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Level structure of ^{129}Ba from the ^{130}Ba(d, t)^{129}Ba reaction*

Roger D. Griffioen
Department of Physics, Calvin College, Grand Rapids, Michigan 49506
and Florida State University, Tallahassee, Florida 32306

Raymond K. Sheline
Department of Physics, Florida State University, Tallahassee, Florida 32306

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The level structure of ^{129}Ba has been investigated by means of the ^{130}Ba(d, t)^{129}Ba reaction using 16 MeV deuterons and a broad-range magnetic spectrograph. The Q value to the lowest observed state was found to be -4001 ± 15 keV. Energies and angular distributions have been measured for 13 levels below 1.0 MeV. The lowest observed state was found to have spin and parity of $\frac{1}{2}^+$ and a level 277 keV above this state with $l = 5$ is suggested to have $J^\pi = \frac{11}{2}^-$. The clearly established absence of a lower lying $\frac{7}{2}^-$ level, together with the well established systematics in the $N = 75$ Nd and Ce nuclei, demonstrates that the $\frac{11}{2}^-$ state is a member of the $\Omega = \frac{9}{2}^-[514]$ band.

NUCLEAR REACTIONS ^{130}Ba(d,t), E = 16 MeV, enriched targets; measured $\sigma(\theta)$, θ = 20–85°; measured Q. ^{129}Ba deduced levels, J, π, $(2J+1)S$. Coriolis coupling scheme and intermediate coupling model calculations.

INTRODUCTION

The possibility of a new region of deformation among the neutron deficient isotopes with both N and Z between 50 and 82 was suggested more than a decade ago.[1] Theoretical calculations of the ground state equilibrium deformations and deformation energies were done by Marshalek, Person, and Sheline[2] for even nuclei in this region taking into consideration only prolate deformation. Since then, theoretical calculations by Kumar and Baranger[3] and by Arseniev, Sobiczewski, and Soloviev[4] have indicated that oblate deformations may be preferred in this region of deformation or that states of different shapes may coexist in these nuclides. Several experiments[5-8] on short-lived isomers in odd-A barium, xenon, lanthanum, and cesium isotopes have been interpreted as evidence for the fact that oblate shapes may exist, and the possibility of a shape-hindered γ-ray transition has been suggested[8] in ^{127}Cs. A more recent study[9] of the odd-A lanthanum isotopes from $A = 125$ to 137 by in-beam γ-ray spectroscopy has identified rotational bands built on a low-lying $\frac{11}{2}^-$ level which resemble very strongly the ground state bands in the neighboring even barium isotopes. The interpretation of these bands is based on a model which consists of a single particle coupled to an axially symmetric rotating core.[10] Because the expected rotational schemes are completely different for oblate and prolate deformation at $\rho \simeq 0.2$ for odd proton nuclei in this region, this interpretation requires a prolate deformation for these nuclei. In recent calculations,[11] the inclusion of the Strutinsky shell correction[12] to the liquid drop energy gives a systematic downward shift of the prolate minimum relative to the oblate minimum, suggesting that very few, if any, of the ground states in this region should be expected to have oblate deformations.

Since a positive identification of Nilsson orbitals in odd-mass nuclei would distinguish between oblate and prolate deformation, we have studied the levels of ^{129}Ba by means of the ^{130}Ba(d, t)^{129}Ba reaction in order to look for the possibility of Nilsson orbitals and rotational bands. This reaction was chosen because ^{130}Ba is the lightest stable barium isotope and therefore, ^{129}Ba is the nucleus furthest away from the 82 neutron shell, which can be studied by a single-particle-transfer reaction. Very little previous knowledge of the levels in ^{129}Ba exists. It is known that there are two isomers, within 700 keV of each other, which decay by electron capture and positron emission with half-lives of 2.20 h and 2.13 h.[13] The suggested spins and parities of these two levels are $\frac{1}{2}^+$ and $\frac{11}{2}^-$. From the decay of ^{129}La, only one γ ray of 110 keV is known.[13]

EXPERIMENTAL METHOD

Targets of essentially 100% ^{130}Ba were prepared with the Florida State University isotope separator, beginning with enriched ^{130}Ba obtained from Oak Ridge National Laboratory. Targets of thick-

TABLE I. The optical model parameters used in the DWBA calculations for ^{130}Ba$(d,t)^{129}$Ba and ^{130}Ba(p,d)-^{129}Ba. Energies are in MeV, distances in fm.

	V	r	a	W_v	W_s	r_i	a_i	V_{so}	r_c	a_c
d	100	1.18	0.80	···	13.0	1.34	0.68	5.0	1.25	0.65
t	155	1.24	0.70	30.0	···	1.37	0.70	···	1.25	0.65
P	52	1.25	0.67	···	10.0	1.20	0.69	4.5	1.25	0.65

ness in the range of 50–100 μg/cm^2 were deposited on 50 μg/cm^2 carbon backing. These targets were bombarded with 16 MeV deuterons from the Florida State University (FSU) super FN tandem Van de Graaff accelerator using beam currents between 0.5 and 1.0 μA.

Tritons from the ^{130}Ba$(d,t)^{129}$Ba reaction were analyzed with a broad-range magnetic spectrograph and recorded on 50-μm-thick Kodak NTA nuclear emulsion plates. After the plates were developed, triton tracks were counted in 0.5 mm strips. The computer code STRILDE[14] was used to make a least-squares fit of the data to sums of Gaussian peaks and to extract peak positions and areas. From the peak positions, excitation energies can be determined and from the areas, relative cross sections are determined.

Absolute cross sections were obtained in the following manner. Before each (d,t) run, a short deuteron elastic scattering run was taken under identical geometry and target positioning conditions. At the forward angles (20–25°), the elastic scattering cross sections are a high percentage of the Rutherford scattering cross sections as calculated by distorted-wave-Born-approximation (DWBA) code DWUCK[15] using optical model parameters[16] shown in Table I. At these angles, the dependence of the calculated elastic scattering cross section on either the optical model parameters or the DWBA code is very small. This means that we know the elastic scattering cross section to better than 10% and can therefore determine the target thickness, at these angles, to that accuracy. Normalization of the runs at various angles, taken at different times and therefore with different target positioning, was accomplished by taking a short deuteron elastic scattering run at each angle with the target in a fixed position. This normalization run indicated that on different days, the actual target thickness where the beam was hitting varied by about ±25%.

Because the deuteron elastic scattering runs could be made under the identical conditions as the (d,t) runs, the elastic scattering peak could be used as an internal energy calibration standard for determining the Q value for the ^{130}Ba$(d,t)^{129}$Ba reaction. The magnetic induction of the spectrograph given by this procedure was quite consistently 0.2% lower than the value set by standard NMR techniques. This consistency indicates that the Q value obtained is accurate to about ±10 keV. At four angles the first excited state peak for the ^{13}C$(d,t)^{12}$C reaction also appeared in the spectrum and since the Q value for this reaction is very

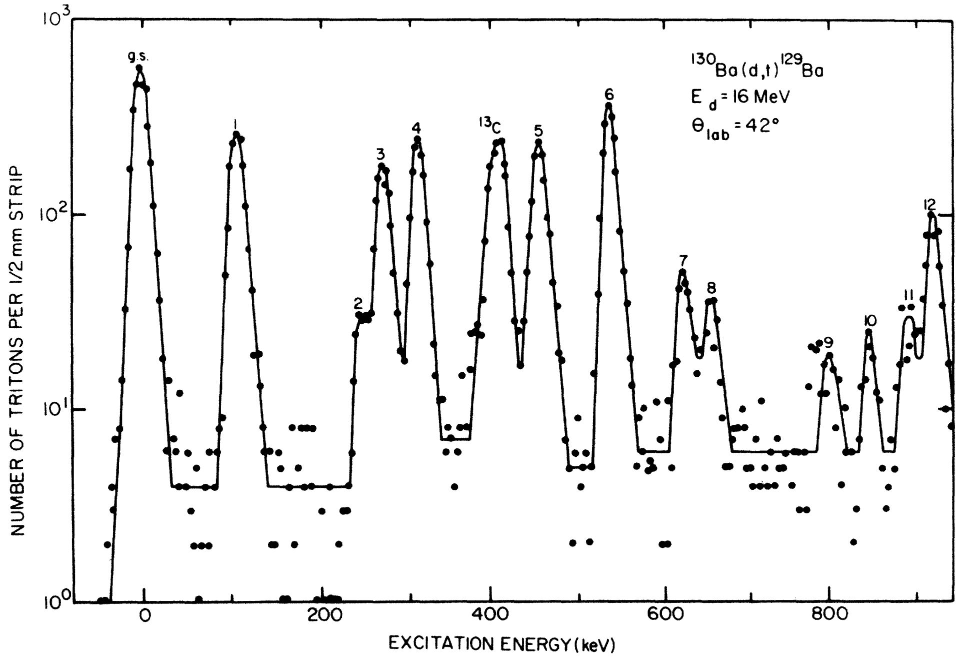

FIG. 1. Triton spectrum resulting from the reaction ^{130}Ba$(d,t)^{129}$Ba.

well known,[17] it could also be used as an internal energy standard and this check gave results consistent with the accuracy quoted above.

RESULTS

Triton spectra for the ^{130}Ba(d, t)^{129}Ba reaction using 16 MeV deuterons were recorded at ten angles between 20 and 85°. The spectrum taken at 42° is shown in Fig. 1. Resolution was normally 16–18 keV full width at half-maximum. The spectra are dominated by six strong peaks below 550 keV and include seven other weak peaks below an energy of 950 keV. Using 16 MeV deuterons, the elastically scattered deuterons came in above 950 keV and obscured any higher energy peaks. One run was carried out with an incident deuteron energy of 18 MeV at an angle of 40°. This pushed the spectrograph to its limit in handling the tritons from the ground state transition. In this spectrum the deuteron elastic scattering peak was up above 1800 keV in the triton spectrum. There were several additional weak transitions which showed up between 950 and 1800 keV but there were no other strong transitions.

The ground state Q value was determined by using the deuteron elastic scattering peak and the ^{13}C(d, t)^{12}C peak as internal energy calibration

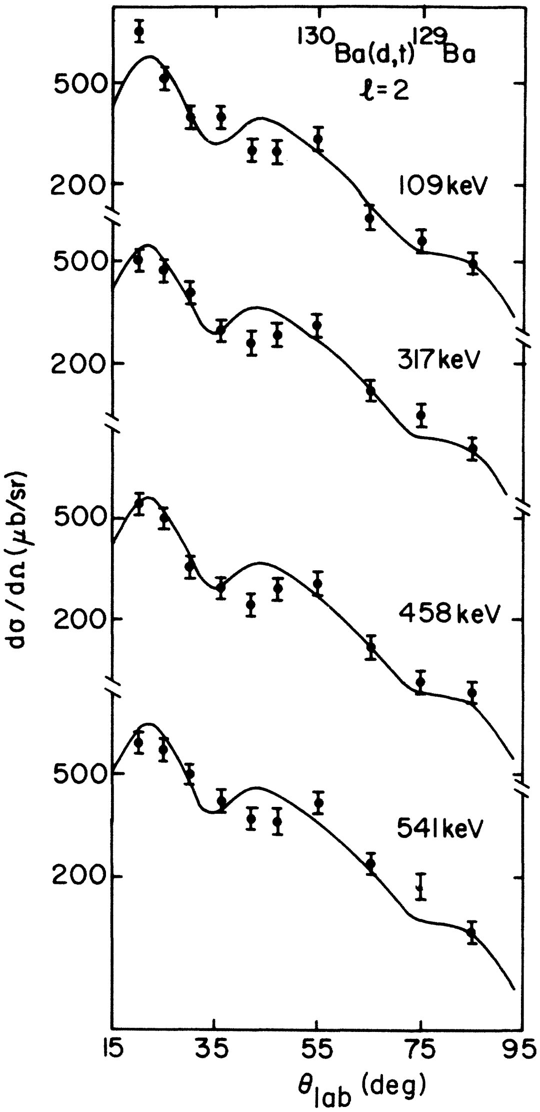

FIG. 2. ^{130}Ba(d,t)^{129}Ba reaction cross section angular distributions, for levels with l = 2 angular momentum transfer. The curves are from calculations with computer code DWUCK using optical model parameters given in Table I. The error bars indicate only the statistical probable error.

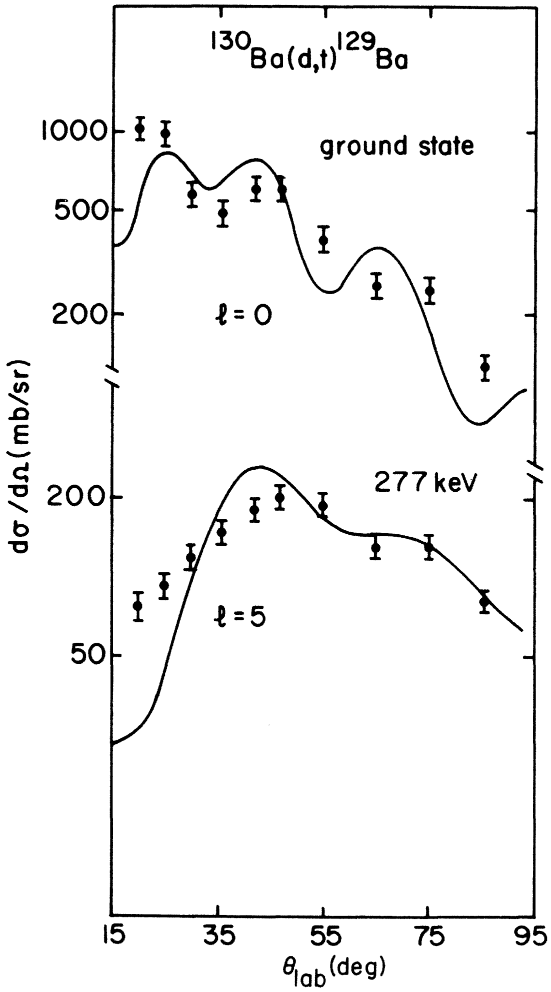

FIG. 3. ^{130}Ba(d,t)^{129}Ba reaction cross section angular distributions, for levels with l = 0 and l = 5 angular momentum transfer. The curves are from calculations with computer code DWUCK using optical model parameters given in Table I. The error bars indicate only the statistical probable error.

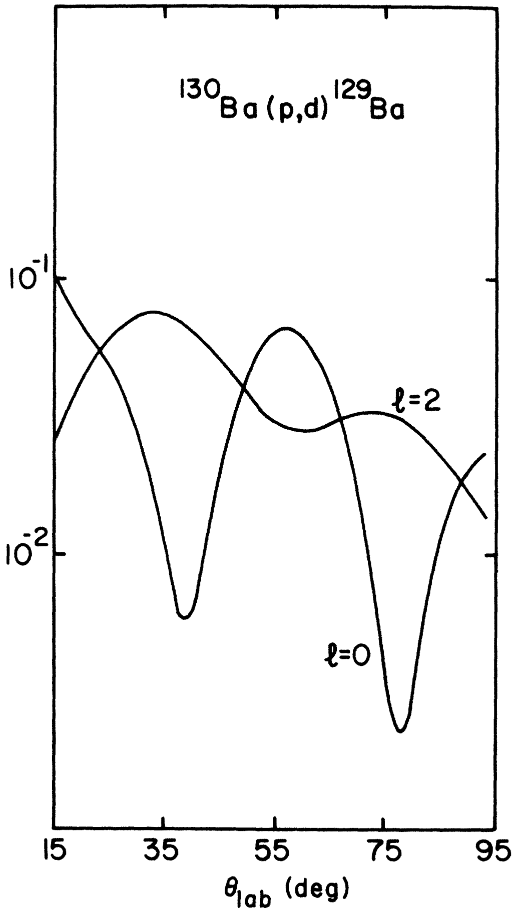

FIG. 4. Angular distributions for the ^{130}Ba$(p,d)^{129}$Ba reaction calculated with computer code DWUCK for 18 MeV protons.

standards. The measured value is −4001 ± 10 keV. This agrees very well with the value of −3960 keV calculated from the 1971 Mass Tables.[18] However, the mass of ^{129}Ba is estimated from systematics in these tables and has never been experimentally determined. Our Q-value measurement gives a value for the mass excess $(M-A)$ of ^{129}Ba as −85 110 ± 15 keV as compared to the table estimated value of −85 150 keV.

Absolute differential cross sections were calculated and the angular distributions have been fitted with DWBA calculations using the computer code DWUCK[15] and using the optical model parameters[16,19] shown in Table I. The angular distributions for four of the strong peaks (as well as several of the weak ones) are fitted very well with an $l=2$ angular momentum transfer as shown in Fig. 2. The error bars indicate only the statistical probable error. Two of the strong peaks have distinctly different angular distributions as shown in Fig. 3. The 277 keV state is fitted fairly well with an $l=5$ distribution. The ground state is shown fitted with an $l=0$ distribution but the poor fit is somewhat disturbing. It is interesting that recent results of (p,d) experiments in the 82 neutron region[20] also give poor fits to $l=0$ transitions while giving good fits to all other angular momentum transfers. In order to confirm the $l=0$ nature of the ground state transition, the ^{130}Ba$(p,d)^{129}$Ba reaction was performed at 43° using 18 MeV protons. Figure 4 shows $l=0$ and $l=2$ angular distributions calculated with DWUCK for the (p,d) reaction. The proton optical model parameters were taken from Wiedner *et al.*[16] (see Table I). The calculated ratio of $l=0$ to $l=2$ for the (p,d) reaction at 43° is one-tenth that same ratio for the (d,t) reaction. Experimentally, the ground state transition in the (p,d) reaction was decreased by a factor of 7 relative to the four strong $l=2$ transitions, thus substantiating the $l=0$ assignment for the ground state transition and establishing the spin and parity of the ground state of ^{129}Ba as $\frac{1}{2}^+$.

TABLE II. ^{130}Ba$(d,t)^{129}$Ba level energies, angular momentum transfers, spectroscopic factors, and spin-parity assignments. The incident deuteron energy is 16 MeV.

E (keV)	l transfer	$(2J+1)S$	J^π
g.s.	0	0.41	$\frac{1}{2}^+$
109.3 ± 0.5	2	0.49	$(\frac{3}{2}^+)$
251.4 ± 1.0	(2)	0.04	$(\frac{3}{2}^+)$
277.1 ± 0.5	5	3.50	$(\frac{11}{2}^-)$
316.8 ± 0.5	2	0.44	$(\frac{3}{2}^+, \frac{5}{2}^+)$
458.2 ± 1.0	2	0.46	$(\frac{3}{2}^+, \frac{5}{2}^+)$
541.2 ± 1.0	2	0.60	$(\frac{3}{2}^+, \frac{5}{2}^+)$
628.8 ± 1.5	2	0.08	$(\frac{3}{2}^+, \frac{5}{2}^+)$
656.7 ± 1.5	2	0.05	$(\frac{3}{2}^+, \frac{5}{2}^+)$
799.6 ± 5.0	(2)	(0.04)	
847.5 ± 3.0	(0,2)	···	
896.0 ± 3.0	(0,2)	···	
925.4 ± 3.0	(0)	(0.05)	

The results of this work are summarized in Table II, which lists level energies, l-transfer values, spectroscopic factors based on the calculations with DWUCK, and J^π assignments.

DISCUSSION

A new coupling scheme[10] has recently been proposed to explain the remarkable similarities between the spectra of the odd-A La nuclei and the isotonic even-even Ba nuclei with one less proton. In this coupling scheme the Coriolis force acts on the odd $\frac{11}{2}^-$ proton decoupling it from the sym-

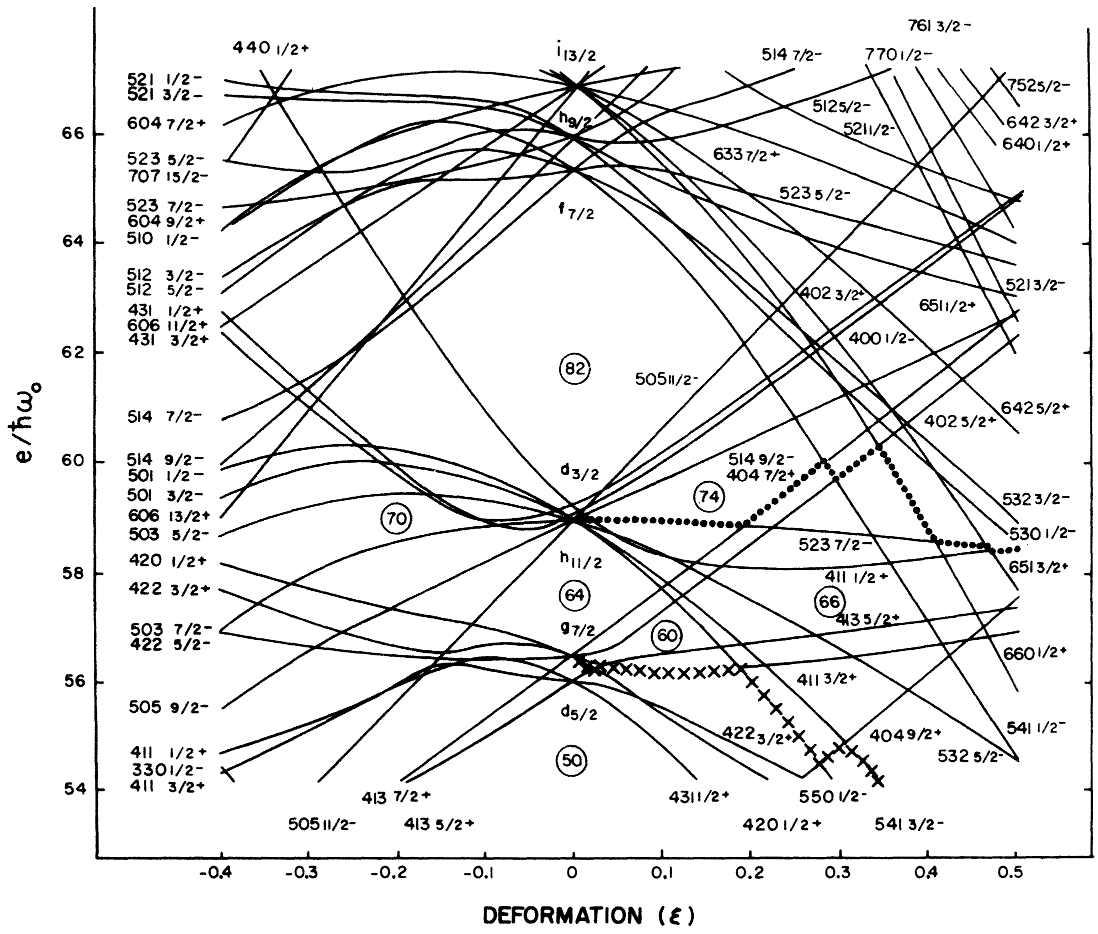

FIG. 5. Nilsson level calculations made by Ingemar Ragnarsson assuming $A = 140$ for the single neutron levels based on linearly extrapolated κ and μ parameters. ϵ_4 is assumed to be 0. The position of the 73rd neutron is shown as a dotted line and the 57th proton as an x'd line. Use of the neutron level diagram for both protons and neutrons should not introduce too serious an error.

metry axis and giving rise to bands with the J^π sequence $\frac{11}{2}^-$, $\frac{15}{2}^-$, $\frac{19}{2}^-$. When the energy spacings of these $\frac{11}{2}^-$ bands are taken into account, the only deformation possible for the odd-A La nuclei (and also their even-even Ba cores) is prolate in the range $0.10 \leq \epsilon \leq 0.25$. Indeed we may expect that the ^{128}Ba core for both ^{129}La and ^{129}Ba will have a deformation of about $\epsilon \cong +0.20$.

However, although the decoupled band with spin sequence $\frac{11}{2}^-$, $\frac{15}{2}^-$, $\frac{19}{2}^-$... is expected and observed in the odd proton nucleus ^{129}La, such a decoupled band is not expected in the odd neutron nucleus ^{129}Ba. This radical difference in the energy level schemes of isobars results because the Fermi surface for the odd nucleon is at quite a different place for the two cases. In the case of ^{129}La, the Fermi surface for the 57th proton lies below, or at the lower edge of, the entire set of $h_{11/2}$ opposite parity intruder orbitals; whereas for ^{129}Ba (for the 73rd neutron) the Fermi surface lies in the middle of the $h_{11/2}$ orbitals. This is shown in Fig. 5 where the Nilsson orbitals[21] are plotted for neutrons assuming $A = 140$ with $\epsilon_4 = 0$, $\kappa = 0.0637$, and $\mu = 0.451$ obtained by a linear extrapolation of the κ and μ parameters from the rare earth to the $A = 25$ region. The 57th proton is shown by a checked path and the 73rd neutron by a dotted path.

The coupling scheme for the odd neutron in ^{129}Ba is expected to be much more complex. However, there are certain things one can say about it on a purely theoretical basis.

Figure 5 suggests that at deformation $\epsilon \cong 0.2$ one should expect to see in the low energy spectrum $\frac{7}{2}^+$ [404], $\frac{7}{2}^-$[523], $\frac{5}{2}^+$[402], and $\frac{1}{2}^+$[411] as hole states and $\frac{9}{2}^-$[514], $\frac{1}{2}^+$[400], and $\frac{3}{2}^+$[402] as particle states.

Table III presents the C_j values and decoupling parameters for the $\kappa = \frac{1}{2}$ bands for the $N = 4$ levels listed above; the $N = 5$ levels, namely $\frac{7}{2}^-$[523] and $\frac{9}{2}^-$[514], are expected to be severely Coriolis dis-

TABLE III. C_j values and decoupling parameters for the $N=4$ states which are of importance in the low lying spectrum of ^{129}Ba. $\epsilon=0.20$, $\epsilon_4=0.00$, $\kappa=0.0638$, $\mu=0.493$.

J	Configurations $\frac{1}{2}[400]$	$\frac{1}{2}[411]$	$\frac{3}{2}[402]$	$\frac{7}{2}[404]$	$\frac{5}{2}[402]$
$\frac{1}{2}$	0.802	−0.399			
$\frac{3}{2}$	0.510	0.722	0.954		
$\frac{5}{2}$	−0.263	0.401	0.203		0.954
$\frac{7}{2}$	−0.158	−0.387	−0.220	0.996	0.276
$\frac{9}{2}$	+0.042	−0.095	−0.037	0.086	−0.119
a	+0.24	−0.96			

torted and are discussed separately. The only reasonable interpretation of the lowest-lying levels that is consistent with the C_j values is that the ground state with spin $\frac{1}{2}^+$, the 109.3 keV state with tentative spin $\frac{3}{2}^+$, and the weak $l=2$ 251.4 keV state (assumed here to have $J^\pi=\frac{5}{2}^+$) are members of an $\Omega=\frac{1}{2}$ band. The intensity ratios and the decoupling parameter are intermediate between those expected for the $\frac{1}{2}^+[411]$ and $\frac{1}{2}^+[400]$ bands. Since the Coriolis coupling matrix between these two bands $\langle 400|j^-|411\rangle=1.638$, considerable mixing is expected and these states are *tentatively* assigned as $\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{5}{2}^+$ members of the mixed band $\frac{1}{2}^+[411]+\frac{1}{2}^+[400]$.

The $\frac{11}{2}^-$ state observed at 277.1 keV in these measurements is surely the $\frac{11}{2}^-$ rotational member of either the $\frac{7}{2}^-[523]$ or the $\frac{9}{2}^-[514]$ Nilsson orbital. The $\frac{11}{2}^-$ state is considerably Coriolis enhanced, very much like the corresponding proton Nilsson orbital in the odd-A Ho and odd-A Lu nuclei. At first inspection it would appear to be very difficult to decide to which band the $\frac{11}{2}^-$ state belongs. However, if the state were a member of the $\frac{7}{2}^-[523]$ band an easily observed $\frac{7}{2}^-$ band head should be present in the spectrum somewhat below the $\frac{1}{2}^+$ state (assuming a moment of inertia consistent with surrounding nuclei). The failure to observe this state, together with the fact that the $\frac{9}{2}^-[514]$ band head expected very approximately in the vicinity of 100 keV could not have been experimentally observed, strongly suggests that the $\frac{11}{2}^-$ state is a member of the $\Omega=\frac{9}{2}^-[514]$ band.

Furthermore, the band systematics of the isotonic nucleus $^{127}_{54}$Xe (and the $N=75$ Nd and Ce nuclei), where the $\frac{9}{2}^-$ band head is observed, supports this assignment. Some of the higher energy $l=2$ transitions must be the $\frac{3}{2}^+$ and $\frac{5}{2}^+$ members of the $\frac{3}{2}^+[402]$ band. The states at 541.2 and 656.7 keV are not unreasonable assignments for this band. However, their assignment must await more complete measurements.

There is one serious discrepancy in this Nilsson scheme. This is the failure to observe an $l=4$ angular distribution arising from the $\frac{7}{2}^+[404]$ band head. This state should be easily observed even though the exact cross section populating it may be difficult to predict because of possible Coriolis enhancement. Measurements of reactions such as Xe($\alpha, xn\gamma$) should prove to be particularly valuable not only in helping to locate the $\frac{7}{2}^+[404]$ band but also in helping to verify and complete assignments for other bands.

Although we feel the description we have given of the levels is reasonably satisfactory even though, in the case of higher band members, quite tentative, we have also considered the intermediate coupling approach of the unified model[22,23] which has been applied with considerable success to a variety of nuclei in this mass region.[24-28] We have carried out calculations with a particle-core coupling model program written by Ikeda.[29] Up to three-phonon states can be included in these calculations. The phonon energy was set equal to the average of the first 2^+ energy levels of ^{128}Ba and ^{130}Ba. The energy gap was chosen as 1.0 MeV, which gave reasonable values for the pairing strength.

The differences in single particle energies were treated as free parameters to be searched, as was the coupling constant. The $d_{5/2}$, $h_{11/2}$, $d_{3/2}$, and $s_{1/2}$ levels were included in the calculations and the initial values for the single particle energies were taken from the ^{138}Ba$(p,d)^{137}$Ba work of Jolly and Kashy.[20] The parameter search was made

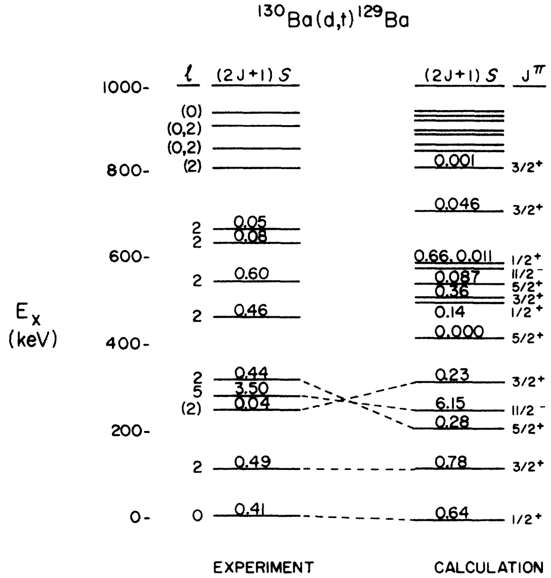

FIG. 6. A comparison between the experimental data and the best intermediate coupling model calculation.

with the computer code STEPIT written by Chandler.[30] At every step of the parameter search the Bardeen equation was solved and the secular equation was diagonalized. The χ^2 value to be minimized was defined as follows:

$$\chi^2=\sum_J (E_J^{\text{obs}}-E_J^{\text{calc}})^2 + \frac{1}{10}\sum_J (S_{d,t}^{J,\text{obs}}-S_{d,t}^{J,\text{calc}})^2 ,$$

where the S's are spectroscopic factors and the E's are level energies (in MeV).

A calculation was first done using only two-phonon states and fitting the lowest-lying $\frac{1}{2}^+$, $\frac{3}{2}^+$, and $\frac{11}{2}^-$ states. This calculation indicated that there should also be a strong low-lying $\frac{5}{2}^+$ state. The best results were obtained, using up to three-phonon states and assuming that the fourth excited state was $\frac{5}{2}^+$. The first and second excited states were assumed to be $\frac{3}{2}^+$ (see above discussion). The results of this calculation are shown in Fig. 6 and the over-all agreement is reasonable if not outstanding.

Thus it may well be that two different sets of basis wave functions can give a description of the spectrum of ^{129}Ba. This is perhaps not surprising for a nucleus like ^{129}Ba with an intermediate amount of deformation. Indeed it is of use to consider both descriptions in explaining the experimental facts. For example, the intermediate coupling model predicts a second $\frac{11}{2}^-$ state at ~600 keV of about one-tenth the strength of the first $\frac{11}{2}^-$ state. Such a state is not seen but would be difficult to see because of its intensity. The considerable decrease in intensity finds a ready explanation in the Nilsson coupling scheme in which the Coriolis coupling to the lowest $\frac{11}{2}^-$ state at 277.1 keV should severely deplete the intensity of the $\frac{11}{2}^-$ state at ~600 keV.

The Nilsson coupling scheme predicts an unobserved $l=4$ state which is not predicted by the intermediate coupling model. This fact, however, only points up the exclusion of the $g_{7/2}$ orbital from the intermediate coupling calculation.

CONCLUSIONS

The low-lying states in ^{129}Ba are consistent with an intermediate quadrupole deformation ($\epsilon \cong 0.2$) which can also be inferred from the decoupled bands observed in isobaric ^{129}La. Either the Nilsson coupling scheme with Coriolis coupling used to explain the levels in ^{129}La or an intermediate coupling scheme gives reasonable agreement with the observed properties of the lowest-lying states in ^{129}Ba.

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