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RAPID COMMUNICATIONS

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Experimental study of the deformed nucleus ^{153}Sm via $(\vec{d},t)$ and average resonance capture as a test case for the multiorbit interacting boson fermion model

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The ^{154}Sm$(\vec{d},t)$ reaction at high energy resolution (n,γ), average resonance capture (ARC), and coincidence measurements were performed to study the deformed nucleus ^{153}Sm. Strength distributions from $(\vec{d},t)$ and completeness for $I^{\pi}=\frac{1}{2}^{-}$ and $\frac{3}{2}^{-}$ states up to 1500 keV from ARC provide one of the first detailed tests of the interacting boson fermion model (IBFM) in a deformed nucleus in a multiorbit environment. For negative parity states the model accounts for the large number of low spin $(\frac{1}{2}^{-}, \frac{3}{2}^{-})$ states much better than the Nilsson model since the even-even core in the IBFM calculations automatically includes excited vibrational states. The IBFM calculations also predict (d,t) spectroscopic factors better than the Nilsson model with pairing and Coriolis mixing. Neither the IBFM nor the Nilsson approach can explain the low lying positive parity states. The IBFM calculations show that for certain combinations of parameters, the monopole term in the boson-fermion Hamiltonian has more than a scaling effect: it can attenuate the Coriolis mixing (energy staggering). Finally suggested improvements in the treatment of pairing in the IBFM are made. [S0556-2813(98)50106-9]

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Low lying Nilsson states in deformed odd-A nuclei have been well studied. However, there is little interpretation of higher lying levels ($\geqslant$0.6 MeV) where core excitations come into play, because the quality of the data rapidly decreases with increasing level density and model descriptions of such complex excitations are complicated.

It is the purpose of this Rapid Communication to address both these issues in a detailed study of ^{153}Sm. In the first place, high resolution (d,t) spectroscopy, including studies with polarized beams, complemented by complete spectroscopy using the average resonance capture (ARC) technique, was used to develop an extensive level scheme that includes

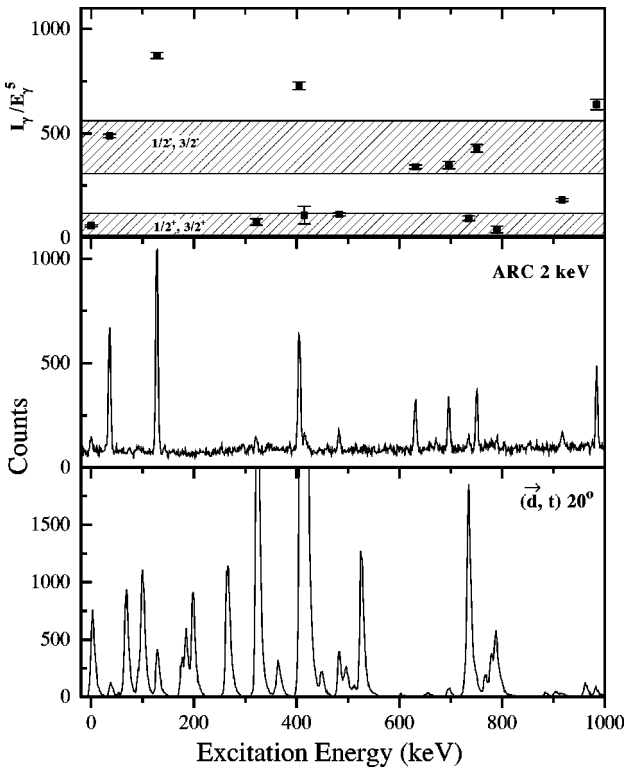

FIG. 1. Parts of the $(\vec{d},t)$ and 2 keV ARC spectra. The upper panel shows reduced ARC intensities, the cross-hatched bands denote the relative intensity range of $\frac{1}{2}^-, \frac{3}{2}^-$, and $\frac{1}{2}^+, \frac{3}{2}^+$ states according to Monte-Carlo calculations of the ARC process.

many levels, often with small cross sections, that may denote core-excited configurations. Secondly, we use these results to carry out one of the first detailed tests of the interacting boson fermion model (IBFM) for a deformed nucleus in a multi-j space [1].

The polarized $(\vec{d},t)$ transfer reactions were performed at the Tandem accelerator of Munich. The sensitivity of neutron pickup reactions to the Nilsson expansion coefficients $C^K_{j,L}$ and hence to Nilsson quantum numbers also implies that states with very small $C^K_{j,L}$ coefficients or states involving predominantly vibrational core excitations may be missed. Thus the transfer data were complemented with the nonselective (n,γ) reaction, in the ARC [2] mode and with $\gamma\gamma$ coincidences both performed at the HFBR at Brookhaven.

The $(\vec{d},t)$ reaction was measured at $E_d=25$ MeV on enriched (99.2%) ^{154}Sm targets of thickness 150 μg/cm^2. The tritons were analyzed in the Q3D spectrograph with a high resolution [6 keV full width at half maximum (FWHM) for $(\vec{d},t)$] focal plane detector [3]. The ARC data were taken with a pair spectrometer at neutron energies of 2 keV and 24 keV on targets of enriched ^{152}Sm ranging from 2 to 20 grams. Parts of the $(\vec{d},t)$ and the 2 keV ARC spectra are shown in Fig. 1. The figure also shows the reduced ARC intensities (I_γ/E_γ^5) and their classification into two bands corresponding to $\frac{1}{2}^-$, $\frac{3}{2}^-$ and $\frac{1}{2}^+$, $\frac{3}{2}^+$ levels [4].

The analyzing power angular distributions (asymmetry) in the ^{154}Sm$(\vec{d},t)$ reaction (see Fig. 2) provide reliable determination of I^π values because of the significantly different patterns for $I=L+\frac{1}{2}$ and $I=L-\frac{1}{2}$ transfer and complement the L assignments from a (p,d) reaction of Blasi *et al.* [5]. In Fig. 2 the behavior of the $I^\pi=1/2^-$ and the $I^\pi=3/2^-$ (both $L=1$) transitions are compared. The distorted-wave Born approximation (DWBA) calculations reproduce both the angular distributions of the cross section and the asymmetries reasonably well. Except for about 20 levels of very low cross sections the I^π values of the ~150 states observed below 2 MeV could be identified. The ARC data provides detection of all $\frac{1}{2}^-, \frac{3}{2}^-$ levels below 1500 keV.

These data lead to several changes in previous I^π assignments [6–10] and to the discovery of a number of new levels up to 2.2 MeV [11]. Interesting is the observation of two

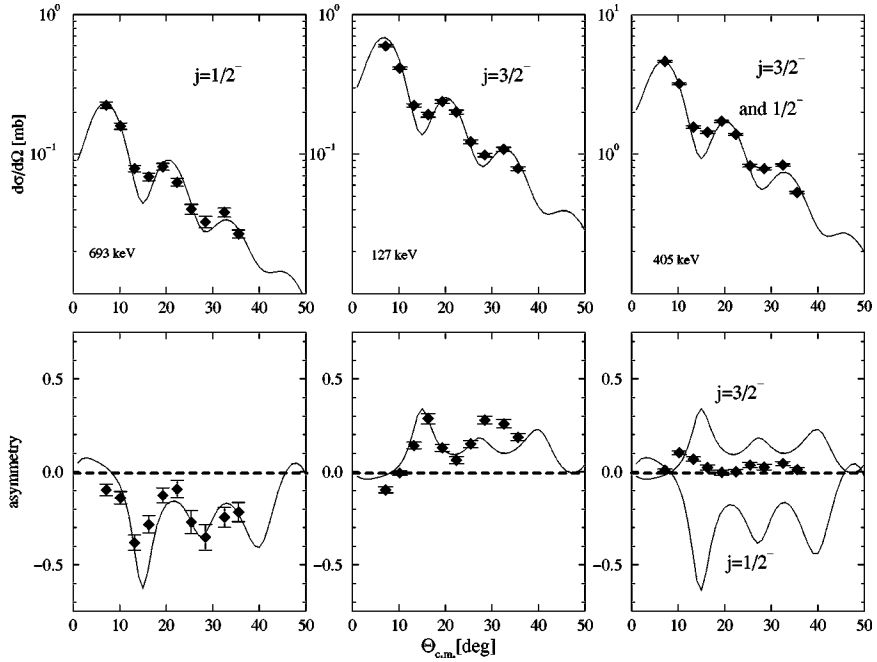

FIG. 2. Cross sections and analyzing powers for $I^\pi=1/2^-$, $I^\pi=3/2^-$ states, and the doublet of $I^\pi=1/2^-$ and $I^\pi=3/2^-$ states at 404 and 405 keV. The solid lines show calculations performed with the code CHUCK [4] in the DWBA limit.

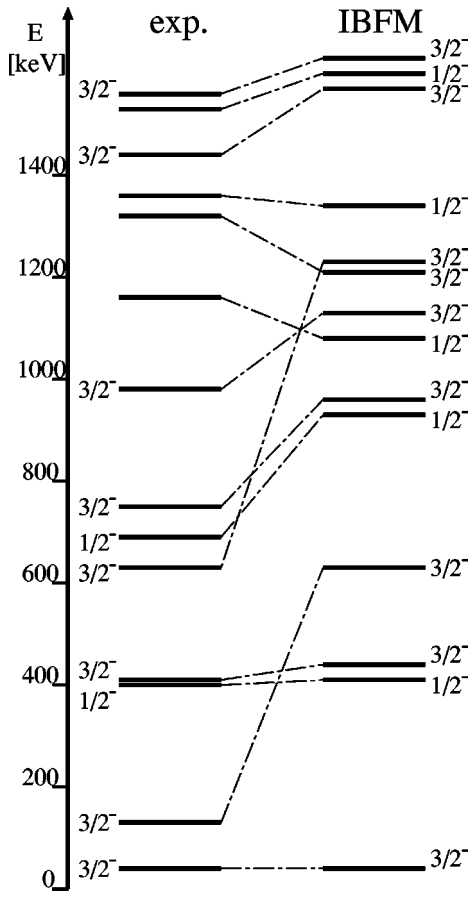

FIG. 3. Comparison of experimental energies with the IBFM for $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states. Levels are correlated taking into account the experimental band structure and the calculated wave functions.

anomalously high peaks in ARC at energies of 405 keV and 127 keV, which result either from incomplete resonance averaging or suggest nearly degenerate doublets of $\frac{1}{2}^-, \frac{3}{2}^-$ states. For the 405 keV level the $(\vec{d},t)$ asymmetry supports a doublet structure as it requires at least a 30% contribution from $I^\pi = \frac{1}{2}^-$ (see Fig. 2). A reinspection of early Bent Crystal data [7] shows transitions in agreement with a $\frac{1}{2}^-$ state at 404.15 keV and a $\frac{3}{2}^-$ state at 405.46 keV. This is also supported by the $\gamma\gamma$ coincidence data. For a doublet structure at 127 keV there is no direct support from the $\gamma\gamma$ coincidence and Bent Crystal data.

Our aim is to compare the observed states with IBFM calculations. For transitional nuclei such as ^{153}Sm the variety of collective core states contained within the IBFM suggests the appropriateness of that model. In the IBFM the even-odd nucleus is a system of a single valence fermion in the single particle orbit j space coupled to the even-even core with all its bosonic excitations. The Hamiltonian is

$$\mathbf{H} = \mathbf{H}_{ee} + \mathbf{H}_F + \mathbf{H}_{\rm int}, \tag{1}$$

where $\mathbf{H}_{ee}$ represents the even-even core, calculated with the IBM-1 [12], $\mathbf{H}_F$ accounts for the single nucleon energies $\mathbf{H}_F = \Sigma_{jm} \varepsilon_j \ \mathbf{a}^\dagger_{jm} \mathbf{a}_{jm}$ with creation (annihilation) operators $\mathbf{a}^\dagger_{jm}$ ($\mathbf{a}_{jm}$) of nucleons in valence orbitals of energy ε_j. The boson-fermion interaction $\mathbf{H}_{\rm int}$ consists of quadrupole-quadrupole, exchange, and monopole-monopole terms

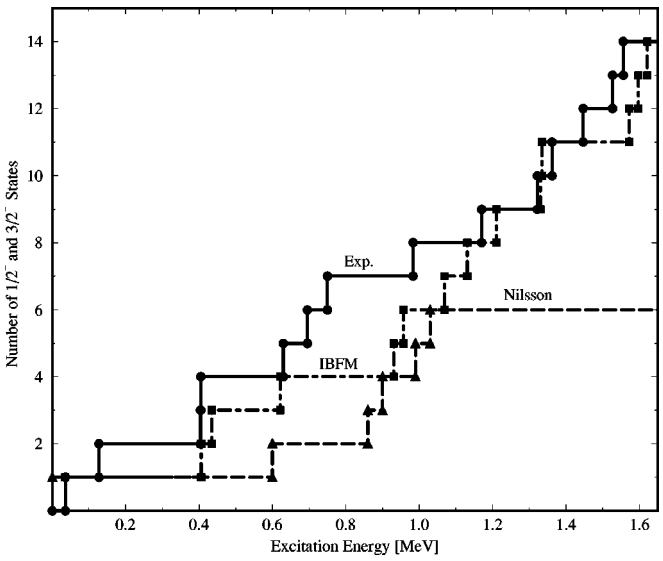

FIG. 4. Comparison of the number of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ experimental states (solid line) with the IBFM (dot-dashed line) and the Nilsson model (dashed line).

$$\mathbf{H}_{\rm int} = \mathbf{H}^Q_{BF} + \mathbf{H}^E_{BF} + \mathbf{H}^M_{BF} \tag{2}$$

$$\text{with} \quad \mathbf{H}^Q_{BF} = \sum_{jj'} \Gamma_{jj'} [\mathbf{Q}^{(2)} (\mathbf{a}^\dagger_j \tilde{\mathbf{a}}_j)^{(2)}]^{(0)}_0,$$

$$\mathbf{H}^E_{BF} = \sum_{jj'} \sum_{j''} \Lambda^{j''}_{jj'} [\mathbf{d}^\dagger \tilde{\mathbf{a}}_j]^{j''} [\tilde{\mathbf{d}} \mathbf{a}^\dagger_{j'}]^{j''(0)}_0,$$

$$\mathbf{H}^M_{BF} = \sum_j A_j [\mathbf{d}^\dagger_j \tilde{\mathbf{d}}_j]^{(0)}_0 [\mathbf{a}^\dagger_j \tilde{\mathbf{a}}_j]^{(0)}_0,$$

and $\mathbf{Q}^{(2)}$ is the usual IBM [12] quadrupole operator.

For ^{153}Sm the large number of relevant single particle orbits necessitates that one reduce the number of parameters. Scholten and Blasi have written the interaction strength in a simplified form based on microscopic arguments [13]. Then the boson-fermion interaction [14] is fully specified by three interaction strengths Γ, Λ, and A (related to the parameters BFQ, BFE, and BFM of the code ODDA [15]). The remaining parameters are χ in the boson quadrupole operator, and the strength of the fermion pairing interaction which was used in the BCS to relate Γ, Λ, and A to their specific values for each orbit.

The core nucleus ^{152}Sm was calculated with the code PHINT [15] taking the parameters from Ref. [16]. The coupling to the octupole vibration is neglected, i.e., p or f bosons are not included. An important and unique feature of these IBFM calculations was the inclusion of the $h_{11/2}$ orbit from the neutron $N = 50-82$ shell. Because of the restriction of the code ODDA [16] to five spherical single particle orbits the very high lying $p_{1/2}$ orbit was neglected. Comparing four and five single particle calculations we convinced ourselves that in the low energy spectrum ($E_x \leqslant 1.6$ MeV) the effect of neglecting the $p_{1/2}$ orbit on calculated excitation energies is minor. Nevertheless the present study shows that an improved and expanded IBFM code is needed to allow more comprehensive calculations.

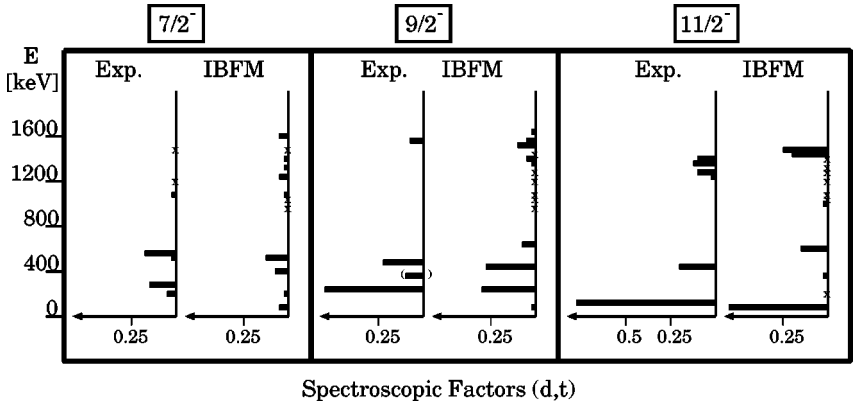

FIG. 5. Comparison of observed and calculated (d,t) spectroscopic factors.

The single particle energies ϵ_j were taken from the spherical limit of usual Nilsson calculations with minor modifications ($E_{h_{11/2}}=0.0$, $E_{f_{7/2}}=5.0$, $E_{h_{9/2}}=5.2$, $E_{p_{3/2}}=6.4$, and $E_{f_{5/2}}=6.9$ MeV).

Variations of BFE and BFQ correlate to changes of the Fermi surface and the deformation. The parameter values BFQ=0.4 MeV, BFE=2.8 MeV, and BFM=−0.9 MeV give a reasonable reproduction of the observed level structure. Contrary to common perception, the monopole term does not merely scale the energies. For these parameters it also controls the staggering in $K=\frac{1}{2}$ bands and, in effect, acts like an attenuation of Coriolis mixing. This feature deserves further microscopic study for other sets of parameters.

In the IBFM the positive parity states are based on the spherical orbits $s_{1/2}$, $d_{3/2}$, $i_{13/2}$, and $g_{9/2}$. Due to the angular momentum couplings in $H_{\rm int}$ there is no mixing of $s_{1/2}$,$d_{3/2}$ with $i_{13/2}$. This prohibits meaningful comparison of experimental positive parity cross sections for $\frac{13}{2}^+$ states with IBFM calculations. For the energies, however, we find that it is impossible to reproduce the large splitting (734 keV) of the $\frac{3}{2}$[651] and $\frac{1}{2}$[660] orbits [6]. A complete Nilsson calculation [11], which includes main shell ($\Delta N=2$) and Coriolis mixing, also fails to reproduce this separation. The same feature was observed in ^{155}Gd and was not reproduced in calculations by Soloviev [17].

For the negative parity states the completeness in $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states provides a stringent model test. In fact, in the energy region below 1.6 MeV, as shown in Fig. 3, the IBFM reproduces these states reasonably well. There is nearly a 1-1 correspondence in the number of levels, although, above 1 MeV, the IBFM energies tend to be calculated high. This may be quite reasonable since, if octupole core excitations were added to the IBFM a few additional $\frac{1}{2}^-$,$\frac{3}{2}^-$ levels, formed by coupling $K=0^-$ and 1^- excitations to the positive parity Nilsson orbits from the $i_{13/2}$ shell, would appear in that energy region. Note that the Nilsson model accounts for less than half of the observed states. This again suggests that many of the observed $\frac{1}{2}^-$, $\frac{3}{2}^-$ states have significant core vibrational components as also shown in the (p,d) study of [5] (see Fig. 4).

The calculation of (d,t) spectroscopic factors with the program SPEC [13] does not require additional parameters except that an IBM calculation of the target nucleus ^{154}Sm is needed: This was done with parameters similar to those for ^{152}Sm. The IBFM calculations do not give the $\frac{1}{2}^-$ cross sections because of the neglect of the $p_{1/2}$ orbit. Since in the code ODDA pairing occupancies are calculated for *spherical* states all K projections of a given j orbit in the deformed states have the same occupation probability. For the $p_{3/2}$ and $f_{5/2}$ orbits this implies that the code ODDA uses $U^2\approx 1$ which is unrealistic for low K states near the Fermi surface in ^{153}Sm. Therefore, with this treatment of pairing and the structure of the single particle transfer operator the present implementation of the code cannot give reliable $I^\pi=\frac{3}{2}^-$ and $\frac{5}{2}^-$ cross sections. The pairing issue, however, is not severe for the $h_{11/2}$, $h_{9/2}$, and $f_{7/2}$ orbits and the comparison of the respective experimental and theoretical cross sections in Fig. 5 shows good agreement. For the strong low-lying states IBFM calculations reproduce the spectroscopic factors better than those obtained with the Nilsson model with pairing and Coriolis mixing [11]. Moreover, the IBFM also predicts a number of states with small spectroscopic factors (marked with a cross in Fig. 5). Due to the high sensitivity of the Q3D spectrometer and the low background in the spectra, $I^\pi=\frac{7}{2}^-$, $\frac{9}{2}^-$,$\frac{11}{2}^-$ states with low cross sections have been detected in the same energy range.

In summary, the combination of the high resolution in particle transfer reactions, the polarization measurements, and the completeness provided by ARC, leads to an extensive set of data up to 1600 keV in ^{153}Sm. This allows one of the first detailed studies of the IBFM in a multi-j case for a deformed nucleus. Deformed nuclei, and multi-j sets of single particle levels, have been used before in the IBFM but the combination of a nearly full set shell (five single particle orbits) and a deformed nucleus have seldom if ever been tackled. Calculations of $\frac{1}{2}^-$ and $\frac{3}{2}^-$ states give the correct number of states (far more than in the Nilsson model) and reasonable predictions of the energies. The excess states have small (d,t) cross sections and occur at energies near the region of vibrational states in the core nucleus indicating that they involve core coupled excitations. For $I^\pi=\frac{7}{2}^-$, $\frac{9}{2}^-$, $\frac{11}{2}^-$ the (d,t) spectroscopic factors are well described by the IBFM. The often ignored monopole interaction term in the IBFM can be important in affecting the energy staggering in low K bands. For the positive parity levels the large empirical separation of bands with predominantly $\frac{1}{2}$[660] and $\frac{3}{2}$[651] configurations stemming from the same single particle orbit, $i_{13/2}$, is reproduced neither by the Nilsson model,

nor by the QPA calculations of Soloviev [17], nor by the IBFM. Finally, this study points to the importance of improving the existing IBFM codes to include more single particle orbits, a better treatment of pairing, and an improved form for the single particle transfer operator.

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