Quasideuteron Configurations in $^{46}$V and $^{58}$Cu

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The data on low spin states in the odd-odd nuclei $^{46}$V and $^{58}$Cu investigated with the $^{46}$Ti (p,n$\gamma$)$^{46}$V, $^{32}$S ($^{16}$O,pn)$^{46}$V and $^{58}$Ni (p,n$\gamma$)$^{58}$Cu reactions at the FN-TANDEM accelerator in Cologne are reported. The states containing large quasideuteron components are identified from the strong isovector M1 transitions, from shell model calculations and from experimental data for low-lying states.

1. INTRODUCTION

An understanding of the nuclear phenomena related to the proton-neutron interaction is a cornerstone of many contemporary investigations in nuclear structure physics [1–16]. An important laboratory to study the effects coming from the pn interaction in the $T=0$ channel and its competition with the $T=1$ pn channel are odd-odd $N=Z$ nuclei where the low-lying $T=0$ and $T=1$ states are almost degenerate. One of the interesting phenomenon related to the interplay between low-lying $T=0$ and $T=1$ states is the occurrence of very strong $\Delta T=1$ M1 transitions between them in some odd-odd $N=Z$ nuclei (see Fig 1). The positive interference of orbital and large spin parts of reduced $\Delta T=1$ M1 matrix elements between the states formed by the odd proton and the odd neutron occupying single $j=l+1/2$ orbitals explains the enhancement of M1 transitions in odd-odd $N=Z$ nuclei [17]. In other cases ($j = l−1/2$) the M1 strength almost vanishes due to the destructive interference of orbital and spin parts. The states having one proton one neutron ($\pi j \times \nu j$)$_{L,T}$ structure with $j = l+1/2$ contain a large component with total orbital angular momentum $L = J−1$ similarly to the ground state of real deuteron : $J^\pi = 1^+$, $L = 0$. Moreover the theoretical $B(M1;0^+ \rightarrow 1^+)$ value for the hypothetical deuteron with a bound $J^\pi = 0^+$, $T=1$ state would be very large and amounts to $16 \mu_N^2$. Therefore we propose to call one proton one neutron configurations in a single $j = l+1/2$ orbital quasideuteron configurations and to consider strong M1 transitions between the states of this structure as an indication of deuteron-like correlations.

In light and medium-heavy nuclei the $j = N+1/2$ orbital ($N$ is the principal quantum number) is well separated from other spherical orbitals. In this case quasideuteron configurations are weakly mixed with other configurations resulting in very strong $M1$ transitions in $^6$Li, $^{18}$F and $^{42}$Sc (see Fig. [18]). An experimental indication of comparably
strong M1 transition was also found recently in $^{54}$Co.

For larger number of valence protons and neutrons in a single $j = N + 1/2$ orbital in odd-odd N=Z nuclei the quasideuteron configurations are fragmented among two or three states due to the collective effects [18]. This is actually observed in $^{10}$B, $^{22}$Na and $^{26}$Al nuclei (see Fig. 1b). In the case when $j = l + 1/2$ and $l = N - 2$, the quasideuteron configurations are strongly fragmented due to the mixing with the configurations which involve other closely lying orbitals.

In the present work we would like to illustrate both effects (collectivity and nearness of $j = l - 1/2$ orbitals) causing the fragmentation of the quasideuteron configurations using experimental data for odd-odd N=Z nuclei $^{46}$V and $^{58}$Cu.

2. LOW-SPIN BAND STRUCTURE OF $^{46}$V

Recently the low spin structure of odd-odd N=Z nucleus $^{46}$V was studied in Cologne [3,19,20]. Parallel to this work there were two studies of high spin states performed by C.D. O’Leary et.al. [2] and by S.M.Lenzi et.al. [1].

Low-spin states of $^{46}$V were populated using fusion evaporation $^{46}$Ti(p, n$\gamma$) $^{46}$V [3,19] and $^{32}$S($^{16}$O, pn)$^{46}$V reactions [20]. The beam was delivered by the FN-TANDEM accelerator of the University of Cologne. In total, seven new spin assignments and five new parity assignments were made [3] as well as four lifetimes were measured [19,20]. Using new experimental data we were able to extract the absolute B(M1) and B(E2)
values or to determine their lower limits for 12 transitions between negative and positive parity states (some of them are shown in Table 1).

The experimental data were compared to shell model calculations of the positive parity states of $^{46}$V in the full pf-shell without truncation with KB3 and FPD6 residual interactions. The calculations were done by the Tokyo group [3]. Most of the experimental data are well reproduced in shell model calculations [3] (see Table 1 and Fig. 2). Experimental and shell model results can be interpreted also in terms of the Nilsson scheme. According to this model the odd proton and the odd neutron in $^{46}$V should occupy the Nilsson [321]Ω=3/2− orbital. Then the low-lying states in $^{46}$V should form K=0,T=1 (even spins), K=0,T=0 (odd spins) and K=3, T=0 bands. An analysis of experimental and theoretical B(E2) values shows that such a classification of low-spin states in $^{46}$V is possible (see Fig. 2). Based on the B(E2;2− → 0+ ) value one can show that the deformation of the K=0,T=1 band corresponds to β ≈ 0.23. Likewise B(E2;4+ → 3+ ) and B(E2;5+ → 3+ ) values help to estimate the value of deformation parameter for the K=3,T=0 band: β ≈ 0.23, which is exactly the same as for the K=0,T=1 band.

Having observed collective features in the structure of $^{46}$V we identified also strong M1 transitions (see Table 1) which have non-collective quasideuteron nature and could be described quantitatively in frames of the Nilsson model too [13]. According to the quasideuteron picture [16] (see also [21]) one should expect a very strong M1 $0^+ → 1^+$ transition (18 $\mu_N^2$) for odd-odd N=Z nuclei in the $f_{7/2}$ orbital. The main part of this strength is predicted by Nilsson model and shell model to be distributed among three $0^+_1 → 1^+_i$ transitions in $^{46}$V nucleus. Supposing that theoretical and experimental ratios of B(M1;3/2+ → 2+ ) and B(M1;0+ → 1+ ) values are similar, one can actually estimate that a large part of this strength [6(2)$\mu_N^2$] is concentrated in the $0^+_1 → 1^+_i$ transition.

Furthermore it follows from large scale shell model calculations for $^{46}$V with KB3 and FPD6 residual interactions that the ratios of B(E2;4^+_2 → 2^+_i) and B(E2;2^+_1 → 0^+_f) values are 1.39 and 1.31 for FPD6 and KB3 interactions, respectively, i.e. the ratio is just slightly model dependent. From our measured lifetime of the $2^+_1$, $T = 1$ state and the

| Transition | $B(M1;J_i^+ → J_f^+)$ | $\Delta T=0$ | $\mu_N^2$ | $\Delta T=1$ |
|------------|------------------------|-------------|------------|-------------|
| (0^+_1, 0) → (1^+_0, 0) | 2.31 | 3.80 | 137(35) | 143 |
| (3^+_2, 0) → (2^+_1, 0) | 1.98 | 1.25 | 169 | 187 |
| (4^+_2, 0) → (3^+_1, 3) | 0.12(3) | 0.08 | 200(50) | 234 |
| (4^+_2, 0) → (3^+_2, 0) | 0.57(15) | 0.85 | 66(14) | 65 |
| (4^+_2, 0) → (5^+_1, 3) | 0.02(1) | 0.02 | |
| (4^+_2, 0) → (5^+_2, 0) | 0.55(13) | 1.75 | |
Figure 2. Band classification of the low-lying states in $^{46}$V. Experimental (left column of the band) and shell model (right column of the band) energies of the levels with certain spin and parity quantum numbers are shown. Shell model results are taken from [3].

extracted $B(E2; 2^+_1 \rightarrow 0^+_1)$ value one can expect that $B(E2; 4^+_2 \rightarrow 2^+_1) = 1.35B(E2; 2^+_1 \rightarrow 0^+_1) = 185(47)$ e²fm⁴. This number is in a good agreement with the lower limit of 169 e²fm⁴ which we have obtained from our new experimental data. The $4^+_2, T=1$ state strongly decays also to some $T=0$ states and we know the intensity and multipole mixing ratios for these transitions. Using these experimental data we obtain the absolute strength of four M1 transitions (see Table 1). This example clearly shows that some of the $\Delta T=1$ M1 transitions are retarded due to the K quantum number selection rule ($\Delta K=3$ M1 transitions are forbidden) while other M1 transitions are enhanced. The latter can be interpreted as an evidence of considerable contributions of quasideuteron configurations to the low-spin K=0 states in $^{46}$V.

3. RESULTS FOR $^{58}$CU

In this section we focus on the results of a very recent work of I.Schneider et al. (work in progress) where the low-spin structure of the odd-odd N=Z nucleus $^{58}$Cu was investigated up to an excitation energy of 4 MeV. Excited states of $^{58}$Cu were populated in the $^{58}$Ni (p, nγ)$^{58}$Cu fusion evaporation reaction. Single γ-spectra and γγ-coincidence spectra of the depopulating γ-cascades in $^{58}$Cu were measured with high energy resolution. Part of the low spin level scheme of $^{58}$Cu constructed from the obtained data is shown in Fig. 3. Our new data together with some recent medium and high spin data for $^{58}$Cu from Rudolph. D et al. enrich our knowledge of the structure of $^{58}$Cu.

To get a qualitative understanding of the structure of the low-lying states in $^{58}$Cu we have performed simplified spherical shell model calculations – one odd proton and one odd neutron were allowed to occupy $p_{3/2}, f_{5/2}$ and $p_{1/2}$ orbitals. The doubly closed shell nucleus $^{56}$Ni was considered as the inert core. The Surface Delta Interaction was used as residual interaction with the same strength of pp, nn and pn T=1 interaction ($A_1 = 0.5$
Figure 3. (Left) Part of the low spin level scheme of $^{58}$Co observed in $^{58}$Ni ($p, n \gamma$)$^{58}$Cu reaction. Transitions for which new branching ratios or absolute strengths (with an exception of $0^+_1 \rightarrow 1^+_2$ transition) were measured are shown. (Right) Results of shell model calculations. The main components of the wave functions and transition strengths are shown.

MeV) and slightly weaker strength of pn T=0 interaction ($A_1 = 0.45$ MeV). The single particle energies are taken to be similar to those from [22]. The result of shell model calculations for the low-lying states are shown in Fig.3.

Isovector M1 transitions are of our special interest. As it follows from the quasideuteron scheme the total M1 $0^+_1 \rightarrow 1^+_1$ transition strength for one proton and one neutron in the $p_{3/2}$ orbital amounts to 13$\mu^2_N$ [10]. If one uses quenched (by a factor of 0.7) spin g-factors this number reduces to 7$\mu^2_N$. However in the configurational space that involves $p_{3/2}$, $f_{5/2}$ and $p_{1/2}$ orbitals one can construct five low-lying (below 4 MeV) $J^\pi = 1^+, T=0$ states. Therefore one can expect significant fragmentation of quasideuteron strength. From the previous studies the lifetime of only one $1^+$ state, namely the $1^+_2$ state is known: $\tau = 114(29)$fs. This lifetime corresponds to $B(M1,0^+_1 \rightarrow 1^+_2) = 2.5(5)\mu^2_N$. This transition is predicted by the shell model to be the strongest one among all other $0^+_1 \rightarrow 1^+_1$ transitions in $^{58}$Cu. However the shell model overestimates its strength as well as the strength of the $2^+_2 \rightarrow 3^+_1$ transition. This indicates that stronger configuration mixing occurs for the $0^+_1$, $1^+_2$, $2^+_2$ and $3^+_1$ states which are predicted by the shell model to contain large quasideuteron $[\pi p_{3/2} \times \nu p_{3/2}]$ component.

In the present experiment we have observed the $2^+_2 \rightarrow 0^+_1$ transition for the first time and have measured its branching ratio. Taking into account that the lifetime of the $2^+_2$ level is known we have deduced the absolute values of the $E2$ $2^+_2 \rightarrow 0^+_1$, $M1$ $2^+_2 \rightarrow 1^+_2$ and $M1$ $2^+_2 \rightarrow 3^+_1$ transition strengths (see Fig 3). It is interesting to note that $B(E2, 2^+_2 \rightarrow 0^+_1)$ value for $^{58}$Cu is not very different from the $B(E2, 2^+_1 \rightarrow 0^+_1)$ value (130(7) $e^2$fm$^4$) for the isospin triplet partner $^{58}$Ni. We note also that the deduced $B(M1)$ values are not very
large. It indicates that contribution of the quasideuteron configurations to the $2^+_2$ state is smaller than to the $1^+_2$ and $3^+_1$ states. This also follows from the structure of the shell model wave functions. It would be very interesting to know how the remaining M1 quasideuteron strengths are distributed in $^{58}\text{Cu}$.

4. SUMMARY

In summary, using new experimental data obtained in Cologne we have illustrated a mechanism of fragmentation of strong isovector M1 transitions in deformed and spherical odd-odd N=Z nuclei. The reduction of the M1 $0^+_1 ightarrow 1^+_1$ transition strength in deformed $^{46}\text{V}$ is caused by the strong coupling of the quasideuteron configurations to the collective core while the suppression of the M1 transitions in near spherical $^{58}\text{Cu}$ nucleus is due to the strong mixing of quasideuteron configurations with other non-collective two nucleon configurations. The studies reported in the present paper indicate that accurate lifetime measurements are needed for odd-odd N=Z nuclei to get clearer understanding of their structure.

We thank J. Eberth, A. Gelberg, K. Jessen, R. V. Jolos for valuable discussions. We gratefully acknowledge the cooperation with the Tokyo group: T. Otsuka and Y. Utsuno for the shell model calculations for $^{46}\text{V}$. This work supported in part by the DFG under Contracts no. Br 799/10-1, Br 799/9-3, Pi 393/1-1 and by the US DOE under Contract No. DE-FG02-91ER-40609.

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