A MICROSCOPIC CLASSIFICATION OF HIGH-SPIN STATES IN ^{56}Fe

P.W.M. GLAUDEMANS
Fysisch Laboratorium, Rijksuniversiteit Utrecht, Utrecht, The Netherlands

and

R. VENNINK
FOM–ECN Nuclear Structure Group, Netherlands Energy Research Foundation, Petten, The Netherlands

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A large-scale shell-model calculation on ^{56}Fe including positive parity states with spins up to $J = 15$ shows that several states in the yrast region may be of a particular nature. These states can be arranged in groups of which the gamma decay and quadrupole moments show a collective behaviour. The signature of each group is the $f_{7/2}$ hole structure. This structure is coupled to a definite J_{hole} and T_{hole} with the spin J_{hole} being as large as possible. The level density above the yrast region turns out to be largely independent of J.

Nuclei near $A = 56$ are interesting for further theoretical and experimental investigation since they are light enough to be treated microscopically in quite some detail, while these nuclei probably are also heavy enough to exhibit some collective properties. A nice example for a microscopic treatment is the nucleus ^{56}Fe for which some collective properties have been the subject of experimental [1–3] and theoretical [2–4] investigations.

Very recently large-scale shell-model calculations on positive-parity states in $^{54-56}$Fe have been performed [5]. It has been demonstrated that many properties of these isotopes can be described well in a $(f_{7/2})^m(f_{5/2}p_{3/2}p_{1/2})^n$ model space with $m \geqslant 13$ and $n \leqslant 3$, i.e. up to three holes in the closed $f_{7/2}$ shell have been taken into account. Two quite different effective interactions have been investigated (i) a realistic interaction derived from slightly modified [5] Kuo–Brown matrix elements (denoted by KB) and (ii) two-body matrix elements from the schematic Surface Delta Interaction [6] (denoted by SDI). In particular for ^{56}Fe a nice one-to-one correspondence exists between theory and experiment for all states below 4 MeV excitation energy. For KB the average deviation between experimental and theoretical excitation energies turns out to be less than 100 keV. Also spectroscopic factors for single-particle transfer as well as electromagnetic transition strengths and moments can be well explained with only very few deviations. In general KB is found to be superior to SDI. For SDI the $f_{5/2}$ occupation numbers are considerably larger than for KB. The experimental S-factor for pick-up on ^{56}Fe favours the SDI value [5].

With the success of the detailed interpretation of the properties of low-lying states in ^{56}Fe in mind, a shell-model investigation of other observables in this nucleus becomes more meaningful. Presently we would like to discuss some remarkable properties of high-spin states ($J = 8$–15) in ^{56}Fe which have been obtained with the same interactions (KB and SDI) and model space as used in ref. [5]. These states are interesting because one can investigate the possible appearance of collective features in the yrast region from a microscopic point of view.

The calculated excitation energies obtained with KB for the ten lowest eigenstates of each J are presented in fig. 1. The excitation energies obtained with the very different SDI matrix elements show a nearly

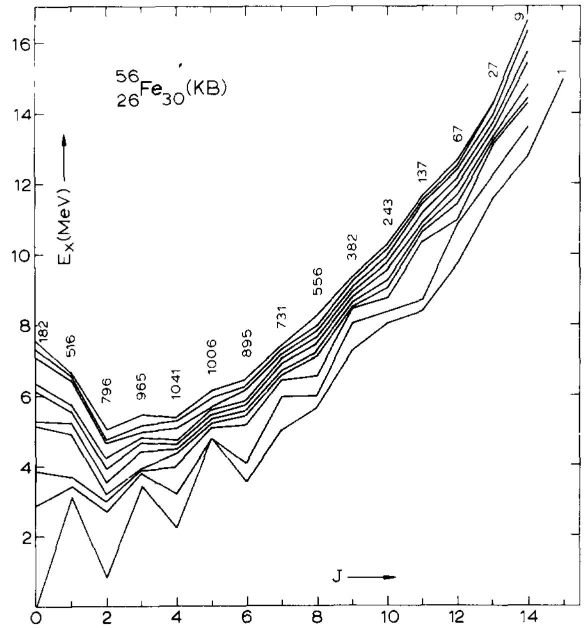

Fig. 1. Excitation energies of the lowest ten states with positive parity of each J obtained with the KB interaction for ^{56}Fe. The vertically placed numbers represent the total number of states for each J in the present model space.

identical behaviour. The yrast and yrast-plus-one states for $J \leqslant 6$ follow a collective pattern, with the typical oscillatory behaviour. For $J > 6$ the excitation energies increase proportionally with J^2. Moving away from the yrast line one finds a smooth behaviour of the excitation energies as a function of J with a dip at about $J = 2$, see fig. 1. The level density as a function of J turns out to be largely independent of the dimensions of the matrices which are also shown in fig. 1. One should note also that the yrast and yrast-plus-one states are barely depressed with respect to the other states.

A detailed investigation of the electromagnetic properties of the lowest four states of each J reveals that the states can be divided into two sets: (i) those connected by rather large M1 and/or E2 transition strengths, and (ii) states fed or deexcited by transitions of which the strengths are in general an order of magnitude smaller. The first set and the corresponding strong transitions are shown in figs. 2 and 3 for KB and SDI, respectively. This set contains nearly all yrast states and many yrast-plus-one states. The breaks at $J \approx 10$ must be related to the fact that $J = 10$ is the largest spin possible in the two-hole $(f_{7/2})^{14}(f_{5/2}p_{3/2}p_{1/2})^2$ model space.

It is seen from figs. 2 and 3 that the KB and SDI predictions agree with each other in many aspects. The most remarkable difference occurs for the $K = 0$ ground-state band, which for KB stops at $J = 8$ but for SDI continues up to $J = 14$.

The electric transition rates and moments for eigenstates of a pure three-hole character ($J \geqslant 11$) as well as for eigenstates dominated by more than 90% intensity of three-hole components ($J = 9_2$, 10_1 for

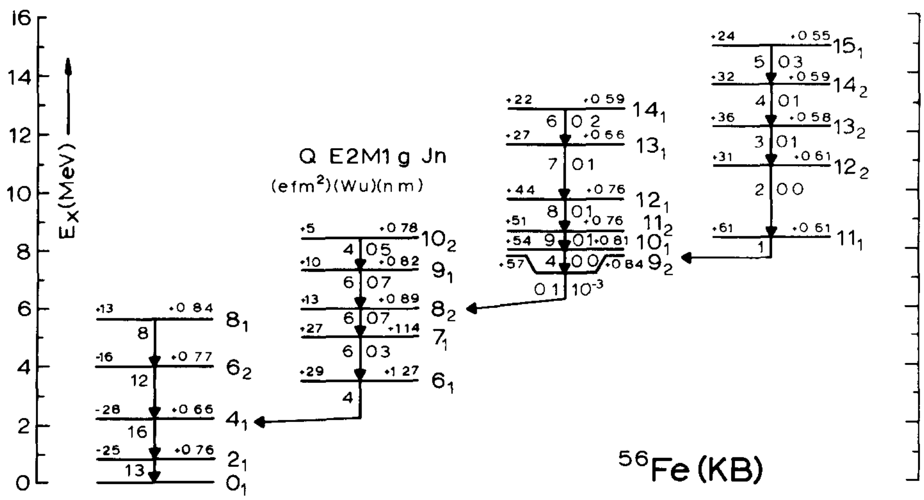

Fig. 2. Electromagnetic properties of selected states (see text) in ^{56}Fe obtained with the KB interaction. The quadrupole and dipole moments as well as E2 and M1 transition strengths are displayed as is indicated on top of the second group of states.

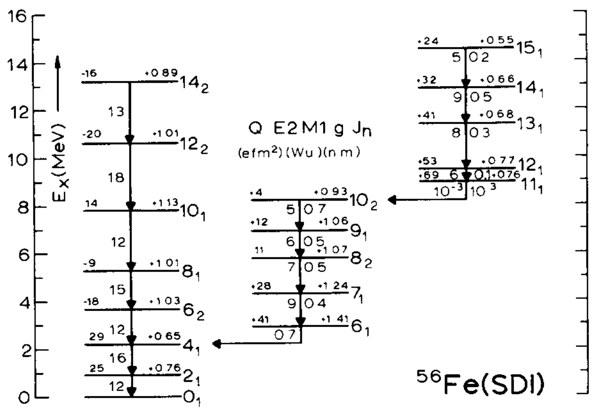

Fig. 3. Electromagnetic properties of selected states (see text) in ^{56}Fe obtained with SDI. See further caption of fig. 2.

KB and $J = 10_1$ for SDI) have been calculated with the effective charges of $e_p = 2.0\ e$ and $e_n = 1.0\ e$. These charges have been used also for the $10_1 \to 8_1$ transition with SDI. For all other moments and transitions which connect eigenstates of a mixed two-hole three-hole character, the effective charges $e_p = 1.5\ e$ and $e_n = 0.5\ e$ have been used. The assumption of different effective charges is based on the idea that for the two-hole states the first-order correction, i.e. three-hole admixtures, are taken into account, whereas the three-hole intruder states do not contain four-hole admixtures in the present model space. It should be remarked that for $\Delta e = 1.0\ e$ all E2 strengths are about a factor of two larger than for $\Delta e = 0.5\ e$. For magnetic dipole transitions and moments the bare-nucleon M1 operator has been used.

The properties of the second group of states (J = 6–10) are nearly identical for both interactions. However, for $J \approx$ 10–15 one finds only one group for SDI and two groups for KB. The latter two KB groups contain the states $J_n = 10_1$, 12_2 and 14_2 which for SDI belong to the ground-state band. However, within the lowest four KB states of each J no candidates are found for a continuation of the $K = 0$ ground-state band. It should be stressed that almost all transition strengths between states of different groups are much smaller than those presented in figs. 2 and 3. The J_n = 1, 3 and 5 yrast states are not shown since they do not belong to one of the groups given and moreover their decay properties depend very much on the choice of the interaction.

The states shown in figs. 2 and 3 are also interesting since they are described by typical wave functions, which distinguish them clearly from all other states. Although the number of components for each wave function is rather large (in general several hundreds, see fig. 1) the main intensity, i.e. more than 50%, is concentrated in at most ten components. Moreover, states in one group all have the same structure. The latter can be specified as follows. For both interactions the ground-state band for $J \leqslant 8$ and the second group (J = 6–10) are dominated (≈60%) by $f_{7/2}^{-2}$ contributions. The SDI ground-state band for $J \geqslant 10$ is characterized by excitation of an $f_{7/2}$ proton into the orbits $f_{5/2}$, $p_{3/2}$ and $p_{1/2}$, whereas the members of the remaining groups are described by excitation of an $f_{7/2}$ neutron into the upper fp-shell orbits, see also ref. [5].

Except for the J = 0, 2, 4 and 6 states of the ground-state band the holes are always coupled to maximum spin J_{hole} which is constant within each group. The particles are coupled to J_{particle} which increases with J. One has $J = J_{\mathrm{hole}} + J_{\mathrm{particle}}$ in a stretched coupling scheme when this is possible for a given J, J_{hole} and J_{particle}, see below. The dominant structure of the groups shown in figs. 2 and 3 can be interpreted in a weak-coupling picture with a ^{56}Ni core as follows:

(i) the SDI ground-state band with $J \geqslant 8$:

$$(f_{7/2}^{-3})_{J_h=15/2, T_h=3/2} \otimes (r^3)_{J_p=1/2,5/2,\ldots,13/2, T_p=1/2},$$

(ii) the J = 6–10 group:

$$(f_{7/2}^{-2})_{J_h=6, T_h=1} \otimes (r^2)_{J_p=0,2,4, T_p=1}\ ,$$

(iii) the $J \geqslant 9$ groups:

$$(f_{7/2}^{-3})_{J_h=19/2, T_h=1/2} \otimes (r^3)_{J_p=3/2,5/2,\ldots,11/2, T_p=3/2},$$

where $J_h = J_{\mathrm{hole}}$ and $J_p = J_{\mathrm{particle}}$ while r denotes the $p_{3/2}$, $f_{5/2}$, $p_{1/2}$ orbits. The weak-coupling interpretation is supported also by the calculated magnetic moments. The results obtained from the additivity relation for g-factors [6], using the hole and particle structures mentioned above as building blocks, have been calculated from available wave functions for the $f_{7/2}^{n}$ nuclei ^{53}Mn, ^{53}Fe and ^{54}Fe and the r^n nuclei ^{58}Ni, ^{59}Ni and ^{59}Cu. The g-factors thus obtained from the additivity relation are in quantitative agreement with the exact values given in figs. 2 and 3. The quadrupole moments given in figs. 2 and 3 are found to satisfy the relation $Q \approx Q_{\text{hole}} + Q_{\text{particle}}$.

Experimentally only the properties of states with $J \leqslant 8$ are investigated. The strong transitions observed between the first four members of the ground-state band support the present description, although the rather large experimental errors prevent a more detailed comparison with the theory. For example, the 6_1 state decays [1] by a $(1.3 \pm 0.3)\%$ branch to the 4_2 state, but with the lifetime of at most 8 ps as given in ref. [2] one obtains a strength of at least 60 W.u., which seems to be exceptionally large and in disagreement with the calculated strength of about 1 W.u.

Summarizing one can say that the present extensive microscopic calculation on ^{56}Fe yields several states of a remarkable nature, at least for the two interactions KB and SDI presently investigated. Experimental investigations on ^{56}Fe as a test of the present predictions would be most interesting for a better understanding of the relation between microscopic and collective properties.

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References

[1] D.G. Sarantites, J. Urban and L.L. Rutledge, Phys. Rev. 14 (1976) 1412.
[2] N. Bendjaballah, J. Delaunay, T. Nomura and H.J. Kim, Phys. Rev. Lett. 36 (1976) 1536.
[3] N. Bendjaballah et al., Nucl. Phys. A284 (1977) 513.
[4] Y. Tanaka and R.K. Sheline, Phys. Lett. 56B (1975) 309.
[5] R. Vennink and P.W.M. Glaudemans, Z. Phys. A294 (1980) 241.
[6] P.J. Brussaard and P.W.M. Glaudemans, Shell-model applications in nuclear spectroscopy (North-Holland, Amsterdam, 1977).