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Projected quasiparticles calculations in the heavy $N=82$ isotones

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Number-projected quasiparticles calculations in the heavy $N=82$ isotones with $62\leq Z\leq 68$ have been performed. We discuss in some detail the results obtained for the energy spectra and electromagnetic decay properties of the even-mass isotones ^{144}Sm, ^{146}Gd, ^{148}Dy, and ^{150}Er and the odd-mass isotones ^{145}Eu, ^{147}Tb, ^{149}Ho, and ^{151}Tm and compare them with the results of a seniority-model calculation.

NUCLEAR STRUCTURE Projected quasiparticles calculations. Heavy $N=82$ nuclei with $62\leq Z\leq 68$. Energy spectra and electromagnetic decay properties.

I. INTRODUCTION

It is known that the structure of the light $N=82$ isotones ^{136}Xe, ^{138}Ba, ^{140}Ce, and ^{142}Cd is generally well explained in terms of quasiparticles degrees of freedom assuming that the low-energy part of the spectrum mainly results from proton two quasiparticles ($2qp$) excitations.[1] It would be interesting to know whether the same line of approach remains valid for the heavy $N=82$ nuclei ^{144}Sm, ^{146}Gd, ^{148}Dy, and ^{150}Er for which new experimental data have recently become available. Most of these experimental results may be found in Refs. 2 and 3 for ^{144}Sm, in Refs. 4–7 for ^{146}Gd, in Ref. 8 for ^{148}Dy, and in Ref. 9 for ^{150}Er. So, the aim of this work is to investigate the importance of proton $2qp$ degrees of freedom in ^{144}Sm, ^{146}Gd, ^{148}Dy, and ^{150}Er using the Bardeen-Cooper-Schrieffer (BCS) formalism.

Some work along this line has already been undertaken in Ref. 10 in the case of ^{144}Sm and ^{146}Gd. However, this work will differ from Ref. 10 on some important points (apart from the fact that since the time of publication of Ref. 10 a complete revision of the experimental data on ^{146}Gd has been proven necessary). In Ref. 10 the particle number unprojected BCS formalism has been used although the influence of the nonconservation of the exact number of extra protons in the BCS vacuum was investigated by performing a projection of the wave functions onto the state with an exact number of extra protons. It turned out that in the case of ^{144}Sm the distribution of extra protons in the BCS vacuum seemed to be of a Gaussian type with mean value $m\{p\}=6$ proton pairs and dispersion $\sigma\{p\}=1.37$ proton pairs. This also means that the BCS ground state is composed with the exact number of extra protons for only about 35%, as also for ^{144}Sm. Consequently, this formalism is best suited for describing average properties of series of nuclei and is less adequate in describing individual nuclear properties. To remedy this we now use a standard qp Tamm-Dancoff approximation with a fixed number of zero and two qp configurations in which the projection is performed before the minimization of the ground state energy.[11,12] It is sometimes called the fixed BCS approximation (FBCS).[12–15] In Refs. 12–15 full details on the formalism and many applications of it may be found. Moreover, in Refs. 1 and 10 the relative proton single particle energies as well as the interaction strength of the residual interaction was calculated by means of the inverse gap equation (IGE) method.[16] In this way one can extract the input parameters from the neighboring odd-mass nuclei. However, no particle-number projection is performed in the IGE method. Particle-number projection may have a considerable effect, and therefore, one should rather use the inverse modified gap equation (IMGE)+seniority $v=1$ fit.[13] To perform such an IMGE+$v=1$ fit unambiguously, one needs a detailed knowledge of the spectra of the neighboring odd-mass nuclei: For all single-particle levels with angular momentum and spin j^π the lowest level has to be known (when more than one low-lying j^π level occurs, the spectroscopic factor from one-nucleon transfer should also be known) as well as the odd-even mass differences. A detailed knowledge of all the odd-mass nuclei ^{145}Eu, ^{147}Tb, ^{149}Ho, and ^{151}Tm does not as yet exist in order to perform such an IMGE+$v=1$ fit analysis (crucial information on ^{149}Ho and ^{151}Tm is lacking), although recently substantial progress has been made.[17,18] In this work, the set of input parameters has been obtained in a different, albeit related way, to be discussed in some length in Sec. II. In Sec. III we present the detailed results (energy spectra and electromagnetic decay properties) of our calculations and compare them with experiment. In Sec. IV some conclusions are drawn.

II. THE INPUT-PARAMETERS AND THE ODD-MASS NUCLEI

A. Force strength; single-particle energies; iterative method

As a residual interaction we took a Gaussian form, i.e.,

$$V(r)=-V_0\exp(-\beta r^2)(P_S+tP_T)\ . \qquad (2.1)$$

In (2.1), P_S and P_T denote, respectively, the spin-singlet and spin-triplet projection operator and t stands for the triplet-singlet ratio. In this particular mass region $\beta=0.325$ fm^{-2} seems appropriate.[10] Furthermore, we limit ourselves to considering proton single-particle configurations in the $Z=50-82$ core, i.e., the $N=4$ $2d_{5/2}$, $2d_{3/2}$, $3s_{1/2}$, and $1g_{7/2}$ and the $N=5$ $1h_{11/2}$ level.

The values for the interaction strength V_0, the triplet parameter t, and the proton single particle energies relative to the $1g_{7/2}$ level are obtained in the following iterative way.

(i) We start with an initial set of these parameters for the nuclei with $62\leq Z\leq 65$ and we calculate the binding energy (BE) of ^{144}Sm and ^{146}Gd in a FBCS $0qp+2qp$ calculation. By setting

$$S_{2p}(A,Z)=\mathrm{BE}(A,Z)-\mathrm{BE}(A-2,Z-2)\ , \qquad (2.2)$$

we are able to calculate two-proton separation energies. The set of input parameters is rejected when the thus calculated value for ^{146}Gd is not within 200 keV of the Wapstra and Bos value.[19]

(ii) In the case of an accepted input, a FBCS $1qp$ calculation is performed on ^{145}Eu and ^{147}Tb. We now set the constraint that all calculated $1qp$ states in both nuclei lie within 20 keV from the known, low-lying ($\lesssim 1$ MeV) experimental states.[2,17]

(iii) Moreover, by using

$$S_p(A,Z)=\mathrm{BE}(A,Z)-\mathrm{BE}(A-1,Z-1)\ , \qquad (2.3)$$

three additional proton-separation energies [S_p (^{145}Eu), S_p (^{146}Gd), S_p (^{147}Tb)] can be calculated and again we constrain these values to be within 200 keV of the Wapstra and Bos values. Note that the calculated separation energies are quite sensitive to the actual values of V_0 and t while the resulting spectra are less sensitive to these values but, on the contrary, show a strong dependence on the precise location of the proton single-particle levels.

Such an analysis now becomes impossible for the nuclei with $Z\geq 66$. Indeed, in the case of ^{149}Ho only high-spin negative parity states above $E_x=1.5$ MeV are known decaying into a $J^\pi=\frac{11}{2}^-$ state.[18] Moreover, proton-separation energies are only known from systematics.[19] Therefore, we kept the proton single-particle energies constant and adjusted the values for V_0 and t so that proton-separation energies were reproduced within 250 keV. Consequently, the results of the spectra for the odd-mass (and to a lesser extent also the even-mass) nuclei with $Z\geq 66$ might be improved considerably.

The values of V_0 and t resulting from this analysis are shown in Table I. The single-particle energies are displayed in Fig. 1 and are compared (for ^{145}Eu and ^{147}Tb) with the set of proton single-particle energies obtained by Chasman[20] using the method of correlated quasiparticles[21] in which one includes some of the effects arising from particle number conservation that are neglected in the BCS approximation.

Owing to some theoretical and experimental limitations these fitted parameters probably do not constitute an "optimal set": No blocking effect was in-

TABLE I. Values for the interaction strength V_0 and singlet-triplet ratio t [see Eq (2.1)] for the different $N=82$ nuclei.

Z	62	63	64	65	66	67	68	69
V_0 (MeV)	37.6	37.8	34.7	36.1	37.6	38.3	39.1	39.8
t	0.78	0.78	0.89	0.79	0.68	0.60	0.52	0.44

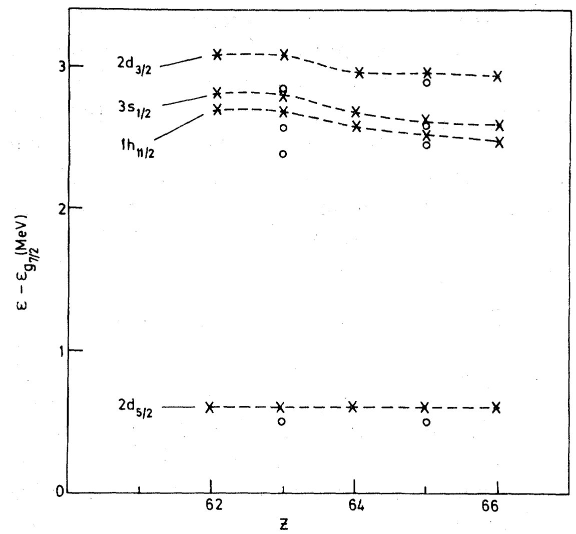

FIG. 1. Proton single-particle energies relative to the $1g_{7/2}$ single-particle configuration for the $N=82$ isotones connected with dashed lines to guide the eye. For nuclei with $Z \geq 66$ the same single-particle energies as in ^{147}Tb were taken. Also shown (open dots) are the values obtained by Chasman (Ref. 20) for ^{145}Eu and ^{147}Tb.

cluded in the description of odd-mass nuclei; the $J^{\pi}=\frac{11}{2}^{-}$ state was *assumed* to be near degenerate with the $J^{\pi}=\frac{1}{2}^{+}$ state in ^{147}Tb, and some small changes in V_0 and t may give results of an equal quality.

For the sake of completeness, we show in Fig. 2 the calculated spectra of ^{145}Eu, ^{147}Tb, ^{149}Ho, and ^{151}Tm in a FBCS $1qp$. The results on Ho and Tm should be regarded as speculative although we believe that the main features [low-lying $J^{\pi}=\frac{1}{2}^{+}, \frac{3}{2}^{+}, \frac{11}{2}^{-}$, and high-lying ($\sim 1$ MeV) $J^{\pi}=\frac{5}{2}^{+}$ and $\frac{7}{2}^{+}$ states] will remain. A similar situation is encountered in the energy level systematics in odd-mass heavy Sn isotopes[26] where the neutron quasiparticle states $J^{\pi}=\frac{1}{2}^{+}, \frac{3}{2}^{+}$, and $\frac{11}{2}^{-}$ are close-lying (with a $J^{\pi}=\frac{1}{2}^{+}$ state as the ground state in ^{127}Sn and $J^{\pi}=\frac{3}{2}^{+}$ as the ground state in ^{129,131}Sn) and the $J^{\pi}=\frac{7}{2}^{+}$ state is found at about $E_x \simeq 1$ MeV.

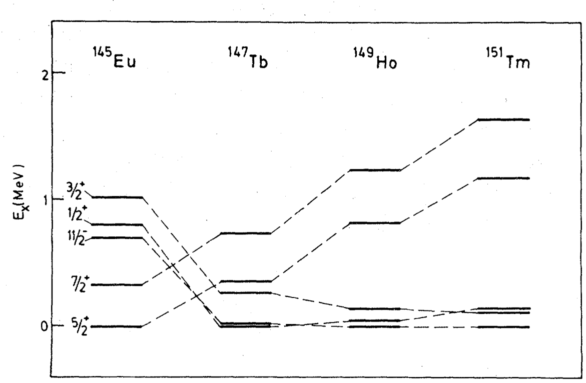

FIG. 2. Calculated spectra of ^{145}Eu, ^{147}Tb, ^{149}Ho, and ^{151}Tm in a projected $1qp$ calculation. See text for further discussion.

B. Seniority-model calculations

It is interesting to compare these results on the odd-mass nuclei with those of Lawson.[22] Lawson calculates the spectra of the $N=82$ with $Z \geq 64$ assuming ^{146}Gd acts as if it was a doubly-closed shell nucleus and assuming that the spectrum will mainly result from $|(1h_{11/2})^{n}_{v};J\rangle$ configurations where n is the number of protons outside the $Z=64$ configuration and v is the seniority quantum number.

The parametrization:

(i) Interaction energies of the $|(1h_{11/2})^{n=2}_{v=2};J^{\pi}\rangle$ states, relative to the energy E_0 of the $|(1h_{11/2})^{n=2}_{v=0};0^{+}\rangle$ state, were taken directly from the experimental spectrum of ^{148}Dy.

(ii) From systematic values[19] the gain of pairing energy by having a pair of particles in the $1h_{11/2}$ level has been evaluated assuming the $J^{\pi}=\frac{11}{2}^{-}$ state in ^{147}Tb is near degenerate with the ground state: $E_0=-2.68$ MeV.

(iii) Particle-particle and particle-hole interaction energies of the $|(1h_{11/2}p);J^{\pi}\rangle$ and $|(1h_{11/2}p^{-1});J^{\pi}\rangle$ configurations ($p=2d_{5/2}$ and $1g_{7/2}$) were calculated using the Schiffer-True interaction.[23] This resulted in the following equation [see Eq. (16) of Ref. 22] for the position of the $J^{\pi}=\frac{5}{2}^{+}$ state relative to the $J^{\pi}=\frac{11}{2}^{-}$ state in the odd-mass nuclei, rewritten in a slightly different way:

$$\Delta E_{5/2}(d_{5/2}{}^{-1})=\Delta(\tfrac{5}{2})+E_0 n +2.571n-3.267 \text{ MeV} , \tag{2.4}$$

where $\Delta(\frac{5}{2})$ is the energy it takes to promote a proton in ^{146}Gd to the $2d_{5/2}$ level, i.e., $\Delta(\frac{5}{2})=3.41$ MeV.[4] This results in

$$\Delta E_{5/2}(d_{5/2}{}^{-1})=0.1429-0.1087n \text{ MeV} . \tag{2.5}$$

For ^{147}Tb ($n=1$) a near degeneracy of the $J^{\pi}=\frac{11}{2}^{-}$

state and the $J^\pi = \frac{5}{2}^+$ state is predicted. By virtue of (ii), however, and from Ref. 17, the $J^\pi = \frac{11}{2}^-$ state is predicted to lie close to the $J^\pi = \frac{1}{2}^+$ state and well below the $J^\pi = \frac{5}{2}^+$ state. This is also suggested by $1qp$ calculations whether these are performed in a number conserving way or not (see, for instance, Ref. 17 and Fig. 2 of this work). The crucial point is, of course, that (2.4) has a negative slope as a function of n. If one assumes that also in ^{149}Ho and ^{151}Tm the $J^\pi = \frac{5}{2}^+$ state is expected well above the $J^\pi = \frac{11}{2}^-$ state, the parametrization (i)–(iii) should be modified in such a way that a positive slope in Eq. (2.4) will result. To do so we preferred to fit E_0 to the spectrum of ^{147}Tb instead of taking it from Ref. 19. [One could also reparametrize the particle-particle and particle-hole interaction energies (iii).] Again assuming a near degeneracy of the $J^\pi = \frac{11}{2}^-$ and $\frac{1}{2}^+$ state in ^{147}Tb one gets

$$E_0 \simeq -2.4 \text{ MeV} \tag{2.6}$$

and subsequently the relation (2.4) becomes

$$\Delta E_{5/2}(d_{5/2}{}^{-1}) = 0.1429 + 0.171n \text{ MeV} . \tag{2.7}$$

The value [Eq. (2.6)] of E_0 differs from the systematic value by 280 keV.

This short discussion of the results obtained by Lawson has been carried out in order to emphasize the fact that crucial experimental information on ground state properties and on nuclear structure aspects in this particular mass region is still lacking so that a more appropriate parametrization may be carried out. Once this has been done, it is clear that this may result in several new predictions for this mass region which can be seen then as a new testing field for the seniority scheme in general.

III. ENERGY SPECTRA AND ELECTROMAGNETIC DECAY PROPERTIES

A. Energy spectra

The detailed results of our calculation of the spectra for ^{144}Sm, ^{146}Gd, ^{148}Dy, and ^{150}Er are shown in Figs. 3–6. For ^{144}Sm all experimentally known levels below 3 MeV are shown. Above 3 MeV, we left out the very high-spin states which, anyway, we cannot reproduce in our calculations or those states for which no definite spin and parity assignments could be given. First, we give a short discussion for each nucleus separately. Afterwards, some general conclusions will be drawn.

1. *Detailed nuclear properties*

(a) ^{144}Sm. Here, the $J_i^\pi = 2^+_{1,2}$, $4^+_{1,2,3}$, and 6^+_1 states are reproduced within 150 keV. Moreover, our calculation suggests that no $J^\pi = 8^+$ or 10^+ state with a proton $2qp$ character will be found below $E_x = 4.5$ MeV. The unambiguous identification of the $J_i^\pi = 0^+_2$ state is rather difficult. It is a general feature of all quasiparticles calculations in even-even nuclei that the first excited $J^\pi = 0^+$ state is found close to the $J_i^\pi = 2^+_1$ state. Experimentally, however, this is not the case for ^{144}Sm. Moreover, the $J_i^\pi = 0^+_3$ state is calculated at about $E_x \simeq 3$ MeV so that in any case we do not reproduce the experimental $J^\pi = 0^+$ state at $E_x \simeq 2.5$ MeV within 0.5 MeV.

The negative parity sequence of levels $J_i^\pi = 3^-_1$, 5^-_1, and 7^-_1 is calculated too compressed with a $J_i^\pi = 3^-_1$ state that is far from the experimental value. This discrepancy will be discussed in Sec. III A 2. There is a reasonable agreement between theory and experiment for the $J_i^\pi = 4^-_1$, $8^-_{1,2}$, and 9^-_1

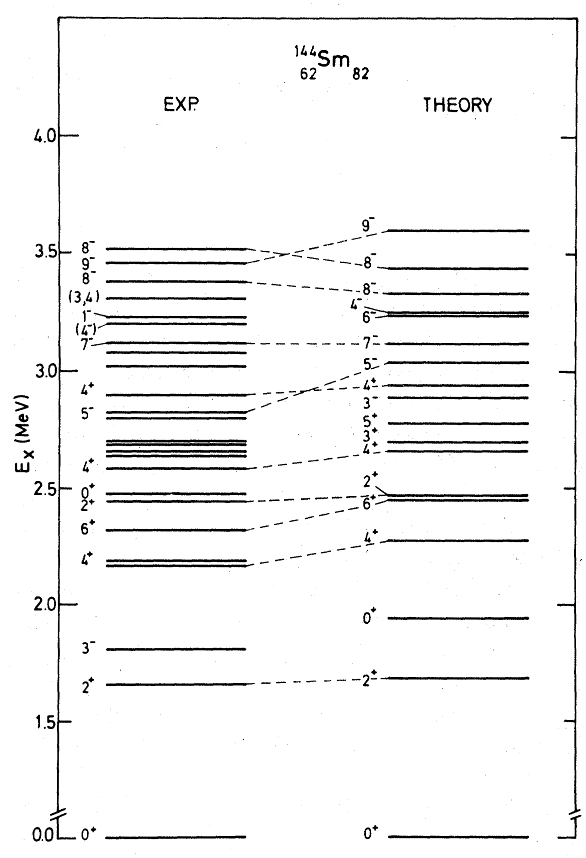

FIG. 3. Calculated and experimental (Refs. 2, 3, and 7) spectrum of ^{144}Sm.

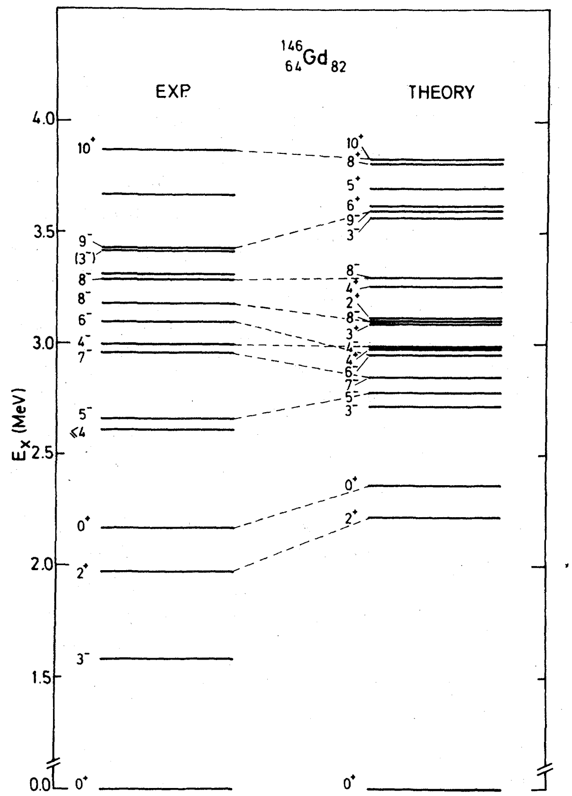

FIG. 4. Calculated and experimental (Refs. 4–7 and 28) spectrum of ^{146}Gd.

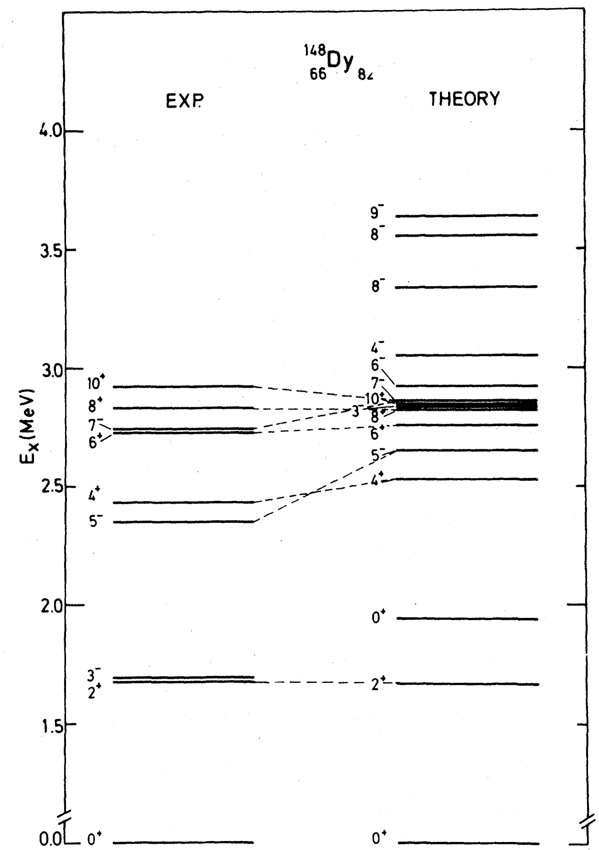

FIG. 5. Calculated and experimental (Ref. 8) spectrum of ^{148}Dy.

states.

(b) ^{146}*Gd.* The recent discovery that a $J^\pi=3^-$ state, rather than the expected $J^\pi=2^+$ state, is the first excited state in this nucleus[4] has stimulated very much nuclear-structure research in this region. In ^{146}Gd more is known about the negative parity states than about the positive parity states. In our calculation the $J_i^\pi=3_1^-$, 5_1^-, and 7_1^- sequence of levels is too compressed. The $J_i^\pi=(3_2^-)$, 4_1^-, and 6_1^- states are well reproduced but the level ordering is reversed. The $J_i^\pi=8_{1,2}^-$ and 9_1^- states are reproduced within 150 keV but are spread out too much.

All positive parity states occur at an unusually large excitation energy. For instance, the $J_i^\pi=4_1^+$ and 6_1^+ states are predicted at $E_x \simeq 3$ MeV and $E_x \simeq 3.5$ MeV, respectively. This particular behavior of the positive parity states will be discussed later.

(c) ^{148}*Dy.* This nucleus has an interesting yrast sequence $J^\pi=10^+$, 8^+, 6^+, 4^+, 2^+, and 0^+ which results[8,22] from the coupling of two $1h_{11/2}$ protons to the appropriate spin. The two-particle-like aspect of this spectrum is reproduced in our quasiparticles calculations. This may be considered a demonstration of the validity of the number-projection technique[15] used here, even when moderately sized gaps occur in the single-particle energies. The $J_i^\pi=8_{1,2}^-$ and 9_1^- states are calculated above $E_x=3$ MeV although, as in ^{146}Gd, they might be expected to lie closer together than predicted.

(d) ^{150}*Er.* Very little is known about this nucleus. The $J^\pi=10^+$ state has not been observed but is expected to lie at about $E_x \simeq 2.8$ MeV. The calculated yrast sequence $J^\pi=10^+$, 8^+, 6^+, 4^+, 2^+, and 0^+ is very similar to that of ^{148}Dy but experimental information on the $J^\pi=6^+$ and 4^+ states is still lacking, for reasons to be discussed later. The $J_i^\pi=8_{1,2}^-$ and 9_1^- states are predicted at $E_x \simeq 3.5$ MeV. These results are more or less in agreement with those of Lawson except for the $J_i^\pi=8_1^-$ state which is predicted in Ref. 22 at a considerably lower energy, i.e., $E_x \simeq 2.78$ MeV.

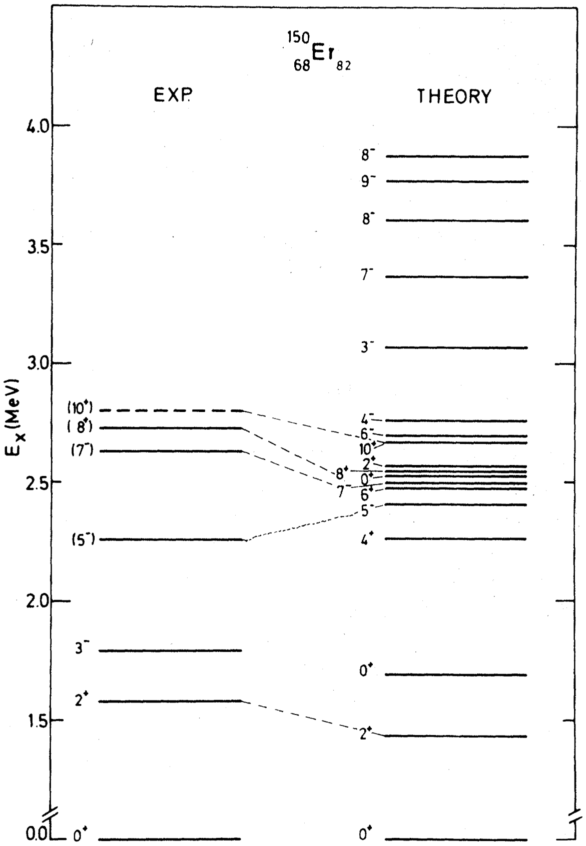

FIG. 6. Calculated and experimental (Ref. 9) spectrum of ^{150}Er.

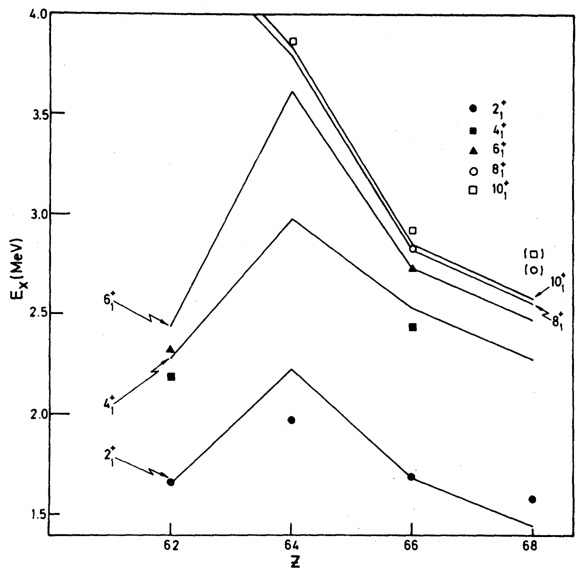

FIG. 7. Systematic behavior of the excitation energy of some calculated (lines) and experimental (marks) positive parity states in Sm, Gd, Dy, and Er.

2. *Systematic features*

In order to illuminate some of the general aspects of the spectra of these nuclei, we show in Figs. 7–9 the systematic behavior of some low-lying states.

(i) The most interesting point is the dramatic peaking in excitation energy of the $J_i^\pi = 2_1^+$, 0_2^+, 4_1^+, and 6_1^+ states in ^{146}Gd compared with ^{144}Sm and ^{148}Dy (Fig. 7). This is in contrast to the behavior of the excitation energy of the $J^\pi = 8^+$ and 10^+ states which lower monotonically. Since for the latter states there is only one basic configuration, i.e., the $|(1h_{11/2})^2;J^\pi\rangle$ configuration, this can be understood as a consequence of the beginning and gradual "filling up" of the $1h_{11/2}$ single-particle configuration. We now discuss in some detail the behavior of the $J^\pi = 6^+$ states (Fig. 8). The conclusion drawn for the $J^\pi = 6^+$ states will also hold, although to a lesser extent, for the $J_i^\pi = 2_1^+$ and 4_1^+ states. There are three basic $2qp$ configurations for the $J^\pi = 6^+$ states, i.e., the $|(2d_{5/2}1g_{7/2});6^+\rangle$, $|(1g_{7/2})^2;6^+\rangle$, and $|(1h_{11/2})^2;6^+\rangle$ configurations. The state with a dominant $|(1h_{11/2})^2;6^+\rangle$ configuration again shows a monotonic lowering in excitation energy when going from Sm to Er. However, the

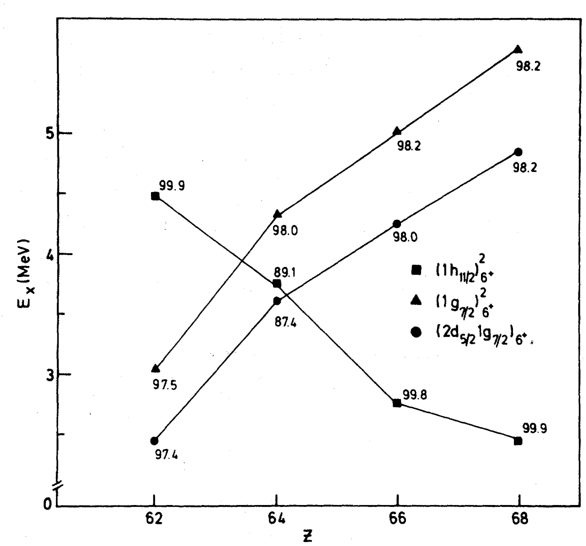

FIG. 8. Calculated excitation energies of the $J^\pi = 6^+$ states in ^{144}Sm, ^{146}Gd, ^{148}Dy, and ^{150}Er. States with the same dominant component (marks) are connected by solid lines. The percentage of the dominant basic configuration is written beside each state. See text for further discussion.

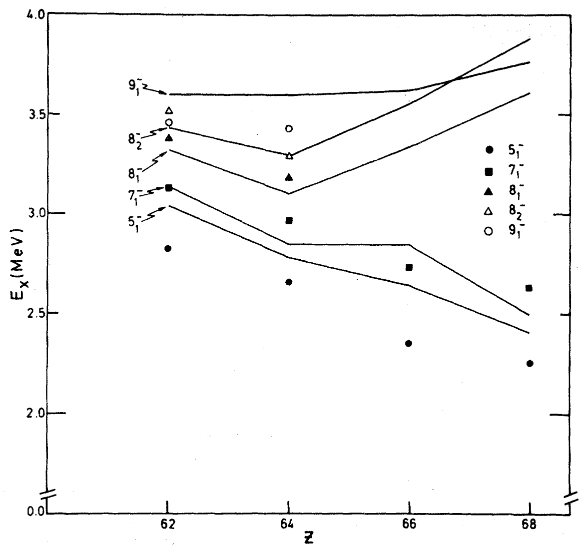

FIG. 9. Same as Fig. 7 but for some negative parity states.

states with a dominant $|(1g_{7/2})^2;6^+\rangle$ and $|(2d_{5/2}1g_{7/2});6^+\rangle$ configuration now show a monotonic upward trend in excitation energy which is a consequence of a further occupation of the $2d_{5/2}$ and $1g_{7/2}$ single-particle configurations (which are already largely occupied in Sm) when going from Sm to Er. The crossing of these states takes place in ^{146}Gd at a rather large excitation energy.

(ii) Concerning the negative parity states (Fig. 9), it has been already remarked that the sequence of $J_i^\pi=3_1^-$, 5_1^-, and 7_1^- states is calculated too compressed and that the $J_i^\pi=3_1^-$ state is not reproduced within a $2qp$ calculation. In general, as will become clear when discussing decay properties, one can conclude that the $J^\pi=3^-$ state (and to a lesser extent the $J^\pi=5^-$ state) is not described as a strongly collective state. This is due to the limitation of only considering proton single particle configurations in the $Z=50-82$ shell. Consequently, only two basic configurations make up to $J^\pi=3^-$ states, i.e., $|(1g_{7/2}1h_{11/2});3^-\rangle$ and $|(2d_{5/2}1h_{11/2});3^-\rangle$. To remedy this one can expand the model space in a straightforward way by including more proton single-particle configurations as well as by allowing for neutron particle-hole excitations through the closed $N=82$ shell. As was shown by Gillet *et al.*,[16] in the case of the Sn isotopes, one finds that this plays a small role for the low-lying even-parity vibrations but is essential for the odd-parity octupole state. Moreover, for electromagnetic transition rates, introduction of core p-h configurations significantly increases the transition rates of $J^\pi=3^-$ states but leaves those for the $J^\pi=2^+$ states almost unaltered.

(iii) Finally, we discuss the behavior of the $J_i^\pi=8_{1,2}^-$ and 9_1^- states (Fig. 9). These states are predicted at a rather large excitation energy in ^{148}Dy and ^{150}Er. Although the calculated energies may be somewhat too high, we believe that these states will be found above the $J^\pi=10^+$ state in both nuclei.

B. Electromagnetic decay properties

When no experimental energy for a level with certain spin and parity was known we guessed the position of this level by comparing with neighboring nuclei and/or theoretical results. In fact, we took: in ^{144}Sm, $E_x(10_1^+)=4.22$ MeV, $E_x(8_1^+)=4.11$ MeV; in ^{146}Gd, $E_x(8_1^+)=3.67$ MeV, $E_x(6_1^+)=3.35$ MeV, $E_x(4_1^+)=2.80$ MeV; in ^{150}Er, $E_x(10_1^+)=2.79$ MeV, $E_x(6_1^+)=2.60$ MeV, $E_x(4_1^+)=2.30$ MeV.

Furthermore, we set $e_{\rm eff}=1.53e$, $g_s=2.9$ nm, and

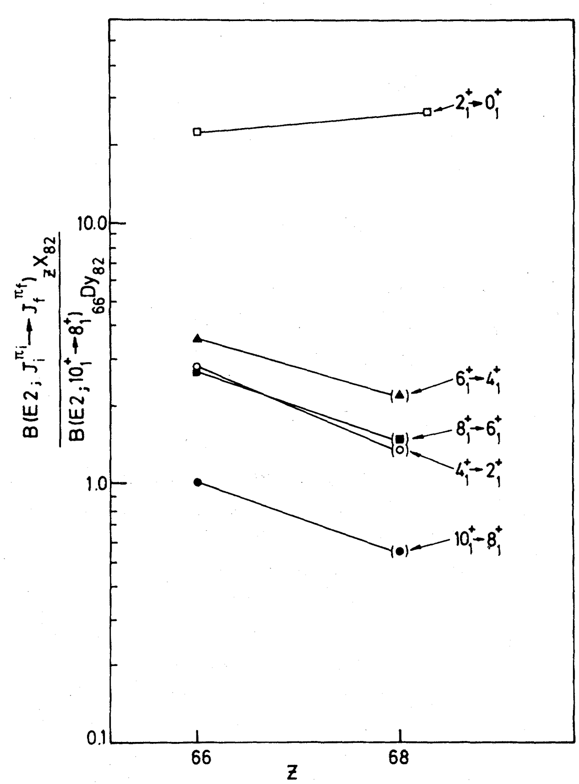

FIG. 10. $B(E2)$ values in Dy and Er relative to the $B(E2;10_1^+\to 8_1^+)$ value in Dy.

TABLE II. Some calculated and experimental half-lives in ^{144}Sm, ^{146}Gd, ^{148}Dy, and ^{150}Er.

Nucleus	$J_i^{\pi_i} \to J_f^{\pi_f}$	E_x (MeV)	$Q\lambda$	$T_{1/2}(\gamma)$ (s)	α	$T_{1/2}$ (s) Theory	$T_{1/2}$ (s) Exp.
^{144}Sm	$8_1^- \to 7_1^-$	0.253	$M1$	0.068×10^{-9}	0.13	0.6×10^{-9}	1.4×10^{-9}
			$E2$	60×10^{-6}	0.01		
	$6_1^+ \to 4_1^+$	0.132	$E2$	3.45×10^{-6}	0.88	1.8×10^{-6}	0.88×10^{-6}
	$3_1^- \to 0_1^+$	1.81	$E3$			0.36×10^{-9}	
	$2_1^+ \to 0_1^+$	1.66	$E2$			92×10^{-15}	90×10^{-15}
^{146}Gd	$7_1^- \to 5_1^-$	0.324	$E2$	23.2×10^{-9}	0.04	22.3×10^{-9}	7.2×10^{-9}
	$3_1^- \to 0_1^+$	1.579	$E3$			2.8×10^{-9}	1.1×10^{-9}
	$2_1^+ \to 0_1^+$	1.972	$E2$			0.04×10^{-15}	$<1.0\times10^{-12}$
^{148}Dy	$10_1^+ \to 8_1^+$	0.086	$E2$	4.01×10^{-6}	4.85	0.68×10^{-6}	0.48×10^{-6}
	$8_1^+ \to 6_1^+$	0.101	$E2$	0.68×10^{-6}	2.65	186×10^{-9}	65×10^{-9}
^{150}Er	$10_1^+ \to 8_1^+$	0.056	$E2$	62.2×10^{-6}	29.49	2.04×10^{-6}	2.7×10^{-6}
	$8_1^+ \to 6_1^+$	0.100	$E2$	0.3×10^{-6}	2.98	75×10^{-9}	

[a]Reference 25.

$g_l=1.2$ nm. These effective charges (electric and magnetic) have been determined by a fit to all known electromagnetic transition rates. Moreover, we found it necessary to include in the $M1$ operator a tensor term $g_p(Y_2\times s)^{(1)}$ (Ref. 24) with $g_p=0.35$ nm.

In Fig. 10 we show the $B(E2)$ values for the $E2$ decay between the $J^\pi=10^+$, 8^+, 6^+, 4^+, 2^+, and in ^{148}Dy and ^{150}Er in reference to the $B(E2;10_1^+\to 8_1^+)$ value in ^{148}Dy.

What is quite remarkable is that the $B(E2)$ values between corresponding states in Dy and Er change by a factor of 2 rather than by a factor of 4 as predicted in seniority-model calculations.[22] As already discussed in Ref. 22, it is quite possible that in Dy and Er the main decay sequence is $10^+\to 8^+\to 7^-\to 5^-\to 3^-\to 0^+$ rather than $10^+\to 8^+\to 6^+\to 4^+\to 2^+\to 0^+$. Since $E1$ transitions are single particle forbidden in the model space considered here, we could not test this statement. Anyway, the calculated half-lives for the $J_i^\pi=8_1^+$ states in Dy and Er should be regarded as upper limits rather than as precise values.

In Table II we show some calculated half-lives and compare them with experiment. It is remarked that the $J^\pi=3^-$ state has a half-life which is too long compared with experiment, again pointing towards a lack of collectivity in these states. The calculated half-lives of the $J_1^\pi=10_1^+$ states in Dy and Er agree well with the experiment. Other half-lives, however, are overestimated with respect to the experimental situation. This is the case in ^{146}Gd with the half-life of the $J_i^\pi=7_1^-$ state resulting from the $E2$ decay to the $J_i^\pi=5_1^-$ state and in ^{148}Dy with the half-life of the $J_i^\pi=8_1^+$ state. In the latter case, however, we have mentioned that this calculated value should be considered as an upper limit. We believe the same holds true for the $T_{1/2}(8_1^+)$ in Er. We also would like to mention the fact that there is very little known about magnetic decay modes so that our effective magnetic charges are somewhat arbitrary.

IV. CONCLUSIONS

We have performed projected $0qp+2qp$ calculations (FBCS) in ^{144}Sm, ^{146}Gd, ^{148}Dy, and ^{150}Er using a Gaussian force as the residual interaction. The different input parameters, proton single particle energies, interaction strength, and the triplet singlet ratio, were obtained via a fit to ground state properties of the $N=82$ nuclei with $62\le Z\le 69$ and a fit to the experimental spectra of ^{145}Eu and ^{147}Tb. Results for the spectra of the odd-mass nuclei ^{145}Eu, ^{147}Tb, ^{149}Ho, and ^{151}Tm were presented and compared with results from seniority-model calculations. At this point it was argued that crucial experimental information on masses in this particular mass region is still lacking and that perhaps the experimental values may differ by more than 200 keV from the systematic ones. Results for the spectra of ^{144}Sm, ^{146}Gd, ^{148}Dy, and ^{150}Er were presented as well as electromagnetic decay properties. A closer investigation of the systematic behavior of some positive and negative parity yrast states was made. A mechanism to explain the rather large excitation energies of positive parity states in ^{146}Gd compared with ^{144}Sm and ^{148}Dy was offered. It was suggested that some of the shortcomings in our calculation, especially concerning the $J^\pi=3^-$ and 5^- states, may be removed by enlarging the model space.

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