depopulating the same state. It turns out that the spin of the state populated by the 100.3 and 215.7 keV γ rays is 9, which is three units larger than the tentative assignment in [1], two units larger than the suggested value in [2,3], and in agreement with the recent assignment based on the arguments of level energy systematics and alignment additivity [4].

In the mass region of $A\sim 160$, the yrast bands of deformed odd-odd nuclei have always been observed to be built on the configuration $ph11/2\otimes ni13/2$ [4]. $7/2^-[523]$ is the only $h11/2$ orbital with lower excitation energy observed in neighboring ^{157}Ho and ^{159}Ho, and $3/2^+[651]$ is the only $i13/2$ orbital with lower excitation energy observed in the neighboring isotones ^{157}Dy and ^{159}Er as listed in Table II. Therefore, it is natural to assign $\{p7/2^-[523]\otimes n3/2^+[651]\}K^{\pi}=5^-$, instead of $\{p7/2^-[523]\otimes n5/2^+[642]\}K^{\pi}=6^-$ [1], as the configuration of the yrast band (band 3). This configuration assignment is consistent with the facts that the predicted values of A and G^{kk} of this configuration are compatible with the experimental ones (see Tables I and III). The predicted G^{kk} for the configuration $\{p7/2^-[523]\otimes n5/2^+[642]\}K^{\pi}=6^-$ is about 1.7(3), in comparison with the predicted G^{kk} for the configuration $\{p7/2^-[523]\otimes n3/2^+[651]\}$, which deviates much further from the experimental G^{kk} as seen in Table III.

The spin and parity of band 2 as indicated in the level scheme of Fig. 1 suggest that the configuration of band 2 should have positive parity and its bandhead should have spin $I\leqslant 6$. The experimental A value extracted from band 2 is 5.2 keV (see Table I). Among the configurations listed in Table I, $\{p7/2^+[404]\otimes n3/2^+[651]\}K^{\pi}=5^+$ and $\{p5/2^+[402]\otimes n3/2^+[651]\}K^{\pi}=4^+$ are the configurations whose predicted A values are most close to 5.2 keV, and therefore they are the probable candidates for band 2. However, the latter possibility is rejected by the large difference between the predicted G^{kk} value (2.3) of the $\{p5/2^+[402]\otimes n3/2^+[651]\}K^{\pi}=4^+$ configuration and the experimental G^{kk} value (1.3) of band 2 as seen in Table III. Therefore, $\{p7/2^+[404]\otimes n3/2^+[651]\}K^{\pi}=5^+$ is assigned as the configuration of band 2. In addition, strong $E1$ transitions from the $g7/2(7/2^+[404])$ band to the $h11/2(7/2^-[523])$ band have been observed as a general feature in ^{157}Ho [6] and other odd-A holmium isotopes. The fact that strong $E1$ transitions have also been observed from band 2 to band 3 in ^{158}Ho is consistent with the configuration assignments for bands 2 and 3 where the valence proton of bands 2 and 3 is situated in the $g7/2(7/2^+[404])$ and $h11/2(7/2^-[523])$ orbitals, respectively, while the valence neutron of bands 2 and 3 has the same orbital of $i13/2(3/2^+[651])$.

Linking transitions between band 4 and the other three $K=5$ bands have been searched for extensively. The failure of such an effort suggests that band 4 may be built on an isomeric state with a K value which is quite different from 5. The K value of band 4 deduced from the first two cascade γ rays (225.0 and 247.3 keV), using the method of Kreiner

TABLE IV. Parameters used in the calculation and extraction of G^{kk} and $B(M1)/B(E2)$.

Orbitals	$\Omega(\hbar)$	g_{Ω}	g_R	$i_x(\hbar)$
$\pi 7/2^-[523]$	7/2	+1.35(2)	0.59(5)	1.59(9)
$\pi 7/2^+[404]$	7/2	+0.73(1)	0.42(3)	0.95(8)
$\pi 5/2^+[402]$	5/2	+1.32(1)	0.33(3)	0.45(3)
$\nu 3/2^-[521]$	3/2	−0.21(1)	0.25(2)	0.64(5)
$\nu 5/2^-[523]$	5/2	+0.25(1)	0.25(2)	0.40(2)
$\nu 3/2^+[651]$	3/2	−0.29(1)	0.16(2)	5.03(7)
$\nu 11/2^-[505]$	11/2	−0.27(6)	0.32(3)	1.03(2)
$g_R^{ee}=0.36(4)$		$Q_0\,(e\mathrm{b})=7.0(4)$		

et al. [10,16], is 9.1. By assuming $K=9$ for band 4, the deduced experimental A and G^{kk} agree well with predicted values of the configuration $p7/2^-[523]\otimes n11/2^-[505]$ as seen in Tables I and III. The proposed configuration for band 4 coincides with the one of the 21 min 9^+ isomeric state whose excitation energy is experimentally not known in ^{158}Ho [12,13]. Therefore, band 4 should be considered as the rotational band built on the 21 min isomeric state with $\{p7/2^-[523]\otimes n11/2^-[505]\}K^\pi=9^+$.

The configuration assignments of the four observed bands in ^{158}Ho are also supported by the argument of alignment additivity. And as an evaluation of the reasonableness of the adopted configurations, the $B(M1)/B(E2)$ ratios calculated from the adopted configurations on the basis of the semiclassical theory [14] are compared with the experimental $B(M1)/B(E2)$ ratios extracted from the observed bands as shown in Fig. 4. The formulas and methods which were used to extract the experimental $B(M1)/B(E2)$ ratios and to calculate the theoretical $B(M1)/B(E2)$ ones are detailed in [10]. The relevant quantities used in the calculations are listed in Table IV. General agreement between experimental and calculated ratios is obtained. The increasing trend of the experimental $B(M1)/B(E2)$ ratios of the yrast band in the higher-spin region, which has been reported in the case of ^{160}Ho [10,15], is also observed in the present study.

In summary, high-spin states in ^{158}Ho have been studied through the ^{152}Sm(^{11}B,5n)^{158}Ho reaction at the beam energy of 60 MeV. In addition to the previously known yrast band, three new rotational bands, namely, the $\{p7/2^-[523]\otimes n3/2^-[521]\}K^\pi=5^+$ ground-state band, the $\{p7/2^+[404]\otimes n3/2^+[651]\}K^\pi=5^+$ band, and the $\{p7/2^-[523]\otimes n11/2^-[505]\}K^\pi=9^+$ band, are proposed. The yrast band has been extended and connected to the ground-state band, and its configuration is reassigned as the $\{p7/2^-[523]\otimes n3/2^+[651]\}K^\pi=5^-$ rather than the $\{p7/2^-[523]\otimes n5/2^+[642]\}K^\pi=6^-$. On the basis of the present study, the spin values of the member states of the yrast band turn out to be larger by three units with respect to the earlier tentative spin assignments [1] and in agreement with the latest spin reassignments [4].

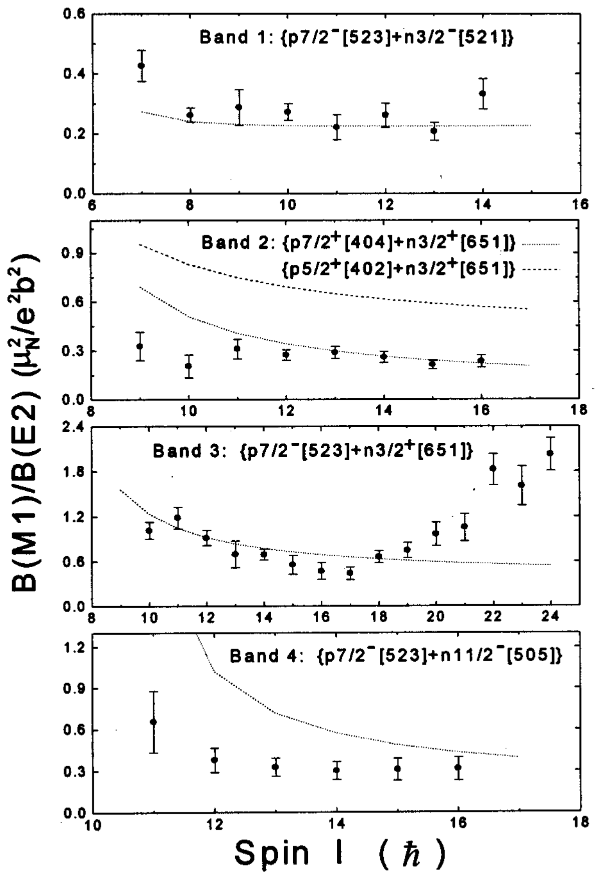

FIG. 4. Experimental $B(M1,I\to I-1)/B(E2I\to I-2)$ (open circles) as a function of spin I for the observed bands of ^{158}Ho. The curves represent the theoretical predictions.

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