Yrast bands in ^{136,138}Sm and ^{132}Nd

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Nuclear structures of $^{136,138}_{62}$Sm and $^{132}_{60}$Nd have been studied through heavy ion fusion reactions. In order to select particular reaction channels, charged particle-gamma coincidences were measured with a charged particle multiplicity filter "silicon box." Yrast bands with spins up to 14 have been observed in all nuclei investigated. Lifetimes of excited states were also measured with the recoil distance method. The experimental results were compared with the interacting boson model predictions.

Neutron-deficient Sm isotopes ($^{136}_{62}$Sm$_{74}$ and $^{138}_{62}$Sm$_{76}$) and a Nd isotope ($^{132}_{60}$Nd$_{72}$), which lie in the vicinity of the proton subclosed shell of 64, have been investigated.

Until recently, there had been no experimental data for $N \leq 76$ in Sm isotopes and there had been only limited data for $N \leq 72$ in Nd isotopes. For this region of neutron-deficient isotopes, considerable permanent ground-state deformation is expected from quasiband systematics[1] as the neutron number departs from 82. In this respect, measurements of lifetimes as well as level energies of the ground-state band members of nuclei in this region are of great value. Very recently, after the present experiment was completed, Lister *et al.*[2] published their data on the ground-state bands of nine neutron-deficient even-even nuclei including three nuclei in the present study, and Lunardi *et al.*[3] published their data on ^{138}Sm including level energies of the ground-state band members and lifetimes of some of the levels. Lister *et al.* have reported only the level energies of the members in the ground-state bands and discussed the systematic trends for deformations.

With heavy ion fusion reactions, where the mass of the projectile is comparable to that of the target, new nuclei far from the stability line are frequently produced near the proton drip line following the emission of charged particles as well as neutrons. Under such circumstances, γ-ray spectra following the reaction are a complicated mixture of those from many different nuclides. Therefore, a new device to select particular reaction channels in analyzing γ rays is vitally needed. For this purpose, we have developed an apparatus which we call the "silicon box"[4] as a charged particle multiplicity filter. With this apparatus, one can selectively intensify particular reaction channels in which charged particles are emitted besides neutrons.

A schematic drawing of the silicon box is shown in Fig. 1. This apparatus consists of ten pieces of rectangular metal-oxide-semiconductor-type (MOS) surface barrier Si detectors. Incident heavy ion beams enter into the box through the hole of the front annular detector, bombard the target, and go out through the hole of the back annular detector. The size of the annular detector is 35 mm$\times$35 mm with a central hole of 12 mm in diameter, and that of plain detector is 30 mm$\times$35 mm. These ten pieces of Si detectors altogether subtend more than 95% of the total solid angle surrounding the target.

Each detector of this apparatus works as a partially depleted ΔE counter and discriminates between protons and α particles from the difference in their energy losses. The depletion depth of the detector is chosen such that energies deposited by protons do not exceed the minimum energy deposited by α particles. A typical depletion depth is about 0.4 mm. A charged particle spectrum from the back annular detector is shown in Fig. 2. The horizontal arrows with "p" and "α" in this figure show the region of energy loss deposited by protons and α particles, respectively. A dip between "p" and "α" mainly comes from the fact that the emission of low-energy α particles is depressed due to a higher Coulomb barrier for α particles than for protons, which is of course favorable for the discrimination between protons and α particles. From the number of detectors which detect a proton or an α particle simultaneously, the multiplicity of the charged particle is determined. The atomic numbers of residual nuclei can then be determined from this multiplicity. By taking γ-

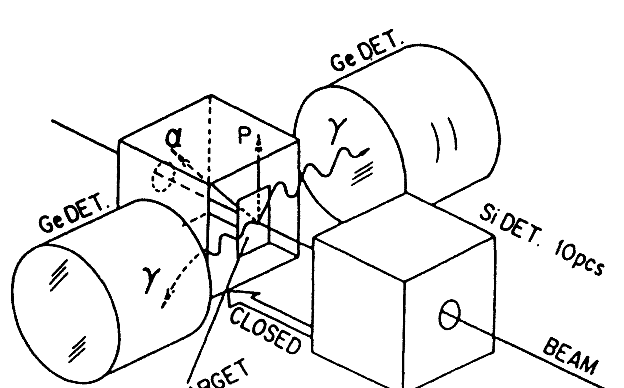

FIG. 1. A schematic drawing of the silicon box.

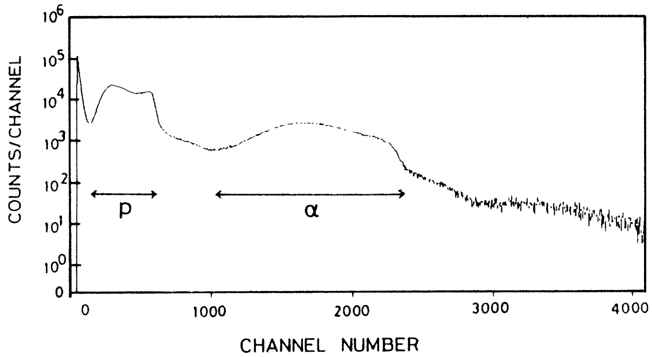

FIG. 2. Charged particle spectrum obtained from the back annular Si detector (see the text).

ray spectra in coincidence with the signals from the silicon box, the structure of a specific nucleus of interest can be intensified relative to background γ rays from the Coulomb excitation and/or the other reaction channels.

Figures 3(a), (b), and (c) show singles, $1p$-gated, and $2p$-gated γ-ray spectra in the reaction ^{107}Ag (with natural Ag backing) $+^{32}$S (160 MeV). As seen in Fig. 3(a), the singles γ-ray spectrum shows strong γ rays from the Coulomb excitations of target and backing materials, but shows rather modest yields with small peak-to-continuum ratios for γ rays from $^{136}_{62}$Sm. In Figs. 3(b) and (c), however, γ rays from the Coulomb excitation are drastically reduced, while peak-to-continuum ratios for γ rays from selected reaction channels are greatly improved. For example, the peak-to-continuum ratio in the spectrum for the 255.1 keV γ rays in $^{136}_{62}$Sm is improved from 1/4 (singles) to more than 1/1 ($1p$ gate).

$^{138}_{62}$Sm was populated mainly via the $^{107}_{47}$Ag($^{35}_{17}$Cl,2p2n)$^{138}_{62}$Sm reaction with 155 MeV ^{35}Cl ions, and $^{136}_{62}$Sm and $^{132}_{60}$Nd were populated mainly via the $^{107}_{47}$Ag($^{32}_{16}$S,p2n)$^{136}_{62}$Sm and $^{107}_{47}$Ag($^{32}_{16}$S,αp2n)$^{132}_{60}$Nd reactions, respectively, with 160 MeV ^{32}S ions. Projectiles were accelerated from the tandem pelletron of the Japan Atomic Energy Research Institute (JAERI). The measurements performed include γ-γ coincidences, γ-ray angular distributions, and recoil-distance lifetime measurements in coincidence with signals from the silicon box. For γ-γ coincidences and γ-ray angular distributions, a 98% enriched ^{107}Ag target of $\sim$3 mg/cm^2 thickness on a natural Ag backing was used. Recoiling fusion residues stopped in the natural Ag backing. For recoil-distance lifetime measurements, a self-supporting ^{107}Ag target of $\sim$0.5 mg/cm^2 thickness was used. Two HP Ge detectors with volumes of approximately 50 cm^3 and an NE213 neutron counter of 12.7 cm diam$\times$5.1 cm were used. Ratios of γ-ray intensities in coincidence with neutrons to without neutrons were used to estimate the number of neutrons evaporated in a specific reaction channel.

The level schemes of $^{136,138}_{62}$Sm and $^{132}_{60}$Nd thus obtained are presented in Fig. 4. Level energies are in good agreement with the results of Refs. 2 and 3. The half-lives of 2^+, 10^+, and 12^+ levels were measured in $^{138}_{62}$Sm, while the half-life of the 2^+ level and upper limits of the half-lives of the 4^+ and 10^+ levels were obtained for the first time in $^{136}_{62}$Sm and $^{132}_{60}$Nd. The half-lives of the levels in $^{138}_{62}$Sm obtained in the present study are nearly consistent with those given in Ref. 3.

Present experimental results were compared with the interacting boson model (IBM) calculations.[5] The IBM-2 (Refs. 6–8) and the extended IBM-2 (Ref. 9) were used for the calculations of the level energies and the reduced transition probabilities in $^{136,138}_{62}$Sm and $^{132}_{60}$Nd by taking $^{146}_{64}$Gd$_{82}$ as the core. The Hamiltonian used for IBM-2 calculations is as follows:

$$H^B=(n_{d_\pi}+n_{d_\nu})\epsilon_d+\kappa(Q^B_\pi Q^B_\nu)+V^B_{\pi\pi}+V^B_{\nu\nu}+M^B_{\pi\nu}\,,$$

with

$$Q^B_\rho=d^\dagger_\rho s_\rho+s^\dagger_\rho\tilde{d}_\rho+\chi_\rho[d^\dagger_\rho\tilde{d}_\rho]^{(2)}\quad(\rho=\pi,\nu)\,,$$

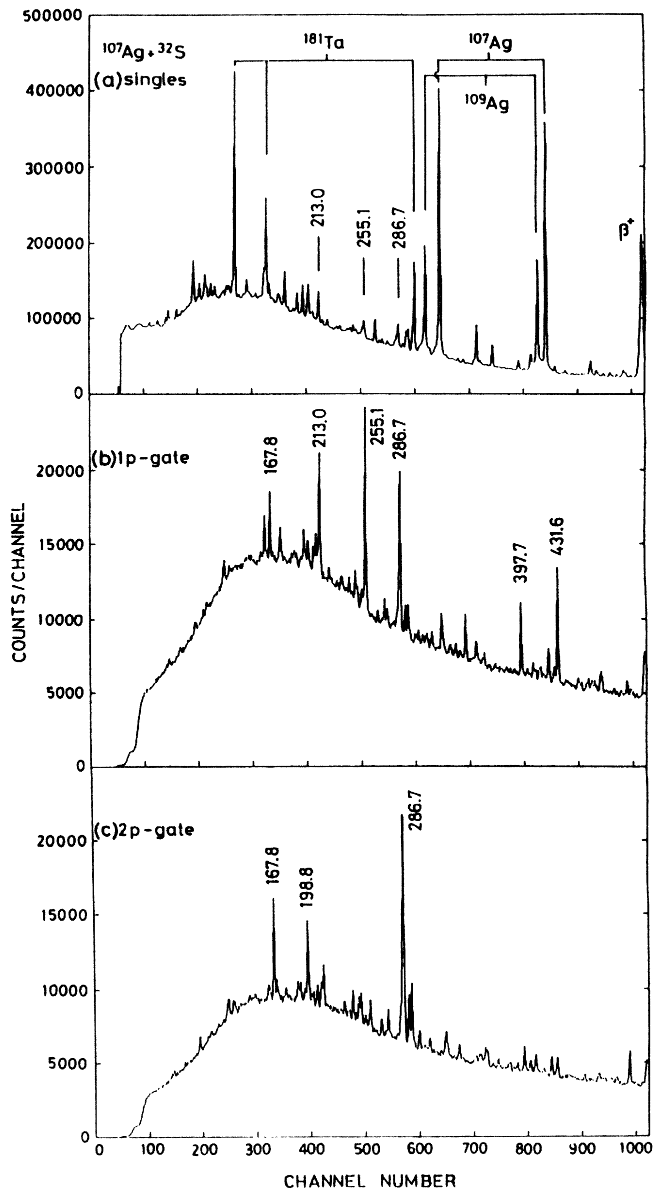

FIG. 3. Gamma-ray spectra obtained from the ^{107}Ag (with natural Ag backing) $+^{32}$S (160 MeV) fusion reaction. (a) Singles, (b) $1p$-gated, and (c) $2p$-gated gamma-ray spectra.

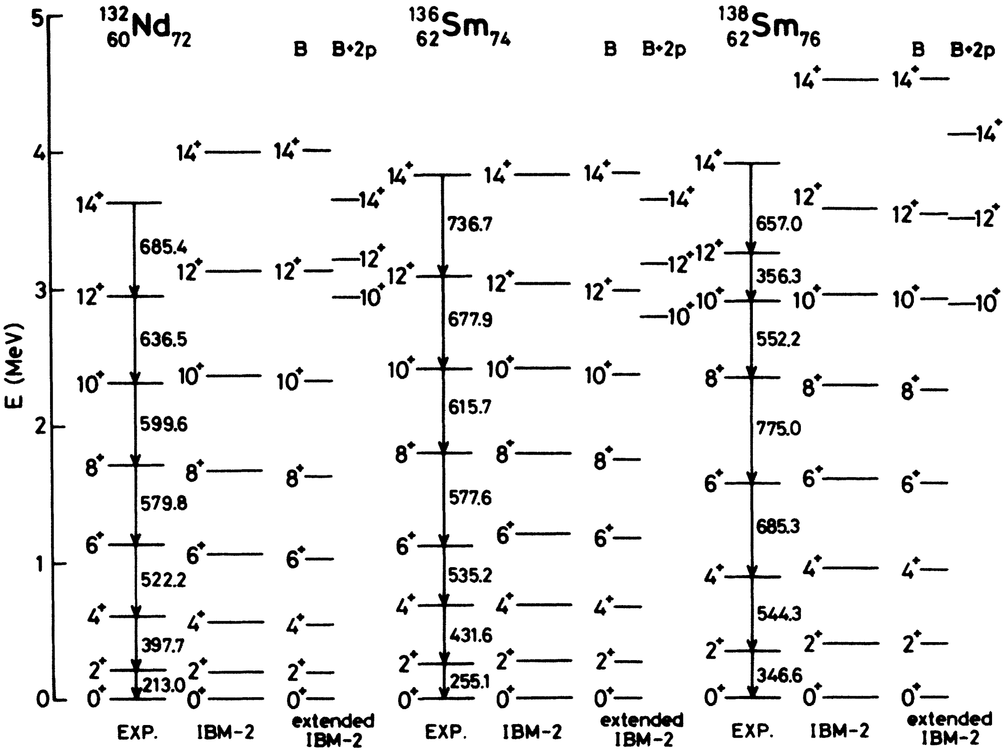

FIG. 4. Level schemes of ${}^{132}_{60}$Nd and ${}^{136,138}_{62}$Sm obtained from the present experiments and the IBM calculations. For the levels calculated with the extended IBM-2, band "B" consists of only bosons, while band "$B+2$p" consists of bosons plus proton two quasiparticles (see the text).

where Q_ρ^B is the quadrupole operator, $V_{\pi\pi}^B$ ($V_{\nu\nu}^B$) is the two-body interaction between proton (neutron) bosons, and $M_{\pi\nu}^B$ is the Majorana force. In the above formulas n_{d_π} (n_{d_ν}) is the number operator of the proton (neutron) boson, ϵ_d is the d-boson energy, κ is the strength of the quadrupole-quadrupole interaction between proton and neutron bosons, and $s^\dagger$ (s) and $d^\dagger$ (d) denote the s- and d-boson creation (annihilation) operators. $\tilde{d}$ is related to the d-boson annihilation operator by

$$\tilde{d}_{jm}=(-1)^{j-m}d_{j-m} \ .$$

The $E2$ operator which is used to calculate the $E2$ transition probabilities is defined as

$$T^B(E2)=e_\pi^B Q_\pi^B+e_\nu^B Q_\nu^B ,$$

where e_π^B (e_ν^B) is the proton (neutron) boson effective charge. For simplicity, we assumed that e_π^B is equal to e_ν^B.

The IBM-2 is extended[9] (we call this version the extended IBM-2) so that the states with two fermions are also included. The Hamiltonian used for extended IBM-2 calculations which include the states with two quasiprotons, is expressed as

$$H=H^B+H^F+V^{BF} .$$

The fermion Hamiltonian is

$$H^F=\epsilon_\pi n_\pi+\langle j_\pi^{F^2};J\mid V\mid j_\pi^{F^2};J\rangle \quad (J=4,6,8,10;j_\pi^F=\pi h_{11/2}) ,$$

where ϵ_π is the proton single-particle energy and n_π is the number operator of the protons. The interaction between bosons and fermions, $V^{\rm BF}$, is expressed as

$$V^{\rm BF}=\kappa(Q_\pi Q_\nu-Q_\pi^B Q_\nu^B) ,$$

with

$$Q_\rho=Q_\rho^B+\alpha_\rho[a_\rho^\dagger\tilde{a}_\rho]^{(2)}+\beta_\rho[[a_\rho^\dagger a_\rho^\dagger]^{(4)}\tilde{d}_\rho]^{(2)} -\beta_\rho[d_\rho^\dagger[\tilde{a}_\rho\tilde{a}_\rho]^{(4)}]^{(2)} \quad (\rho=\pi,\nu) ,$$

where $a^\dagger$ denotes the fermion creation operator

$$[\tilde{a}_{jm}=(-1)^{j-m}a_{j-m}] .$$

The parameters α_ρ and β_ρ together with ϵ_π determine the amount of mixture of the two quasiparticles and the bosons band. The $E2$ operator used is expressed as

$$T(E2)=e_\pi^B Q_\pi^B+e_\nu^B Q_\nu^B+e_\pi^F[a_\pi^\dagger\tilde{a}_\pi]^{(2)} ,$$

where e_π^F is proportional to the proton effective charge.

Parameters used in these calculations were first derived by extrapolating or interpolating the values used for ${}_{54}$Xe, ${}_{56}$Ba, ${}_{58}$Ce, and heavier ${}_{62}$Sm isotopes. The parameters thus obtained were then adjusted to reproduce energies of the levels up to $J^\pi=8^+$ in ${}^{136}_{62}$Sm. Parameters for ${}^{138}_{62}$Sm and ${}^{132}_{60}$Nd were obtained by extrapolating those for ${}^{136}_{62}$Sm. Table I summarizes the employed parameters. The level schemes obtained by the IBM calculations are also shown in Fig. 4. The IBM-2 calculations reasonably account for the experimental trends of the level energies in ${}^{136}_{62}$Sm and

TABLE I. Half-lives, transition probabilities W, and $B(E2)$ values for levels in $^{136,138}_{62}$Sm and $^{132}_{60}$Nd. For $B(E2)$ values, theoretical values with both the IBM-2 and the extended IBM-2 as well as experimental values are given. On the right, parameters used for the IBM calculations are listed. Fixed parameters are $\kappa=-0.15$ and $e^B=0.13$ e b for the IBM-2 and $\alpha_\pi=\alpha_\nu=0.25$, $\beta_\pi=\beta_\nu=0.50$, $j_\pi^F=h_{11/2}$, and $e_\pi^F=1.00$ e b for the extended IBM-2 (see the text and Refs. 5–9 for notation used).

				$B(E2)$ (e^2b^2)				IBM-2		Extended IBM-2
Nucleus	J^π	$T_{1/2}$	W (W.u.)	Expt.	IBM-2	Extended IBM-2	ϵ_d	χ_π	χ_ν	ϵ_F
	2^+	45(6)ps	59(7)	0.25(3)	0.29	0.30				
$^{138}_{62}$Sm$_{76}$	10^+	0.55(2) ns	0.47(2)	$2.0(1)\times10^{-3}$	0.26	1.0×10^{-3}	0.78	-1.00	0.60	1.65
	12^+	33(2) ps	71(5)	0.30(2)	0.14	0.34				
	2^+	0.13(1) ns	96(7)	0.40(3)	0.38	0.38				
$^{136}_{62}$Sm$_{74}$	4^+	<15 ps	>60	>0.25	0.54	0.55	0.70	-1.00	0.40	1.70
	10^+	<2 ps	>77	>0.32	0.34	3.7×10^{-4}				
	2^+	0.22(2) ns	148(13)	0.59(5)	0.41	0.42				
$^{132}_{60}$Nd$_{72}$	4^+	<21 ps	>68	>0.27	0.58	0.60	0.67	-1.10	0.20	1.80
	10^+	<2 ps	>93	>0.37	0.28	1.1×10^{-3}				

$^{132}_{60}$Nd, but sizable discrepancies are noted for the level energies above the 10^+ state in $^{138}_{62}$Sm.

Half-lives, transition probabilities (in W.u.), and reduced transition probabilities [$B(E2)$] are also summarized in Table I. For $^{136}_{62}$Sm and $^{132}_{60}$Nd, experimental reduced transition probabilities or their lower limits are reasonably consistent with those of the IBM-2 calculations.[8] For $^{138}_{62}$Sm, however, the experimental value of $B(E2;10^+\rightarrow8^+)$ is two orders of magnitude smaller than the IBM-2 value. On the other hand, the experimental $B(E2;10^+\rightarrow8^+)$ is in good agreement with the extended IBM-2 in which two quasiparticle states coupled to bosons are taken into account.

With the help of the extended IBM-2, the above anomaly in $^{138}_{62}$Sm is interpreted as follows. Since the level spacings in the sequence $14^+\rightarrow12^+\rightarrow10^+$ in $^{138}_{62}$Sm$_{76}$ are similar to those in the sequence $4^+\rightarrow2^+\rightarrow0^+$ in the isotone $^{136}_{60}$Nd$_{76}$, levels above the 10^+ state in $^{138}_{62}$Sm are expected to be mainly those of the rotation aligned band built on the $(\pi h_{11/2})^2_{10^+}$ two quasiparticle state. In other words, the $(\pi h_{11/2})^2_{10^+}$ rotation aligned band crosses the ground-state band at around $J^\pi=10^+$. In fact, a rather small transition probability (~0.5 W.u.) for the $10^+\rightarrow8^+$ transition and enhanced transition probabilities for the $2^+\rightarrow0^+$ (~60 W.u.) and the $12^+\rightarrow10^+$ (~70 W.u.) transitions as well as rather irregular level spacings at around the 10^+ state are all well reproduced by the extended IBM-2 in which two quasiparticle excitation is coupled to bosons to make levels above the 10^+ state. For more neutron-deficient nuclei, $^{136}_{62}$Sm$_{74}$ and $^{132}_{60}$Nd$_{72}$, such a band crossing does not seem to occur at the 10^+ state from the experiment; the present data give regular level spacings and enhanced $B(E2)$'s for all the transitions observed including those for $10^+\rightarrow8^+$, and these are well reproduced with the IBM-2. The extended IBM-2 gives the $(\pi h_{11/2})^2_{10^+}$ two quasiparticle state well above the 10^+ state of the ground-state band. The disappearance of the band-crossing behavior at around the 10^+ level as the neutron number decreases from 76 ($^{138}_{62}$Sm) to 74 ($^{136}_{62}$Sm) is simply a manifestation of the decrease of the level spacings in the ground-state band and hence the increase of the deformation with the neutron number. The present data on reduced transition probabilities $B(E2;2^+\rightarrow0^+)$ in three nuclei indicate a gradual increase of the ground-state deformation ($\beta=0.20$, $^{138}_{62}$Sm$_{76}$; $\beta=0.25$, $^{136}_{62}$Sm$_{74}$; $\beta=0.32$, $^{132}_{60}$Nd$_{72}$) as the neutron number decreases from 76 to 72.

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