Low-spin spectroscopy of $^{50}$Mn

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Abstract

The data on low spin states in the odd-odd nucleus $^{50}$Mn investigated with the $^{50}$Cr (p,$\gamma$)$^{50}$Mn fusion evaporation reaction at the FN-TANDEM accelerator in Cologne are reported. Shell model and collective rotational model interpretations of the data are given.

I. INTRODUCTION

Atomic nuclei along N=Z line where the relative proximity of the neutron and proton Fermi surfaces favors the proton-neutron (pn) correlations on the equal footing with neutron-neutron (nn) and proton-proton (pp) ones are proved to give a unique opportunity to study the different isospin modes of pn interaction in various contexts [1–22].

In contrast to pp (T=1, $T_z$=-1) and nn (T=1, $T_z$=1) configurations the pn pairs can either form isovector (T=1, $T_z$=0) or isoscalar (T=0, $T_z$=0) states. Isovector pn correlations manifest themselves in a similar fashion to like-nucleon correlations that is evident from the properties of the T=1 isobaric analogue nuclei while the pn interaction in isoscalar channel (T=0, $T_z$=0) is much less understood and is currently the subject of active debate [18–21].

In the light of this interest recently the low-spin structure of odd-odd N=Z nuclei $^{54}$Co [1], $^{46}$V [2] and $^{50}$Mn [3] was studied in Cologne. The most interesting findings of our studies are strong isovector M1 transitions which have simple explanation in terms of two particle quasideuteron configurations [4] and collective rotational properties of low-lying states in $^{46}$V [5] and $^{50}$Mn.

This contribution present new results for $^{50}$Mn establishing the equivalence of full pf-shell model and deformed mean field treatments of the low-energy structures in $^{50}$Mn.
II. COLLECTIVE AND QUASIDEUTERON PROPERTIES OF YRAST STATES IN $^{50}$Mn

Recently we have investigated the low-spin structure of the odd-odd $N=Z$ nucleus $^{50}$Mn up to an excitation energy of $E_x \approx 3.6$ MeV. Low spin states of $^{50}$Mn were populated using the fusion evaporation reaction $^{50}$Cr (p, n$\gamma$)$^{50}$Mn at a proton beam energy $E_p = 15$ MeV. The beam was delivered by the FN-TANDEM accelerator of the University of Cologne. A part of the low spin level scheme of $^{50}$Mn, which could be determined from our $\gamma\gamma$-coincidence data, is shown in Fig.1. From the analysis of coincidence spectra, 25 new transitions were placed in the level scheme, establishing 16 new levels. In total, we could assign new spin quantum numbers to six levels. Nine new intensity ratios and eight new multipole mixing ratios $\delta$ were determined. Our new data together with some recent high spin data for $^{50}$Mn from C. E. Svensson, et al. give a consistent and extensive level scheme for $^{50}$Mn.

The $0^+_1$ ground state, the $2^+_1$ state at 800 keV and the $4^+_1$ states at 1931 keV (not at 1917 keV as it was reported previously by C. E. Svensson, et al.) in $^{50}$Mn are interpreted as the $T=1$ isobaric analogues of the $0^+_1$ ground state, the $2^+_1$ state at 783 keV and the $4^+_1$ state at 1882 keV respectively in the isobaric nucleus $^{50}$Cr (see Fig. 1). The interpretation was done using new measured intensity and multipole mixing ratios for the $^{50}$Mn.

The experimental data were compared to shell model (SM) calculations of the positive parity states of $^{50}$Mn in the full pf-shell configurational space without truncation. Two different nucleon-nucleon residual interactions were considered in [3]: the KB3 interaction, adopted from Ref. [23] and the FPD6 interaction taken from Ref. [24]. Close agreement with experiment was obtained for observables (level scheme, intensity and multipole mixing ratios) near the ground state.

As an example the calculated excitation energies with FPD6 interaction for the positive parity levels with spin quantum numbers $J=0-7$ below 3 MeV are compared to the data in Fig. 2. The comparison shows that the calculations lead to almost perfect agreement with experiment. Furthermore we collect SM predictions for $B(E2)$ and $B(M1)$ values in Table I to compare with rotational model results.

Accordingly to the Nilsson model last odd proton and odd neutron in $^{50}$Mn occupy the Nilsson deformed $[312]5/2^-$ orbital which transforms to the spherical $f_{7/2}$ orbital at the limit of zero deformation. Then the low-lying states in $^{50}$Mn should form the lower parts of $K^\pi = 0^+,T=1$ (even spins), $K^\pi = 0^+,T=0$ (odd spins) and $K^\pi = 5^+,T=0$ bands (see Fig.2). Supposing the deformation parameter $\beta$ to be 0.25 we have calculated $B(E2)$ values for $K^\pi = 0^+$ and $K^\pi = 5^+$ intraband transitions (see Table I). One can see that SM results are well matched by the geometrical model indicating band structures in $^{50}$Mn. Furthermore it follows from the Nilsson scheme that promoting one proton or one neutron from the $[312]5/2^-$ ($f_{7/2}$) orbital to the closely lying $[312]1/2^-$ ($p_{3/2}$) orbital one can construct $K^\pi = 3^+$ and $K^\pi = 2^+$ bands in $^{50}$Mn. From the SM we can identify the $3^+_2$, $T=0$ (most probably it corresponds to the observed $J=3,T=0$ level at 1798 keV) and $4^+_2$, $T=0$ (it corresponds to the observed $4^+,T=0$ level at 1917 keV) states as a possible members of the $K^\pi = 3^+$ band taking into account that they are connected by very strong E2 transition (see Table I). This $B(E2)$ value can be reproduced in geometrical model supposing that $K^\pi = 3^+$ band is strongly deformed ($\beta \approx 0.3$). However such a transition was not observed.
in the present experiment due to the small spacing between the levels at 1798 keV and 1917 keV but there is an experimental indication that both states does not decay strongly to the states from other bands. Therefore it would be very interesting to find an experimental support of this theoretical hypothesis of stronger deformed K=3 band.

Another interesting observation which follows from the comparison of theoretical and experimental data is that there are strong isovector M1 transitions in $^{50}$Mn which have non-collective quasideuteron nature and could be described in frames of Nilsson model too [25]. Accordingly to the quasideuteron picture [4] (see also [26]) one should expect very large summed $\mathrm{M1} \ 0^+ \rightarrow 1^+$ transition strength (18 $\mu^2_N$) for odd-odd N=Z nuclei in $f_{7/2}$ orbital. The main part of this strength is predicted by Nilsson model [24] and shell model to be distributed among three $0^+_i \rightarrow 1^+_i$ transitions in $^{50}$Mn nucleus. From the measured decay intensity ratio for $2^+_1, T=1$ state in $^{50}$Mn and $\mathrm{B(E2;2^+_1 \rightarrow 0^+_1)}$ value in the T=1 isospin partner nucleus $^{50}$Cr we have estimated (see for details [3]) $\mathrm{B(M1;2^+_1 \rightarrow 1^+_1)}$ value in $^{50}$Mn which is given in Table I. Supposing that theoretical and experimental ratios of $\mathrm{B(M1;0^+_i \rightarrow 1^+_i)}$ and $\mathrm{B(M1;2^+_1 \rightarrow 1^+_1)}$ values are similar, one can actually estimate also that a large part of the total quasideuteron $\mathrm{M1} \ 0^+_i \rightarrow 1^+_i$ transition strength (up to $\sim 4.5 \mu^2_N$) could be distributed to the $0^+_i \rightarrow 1^+_i$ transition.

Furthermore it follows from SM calculations for $^{46}$V [2] and $^{50}$Mn that ratios of $\mathrm{B(E2;J+2, K=0 \rightarrow J, K=0)}$ and $\mathrm{B(E2;2^+_1 \rightarrow 0^+_1)}$ values are very similar for both FPD6 and KB3 interactions. Applying to this regularity (i.e. assuming that it is true for the experimental values) and using measured intensity ratios we can estimate M1 strengths for some other transitions (see Table I).

This estimation clearly shows that $\Delta K=0 \ \Delta T=1$ M1 transitions are enhanced while other $\Delta T=1$ M1 transitions are indicated by the SM and experimental results to be retarded due to the K quantum number selection rule ($\Delta K > 1$ M1 transitions are forbidden). The strong M1 transitions can be interpreted as a consequence of considerable contributions of quasideuteron configurations to the low-spin K=0 states in $^{50}$Mn.

To summarize, the observations for $^{50}$Mn nucleus were compared to large scale shell model calculations for the positive parity states. An excellent agreement between theory and experiment was noted. The collective rotational properties of the low-lying states in $^{50}$Mn were established basing on the B(E2) values from shell model calculations. Strong enhancement of $\Delta T=1$ M1 transitions caused by the quasideuteron configurations is found to take place for $\Delta K=0$ case.

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TABLE I. Comparison of shell model predictions (columns KB3 and FPD6) for γ transition strengths with collective rotational model (column Coll.) results for $^{50}$Mn. Estimated B(M1) values following the procedure described in the text are given in column Est. The values of K quantum number and deformation parameter $\beta$ used for the rotational model calculations are given.

| $(J_i, T_i) \rightarrow (J_f, T_f)$ | B(E2; $J_i \rightarrow J_f$), ($e^2$fm$^4$) | B(M1; $J_i \rightarrow J_f$), ($\mu_N^2$) |
|-----------------------------------|-----------------------------------------------|-----------------------------------------------|
|                                   | KB3 | FPD6 | Coll. | KB3 | FPD6 | Est. |
| K=0 band $\beta = 0.25$           |     |      |       |     |      |      |
| $(0^+_1, 0) \rightarrow (1^+_1, 1)$ | 2.90 | 1.49 | 1.50  |     |      |      |
| $(2^+_1, 1) \rightarrow (1^+_1, 0)$ | 0.05 | 0.02 | 0     | 1.94| 1.29 | 1.00 |
| $(2^+_1, 1) \rightarrow (0^+_1, 1)$ | 220  | 275  | 202   |     |      |      |
| $(3^+_1, 0) \rightarrow (2^+_1, 1)$ | 0.0  | 0.001| 0     | 3.73| 1.92 | 1.25 |
| $(3^+_1, 0) \rightarrow (1^+_1, 0)$ | 272  | 350  | 260   |     |      |      |
| $(4^+_1, 1) \rightarrow (3^+_1, 0)$ | 0.2  | 0.07 | 0     | 2.71| 1.99 | 1.34 |
| $(4^+_1, 1) \rightarrow (2^+_1, 1)$ | 298  | 385  | 289   |     |      |      |
| $(5^+_2, 0) \rightarrow (4^+_1, 1)$ | 0.4  | 1.4  | 0     | 3.46| 2.11 | 0.77 |
| $(5^+_2, 0) \rightarrow (3^+_1, 0)$ | 227  | 303  | 306   |     |      |      |
| K=5 band $\beta = 0.25$           |     |      |       |     |      |      |
| $(6^+_1, 0) \rightarrow (5^+_1, 0)$ | 293  | 373  | 305   | 1·10$^{-4}$ | 0.003 |
| $(7^+_1, 0) \rightarrow (6^+_1, 0)$ | 285  | 385  | 361   | 3·10$^{-4}$ | 0.01  |
| $(7^+_1, 0) \rightarrow (5^+_1, 0)$ | 48   | 56   | 49    | 0   | 0    |      |
| K=3 band $\beta = 0.3$            |     |      |       |     |      |      |
| $(4^+_1, 0) \rightarrow (3^+_2, 0)$ | 512  | 544  | 526   | 1·10$^{-5}$ | 0.015 |
FIG. 1. Part of the level scheme of $^{50}$Mn, including only those levels for which definite spin or parity quantum numbers are known. The width of the arrows corresponds to the relative intensity of the $\gamma$-transitions observed in the present reaction. In the right panel of the figure the low-lying $T=1$ states of $^{50}$Cr are shown. Adapted from A. Schmidt, et. al, [3].
FIG. 2. Comparison of the experimental (Expt.) low-spin level scheme of $^{50}$Mn to the shell model results (SM) using FPD6 residual interaction. The assigned K quantum number and corresponding quantum numbers of the odd proton and odd neutron are shown. The values given in parenthesis are based only on the results of the SM calculations.