# A STUDY OF THE $^{144}$Nd(d, t) $^{143}$Nd REACTION AND UNIFIED MODEL INTERPRETATION OF THE STATES OF THE $^{143}$Nd NUCLEUS

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Levels in $^{143}$Nd have been studied by means of the $^{144}$Nd(d, t) $^{143}$Nd reaction at a bombarding energy of 12.1 MeV. The reaction products were observed with a magnetic spectrograph and photographic plate recording. The spectroscopic factors for the observed levels were obtained from a DWBA calculation. The energies and spectroscopic factors of the states in the $^{143}$Nd nucleus are calculated in terms of the intermediate coupling unified model.

## 1. Introduction

Nuclei with 83 neutrons are expected to have a closed neutron shell structure. The single-particle shell-model states in the $83 \leqslant N \leqslant 125$ shell are: $3p_{1/2}$, $3p_{3/2}$, $2f_{5/2}$, $2f_{7/2}$, $1h_{9/2}$ and $1i_{13/2}$. A neutron transfer reaction, such as a (d, p) and a (d, t), is well suited for exciting these one-particle states. In a (d, t) reaction we expect to pick-up neutrons from the occupied orbitals outside the closed shell and from the closed shell itself ($2d_{3/2}$, $3s_{1/2}$, $1h_{11/2}$, $2d_{5/2}$, and $1g_{7/2}$).

A coupling of the odd neutron to the $N = 82$ even-even core results in a mixing of the single-particle states. Because of this mixing the single-particle strength is distributed over several states. The sum of the spectroscopic factors $S_J$ for these states should be unity.

Most of the information on the properties of the low-lying levels in $^{143}$Nd nucleus has been obtained from analyses of the (d, p) reaction measurements [1–5], elastic and inelastic scattering of deuterons and protons [1, 6]; (d, t) [7], (n, $\gamma$) [8], and ($\alpha$, $x$n) [9] reaction studies. It appears that independent investigations of the structure of the $^{143}$Nd nucleus using a wide variety of reactions are generally consistent. Although the level scheme of this nucleus is fairly well established below excitation energy of 2 MeV, information about the level structure obtained from the pick-up reactions are rather scarce [7].

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In the present experiment the $^{144}$Nd(d, t) $^{143}$Nd reaction was investigated. The energy spectra of tritons were measured for transitions to a number of final states. The data were analysed by means of the DWBA method. The level scheme is compared with the predictions based on the intermediate coupling unified model.

## 2. *Experimental procedure and results*

The experimental methods are very similar to those used in Refs [10, 11]. The beam of 12.1 MeV deuterons was obtained from the Niels Bohr Institute EN tandem accelerator, and the reaction charged products were analysed in a high-resolution magnetic spectrograph [12] with photographic plate recording.

The targets were prepared by vacuum evaporation onto a thin carbon backing, using isotopically enriched materials in oxide form. The neodymium targets were enriched to about 96% of $^{144}$Nd. The target thickness was approximately 50 μg/cm$^2$ and the carbon

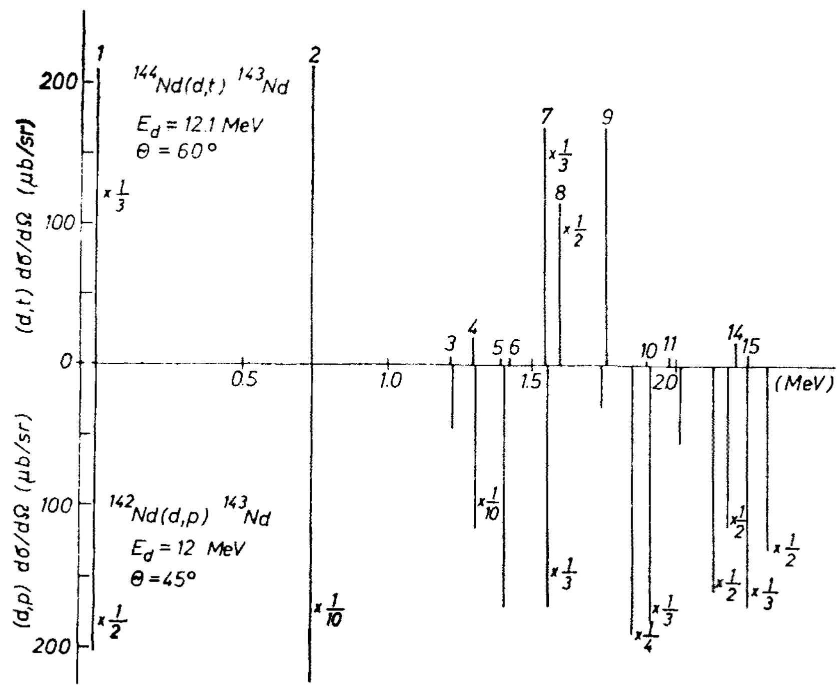


Fig. 1. Triton and proton spectra from the $^{144}$Nd(d, t) $^{143}$Nd and $^{142}$Nd(d, p) $^{143}$Nd reactions. Triton groups have been labelled 1, 2 ... 15. The proton spectra were taken from Ref. [1]

backing about 40 μg/cm$^2$. The spectra were recorded at angles of 60°, 90° and 125°. The energy resolution was approximatelly 12–15 keV. The photographic plates were reviewed by 0.25 mm strips. The absolute cross sections were determined by normalization to the cross section for elastic deuteron scattering [13].

The triton spectrum obtained from the $^{144}$Nd(d, t) $^{143}$Nd reaction at an angle of 60° is shown in Fig. 1 in the form of bars which reflect the intensities of the states. The protons spectrum from the $^{142}$Nd(d, p) $^{143}$Nd reaction taken from paper [1] is shown at the bottom of Fig. 1 for comparison. The level energies obtained by averaging determinations at three different angles are listed in Table I, which also summarizes the measured differential cross

TABLE I

Levels populated in the $^{144}$Nd(d, t) $^{143}$Nd reaction

| No | $J^\pi$ | Energy average (keV) | $d\sigma/d\Omega$ (μb/sr) | | | Spectroscopic factors | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | 60° | 90° | 125° | $S_l^{(-)}$ 60° | $S_l^{(-)}$ 90° | $S_l^{(-)}$ 125° | $S_l^{(-)}$ average | $S_l^{(-)}/(2J+1)$ |
| 1 | 7/2⁻ | 0 | 656 | 413 | 175 | 1.5 | 1.22 | 0.92 | 1.21 | 0.152 |
| 2 | 3/2⁻ | 737 | 228 | 110 | 44 | 0.24 | 0.16 | 0.12 | 0.17 | 0.043 |
| 3 | 13/2⁺ | 1218 | 4 | 0.5 | 1 | 0.17 | 0.01 | 0.03 | 0.07 | 0.007 |
| | | | | | | 0.38 | 0.02 | 0.04 | 0.15 | 0.01 |
| 4 | 1/2⁻ | 1297 | 38 | 15 | 6 | 0.06 | 0.03 | 0.02 | 0.04 | 0.02 |
| 5 | 9/2⁻ | 1396 | 4 | 2 | 0.5 | 0.17 | 0.07 | 0.02 | 0.07 | 0.009 |
| 6 | 11/2⁻ | 1422 | 3 | 6 | 8 | 0.16 | 0.22 | 0.32 | 0.23 | 0.019 |
| 7 | 3/2⁺ | 1548 | 515 | 481 | 298 | 2.91 | 2.67 | 2.55 | 2.51 | 0.63 |
| 8 | 1/2⁺ | 1599 | 271 | 247 | 157 | 0.96 | 0.73 | 0.71 | 0.8 | 0.40 |
| 9 | 1/2⁺ | 1766 | 170 | 151 | 105 | 0.73 | 0.49 | 0.51 | 0.58 | 0.29 |
| 10 | 5/2, 7/2⁻ | 1901 | 1.2 | 2 | 2 | 0.01 | 0.01 | 0.02 | 0.01 | 0.003 |
| 11 | 3/2⁺ | 1980 | 11 | 24 | 24 | 0.1 | 0.19 | 0.27 | 0.18 | 0.046 |
| 12 | | 2166 | — | 5 | 8 | | | | | |
| 13 | | 2193 | — | — | 7 | | | | | |
| 14 | 11/2⁻ | 2213 | 35 | 38 | 29 | 3.32 | 2.44 | 1.88 | 2.55 | 0.21 |
| 15 | | 2240 | 16 | — | | | | | | |

sections and the suggested assignment for most of the investigated levels. The level assignments were taken from Refs [1–7] and also fiom the present measurements, from the ratios $R = (d\sigma/d\Omega)_{60°}/(d\sigma/d\Omega)_{90°}$ and $R = (d\sigma/d\Omega_{60°}/(d\sigma/d\Omega)_{125°}$.

To extract spectroscopic information from the experimental data a series of DWBA calculation were carried out using the computer code DWUCK. The deuteron and triton optical model parameters are taken from paper [14] as those parameters have been successfully applied for the analyses of the (d, t) reactions on rare-earth targets [14, 15]. The calculations were performed for neutrons picked-up from the $3p_{1/2,\,3/2}$; $2f_{5/2,\,7/2}$; $2d_{3/2,\,5/2}$; $1h_{9/2}$, $3s_{1/2}$ and $1h_{11/2}$ shell-model states. The DWBA calculations were used to extract the spectroscopic factors $S_l^{(-)}$ by fitting the experimental cross sections obtained at 60°, 90° and 125° to the DWBA cross sections by means of the equation:

$$\frac{d\sigma}{d\Omega} = 3.0 \times S_l^{(-)} \sigma_l^{(-)}(\Theta),$$

where $\sigma_l^{(-)}(\Theta)$ is the angular function obtained from the DWBA calculation. The normalization factor $N = 3.0$ is the same as that used for the (d, t) reactions in deformed nuclei

[11, 14]. The extracted spectroscopic factors $S_l^{(-)}$ and the spectroscopic factors divided by $(2J+1)$ are listed in Table I.

The earlier, high-resolution studies of the $^{143}$Nd nucleus by means of the (d, p) and (d, t) reaction for the low-lying excited states are summarized in Fig. 2 together with $l$-transfer values and spectroscopic factors.

From Fig. 2 we see that in general there is a reasonably good agreement between the spectroscopic factors obtained from the different (d, p) reactions studied.

The hole states in $^{143}$Nd which have been observed in the $^{144}$Nd(d, t) reaction are not excited or are excited very weakly in the (d, p) experiments. On comparing the results of the present (d, t) experiment with the very similar experiment of Gales et al. [7] we see that a number of important discrepancies exist. The disagreement concerns the energies and the spectroscopic factors. Gales et al. [7] did not observe the weak excited levels at $E_x = 1218$ keV, 1396 keV, 1422 keV, 1901 keV and 2193 keV. On the other hand the spectroscopic factors obtained in (d, t) experiments for strong groups [7] are in close agreement with the present results.

The summed spectroscopic factors from the (d, p) and (d, t) reactions studied for the ground state $7/2^-((2J+1)S_l^{(+)}+S_l^{(-)} \approx 7.2)$ are approximately equal to the expected maximum value for the $2f_{7/2}$ state. This result indicates that the ground state carries nearly all the $2f_{7/2}$ available strength and is an almost pure quasi-particle neutron state.

The states at 737 keV and 1297 keV excitation energies are known to have spins of $3/2^-$ and $1/2^-$, respectively. The summed spectroscopic factors from the (d, p) and (d, t) reactions studied give for these states only about 50% of the available strength, the missing strength is dispersed among several $3/2^-$ and $1/2^-$ states due to the coupling of the single neutron to the even-even core.

The $V^2$ parameter for the $7/2^-$, $3/2^-$ and $1/2^-$ states obtained from the present (d, t) studies are equal 0.15, 0.04 and 0.02, respectively.

The large (d, t) spectroscopic factors for the even parity states $3/2^+$, $1/2^+$ at 1548 keV, 1599 keV, 1766 keV and 1980 keV indicate that these states can be interpreted as hole states in the underlying $N = 82$ neutron core, and that the neutron can be picked-up from the $3s_{1/2}$ and $2d_{3/2}$ filled orbitals.

It should be noted that the sum of the (d, t) spectroscopic factors in the $^{143}$Nd nucleus for the $1/2^+$ and $3/2^+$ states are equal to 1.38 and 2.80, respectively. These values can be directly compared with the spectroscopic factors for the same components in the $^{141}$Nd nucleus which are equal to 1.47 ($3s_{1/2}$) and 3.43($2d_{3/2}$) [17]. The spectroscopic factors for the $3s_{1/2}$ and $2d_{3/2}$ hole states are significantly lower for the $^{143}$Nd nucleus than those for the $^{141}$Nd one.

### *3. Calculations and comparison of theoretical results with experimental data*

The intermediate coupling model [19] is applied to interprete the observed energy spectrum of the $^{143}$Nd nucleus. For the odd parity states it is assumed that the motion of the odd neutron on the orbits $2f_{7/2}$, $1h_{9/2}$, $3p_{3/2}$, $3p_{1/2}$, $2f_{5/2}$ and the neutron hole on the orbit $1h_{11/2}$ is coupled to quadrupole vibrations of the even-even $N = 82$ core (inclusion of the octupole vibrations does not improve significantly the results for the odd parity states). The $13/2^+$ states are assumed to be formed as a result of coupling of the motion of the neutron on the $1i_{13/2}$ and $2f_{7/2}$ orbits to the quadrupole and octupole vibrations of the core, respectively. Two $1/2^+$ and two $3/2^+$ states with appreciable spectroscopic factors are obtained below 2.3 MeV and are due to the coupling of the motion of the neutron hole on the orbits $3s_{1/2}$ and $2d_{3/2}$ to the quadrupole vibrations of the $N = 84$ core and the $2f_{7/2}$ neutron motion to the $3^-$ octupole state of the $^{142}$Nd nucleus.

The calculations have been performed for harmonic and anharmonic oscillations. In the latter case the energy of the twophonon state of the core is assumed to be equal to the energy of the $4^+$ level in the $^{142}$Nd nucleus. The excitations of the core up to three quadrupole phonon and the one octupole phonon states are included. For the single neutron energies the centroid values given in Ref. [4] are used. The values of the parameters are listed in Table II. The theoretical and experimental positions of the energy levels and the spectroscopic factors are presented in Fig. 2. The values of spectroscopic factors smaller than 0.01 are not listed in the figure.

TABLE II

Single neutron energies, one-, two-, three-phonon energies and the strength of the nucleon-surface coupling $\xi$ used in the calculations

| | $\xi_2$ | $\xi_3$ | $2f_{7/2}$ | $2f_{5/2}$ | $3p_{3/2}$ | $3p_{1/2}$ | $1h_{9/2}$ | $1h_{11/2}$ | $1i_{13/2}$ | $E2$ | $E3$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| (a) | 1.22 | 1.5 | 0 | 1.90 | 4.28 | 2.10 | 1.31 | 4.0 | 1.6 | 3.14 | 4.71 |
| (b) | 1.00 | 1.5 | 0 | 1.90 | 1.28 | 2.10 | 1.31 | 4.0 | 1.6 | 2.10 | 3.67 |

The figures in the upper line (a) correspond to the coupling of the neutron to the harmonic vibrations of the core, and those in the lower line (b) to anharmonic ones. All the energies are given in MeV.

The lowest odd parity states observed in the experiments are: $7/2^-$, $3/2^-$, $1/2^-$, $9/2^-$, $5/2^-$. They are reproduced by the calculations, but the order of the spins is not quite correct. The theoretical odd parity level with spin 1/2 is above the pair of levels $9/2^-$, $5/2^-$, while it is observed below these states. The levels $9/2^-$, $5/2^-$ appear about 200 keV too low as compared with experiment. Many levels above 2.0 MeV are observed in the stripping reactions. For this region the model with anharmonic vibrations of the core seems to give better results.

The calculated spectroscopic factors of the odd parity states and the $13/2^+$ states are compared with experimental data obtained in stripping reactions. The small values obtained in the pick-up reactions for these spectroscopic factors are consistent with the assumption that the mentioned states are built as a results of coupling of the particle to the surface. If the values of the occupation factor estimated in the present experiment are taken into account, the calculated spectroscopic factors will be lowered by about 15% for the $7/2^-$ ground state, by about 4% for the first excited state $3/2^-$ and about 2–5% for the first $1/2^-$ state. These lowered values are in agreement with the experiment of Christensen et al. [1].

It results from experiments [1, 4] that the first excited $7/2^-$ state may be located at 1.850 MeV. The observed value of the spectroscopic factor of this state is equal to 0.85. It is possible that this state corresponds to the calculated first excited $7/2^-$ state at 1.65 MeV with $S = 0.63$. The particle spectroscopic factor of the ground state which is equal to about 6.0 and that of the $7/2^-$ level at 1.85 MeV ($S = 0.85$) together with the hole spectroscopic factor of the ground state estimated in the present experiment as 1.21 give the value of about 8.0. Consequently, it seems that there are no other $7/2^-$ states with appreciable spectroscopic factors and that the level observed in the present experiment and in other works at 1.901 MeV with the possibility of spins $5/2^-$, $7/2^-$ should rather have the spin $5/2^-$.

In the present (d, t) experiment two states with $J^\pi = 11/2^-$ are observed, one at $E = 1.422$ MeV with the hole spectroscopic factors $S^{(-)} = 0.23$, and one at $E = 2.213$ MeV with $S^{(-)} = 2.55$. In calculations the first $11/2^-$ state is obtained at 1.35 MeV, and is formed mainly by the component $|f_{7/2}\otimes 2^+\rangle$ with some admixture of the $1h_{11/2}$ state ($S^{(-)} = 0.33$). This state corresponds quite well to the experimental first $11/2^-$ level. In the anharmonic vibrator model the $11/2^-$ levels with small spectroscopic factors are obtained at 1.93 MeV and at 2.09 MeV. It is possible that they correspond to the experimental level at 2.2 MeV.

In the present experiment the even parity state $13/2^+$ is observed at 1.223 MeV with the small "hole" spectroscopic factor $S^{(-)} = 0.15$. In the (d, p) reactions the spectroscopic factor of this same state lies in the range 6.12–6.30. The second $13/2^+$ state appears at $E = 2.7$ MeV with $S = 3.31$–$2.94$ [4]. In the calculations the first $13/2^+$ state is obtained with E = 1.24 MeV and $S = 6.21$. Its main components are $|i_{13/2}\otimes 0^+\rangle$ and $|f_{7/2}\otimes$ $\otimes(3^-, 0^+)\, 3^-\rangle$. The second theoretical $13/2^+$ state has $E = 2.58$ MeV and $S = 2.00$ and contains mainly components $|i_{13/2}\otimes 2^+\rangle$ and $|f_{7/2}\otimes)3^-2^+)\,3^-\rangle$. For low even parity $1/2^+$, $3/2^+$ states an attempt of interpretation in terms of the neutron hole-phonon model is undertaken. To obtain the low lying $1/2^+$, $3/2^+$ states with appreciable hole spectroscopic factors, renormalization of the single neutron hole energies to the values of about 1 MeV is necessary. This renormalization of the $3s_{1/2}$, $2d_{3/2}$ energies is probably due to the interaction of the neutron hole with protons from the $3s_{1/2}$, $2d_{3/2}$, and neighbouring orbits. Using for $E(3s_{1/2})-E(2f_{7/2})$ the value of 1.3 MeV and for $E(2d_{3/2})-E(2f_{7/2})$ the value of 1.15 MeV two $1/2^+$ levels and two $3/2^+$ levels below 2.2 MeV are obtained mainly as a result of the coupling of the neutron hole motion on the $3s_{1/2}$ and $2d_{3/2}$ orbits to the $0^+$, $2^-$ states, and of the neutron motion on the $2f_{7/2}$ orbit to the $3^-$ octupole state of the core.

In conclusion, one can say that in the case of the $^{143}$Nd nucleus the intermediate coupling model gives better results for the particle states than for the hole states. Exlusion of the model space is necessary for describing the detailed structure of the hole states.

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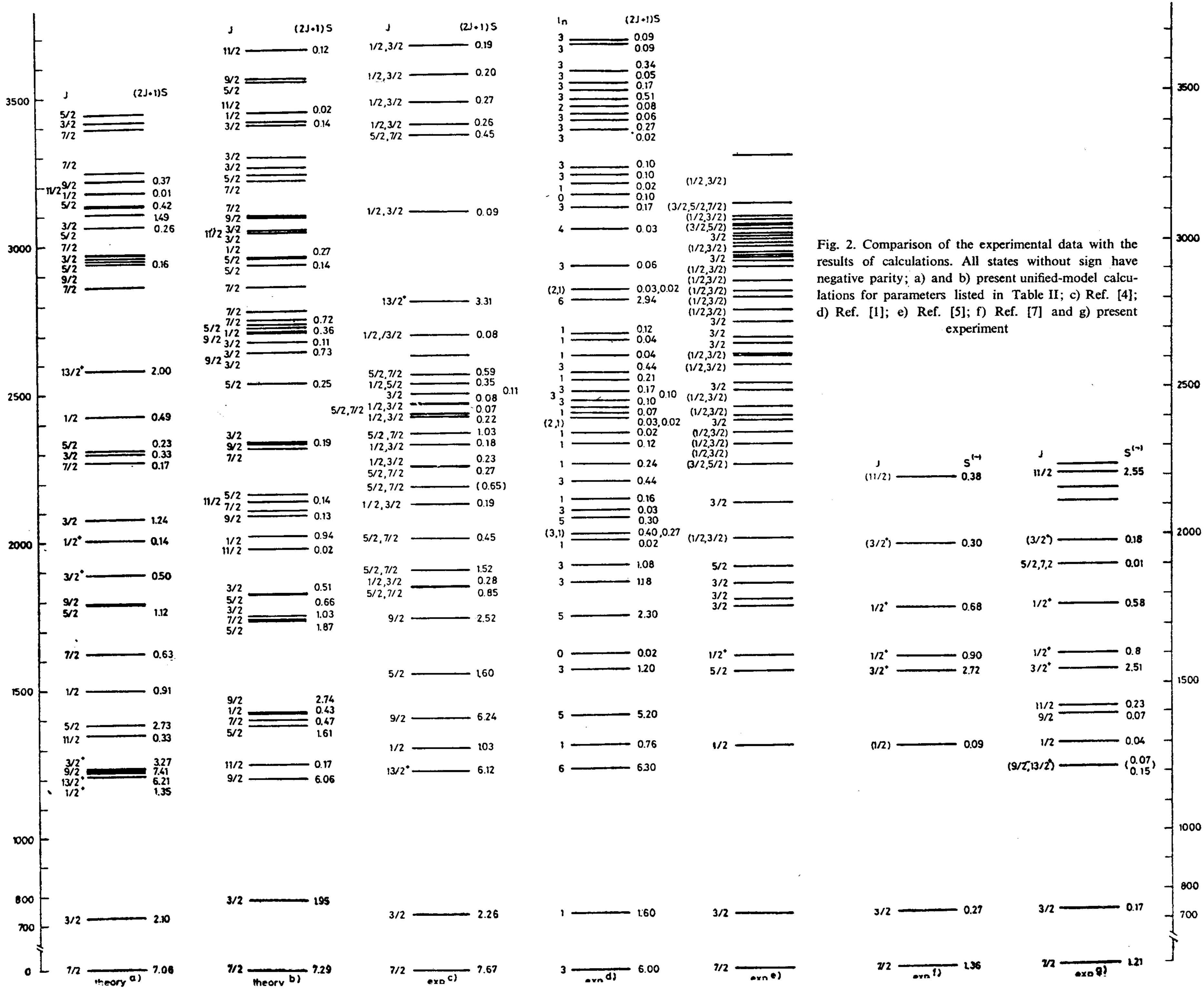


Fig. 2. Comparison of the experimental data with the results of calculations. All states without sign have negative parity; a) and b) present unified-model calculations for parameters listed in Table II; c) Ref. [4]; d) Ref. [1]; e) Ref. [5]; f) Ref. [7] and g) present experiment

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