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SHELL MODEL PROTON NEUTRON HOLE INTERACTION FROM THE PROPERTIES OF ^{208}Bi*

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A very reliable and complete set of data on the one proton one neutron hole levels in ^{208}Bi is available. Spectroscopic factors for proton transfer to ^{207}Pb and neutron pick up from ^{209}Bi have been measured. Recently γ and conversion electron spectroscopy with the ^{208}Pb$(p,n)^{208}$Bi reaction has clarified some questionable points of the level scheme and provided γ-branching ratios. The matrix elements of the shell model residual interaction are calculated by a least square fit from these data. The nondiagonal elements are very sensitive to the γ-branching; therefore for the first time an extensive set could be determined. A comparison of this "measured" interaction with a realistic interaction calculated from the interaction between free nucleons shows remarkably good agreement.

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1. Introduction

Shell structure is central in describing most aspects of nuclear structure. In its basic version the shell model Hamiltonian contains the single particle energies $\langle\phi_i|H|\phi_i\rangle$ and the two particle matrix elements describing the residual interaction between the particles $\langle\phi_i\phi_k|H|\phi_l\phi_m\rangle$. ϕ_i stands for a proton or neutron, particle or hole, in an orbital defined by the radial quantum number (n) and those for the orbital (l) and total (j) angular momentum. The single particle elements are mostly known well from the energies of the nuclei with just one particle or hole outside of a closed shell nucleus. But the residual interaction is not well known. Usually one takes either a schematic

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interaction like the surface delta interaction or a so-called realistic interaction [1, 2] that is calculated from the measured scattering of free nucleons. Realistic interactions account well for level energies. They have also been sometimes adjusted for a few parameters to better match measured properties [3] . The region around doubly magic ^{208}Pb has played a dominant role in these studies. Now with the availability of detailed spectroscopic information on ^{208}Bi [4, 5] it has become possible to determine a major set of interaction elements from the many and reliably measured properties of the excited states of ^{208}Bi. In particular, also nondiagonal elements and their signs have been well defined from the measured γ-branching ratios. In the limited space only some exemplary data can be presented. A forthcoming publication [4] will give the complete data.

2. Experimental data

The measured positive parity levels of the low lying one proton one neutron hole configurations are shown in Fig. 1 ordered by their dominant configuration. The ^{207}Pb(^{3}He,d)^{208}Pb reaction populates the levels with a neutron hole in the $p_{1/2}$ orbital, as in the ^{207}Pb ground state, and the added proton particle in any of the orbitals $h_{9/2}$, $f_{7/2}$, $i_{13/2}$, $f_{5/2}$, or $p_{3/2}$. Likewise the neutron pick up (p, d)-reaction on ^{209}Bi populates the states with the proton in the $h_{9/2}$ orbital and one neutron removed from the $p_{1/2}$, $f_{5/2}$, $p_{3/2}$, $i_{13/2}$, or $f_{7/2}$ orbital. These reactions have been so well measured 35 years ago, that they could hardly be improved upon today [6]. The measured cross section for a level gives the spectroscopic factor or the squared amplitude of the mentioned configuration. In a few cases unresolved dublets have now been resolved by the γ-measurements clarifying also their spectroscopic factors. These measurements have been complete, meaning that if a level is not seen, all spectroscopic factors are 0.

In contrast to the transfer reactions, that populate only specific one particle one hole states, the ^{208}Pb(p,n)^{208}Bi-reaction is statistical and the population of the levels depends only on their spin and energy but is independent of their structure. At the chosen proton energy of 9 MeV low spins are preferred but with decreasing intensity higher spin states including the 10^- isomer are still visible. All one proton one neutron hole levels of positive parity up to 3 MeV have been identified with the one exception of the $(\pi f_{7/2}\nu p_{3/2})$ 5^- level [5]. This gives the energies of all levels to 1 keV accuracy. Many previously claimed states [6], that have not been seen in this experiment, could be discarded. γ–γ-coincidences [5] and conversion electrons [4] have been measured with the (p, n)-reaction and have determined spins and parities together with the knowledge from the transfer studies. The γ-branching ratios are very sensitive to small admixed configurations and consequently the nondiagonal elements of the interaction.

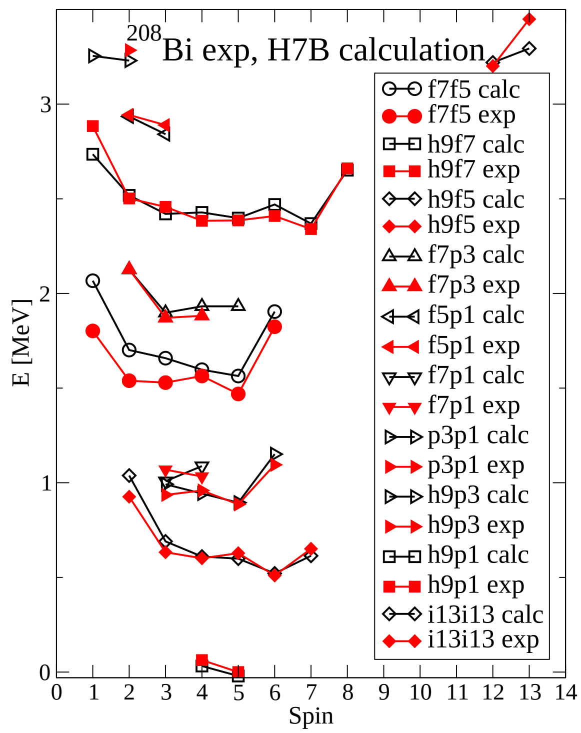

Fig. 1. Energies of the positive parity one proton one neutron hole states in ^{208}Bi as function of spin, grouped by their dominant configuration. Experimental levels (red, filled symbols) are compared with energies calculated with the unadjusted, original H7B-interaction (black open symbols). Some configurations are marked by the same symbols but distinguished by the spin range.

3. Fitting procedure

The realistic H7B interaction [7] is used as a basis and initial guess for fitting the interaction. It reproduces the energies quite well (Fig. 1). Single particle energies are taken from neighboring nuclei and kept fixed. A least square fit routine minimizes the deviations of calculated and measured values for energies, spectroscopic factors, and γ-branching ratios by varying the two particle matrix elements. The fit was performed for positive parity and spins 1^+ to 8^+. Too little information is available for negative parity. If n states were known for a spin, then the submatrix of the interaction between the lowest $n+1$ configurations has been fitted except for the $(n+1)^{\mathrm{st}}$ diagonal element. These are $(n+1)(n+2)/2-1$ elements as the Hamiltonian is symmetric. The remaining elements have been kept unchanged. The program diagonalizes the Hamiltonian with energies and wave functions as result. The spectroscopic factors are simply the squared amplitudes of the relevant configuration in the wave function. A set of mostly measured and otherwise calculated M1 and E2 single particle elements [4], that is with few modifications taken from Ref. [8], is used to calculate the γ-branching from the configuration mixed wave functions by angular momentum recoupling. Other multipolarities are not considered. In the Kuo Herling space 976 elements define the 1^+ to 8^+ levels, 150 have been fitted, the rest are unchanged from H7B.

4. Results

Nearly all levels exhibit little configuration mixing. Their particular main configuration dominates with $> 80\%$ probability. Therefore the level energy is largely determined by the diagonal matrix element of this configuration, and the level energy can be easily fitted by adjusting this one element. Also spectroscopic factors depend on the squared amplitudes and are insensitive to small admixtures and easily fitted. Nevertheless, it is important that they fix the main configuration giving a firm basis for determining the admixtures from the γ-data. Fig. 2 shows as example the γ-decay of the 2^+ level at 2127 keV. 10 out of the 11 branches are well reproduced. For the poorly fitted decay to the first 4^+ level Fig. 2(b) shows the 3 largest contributions of the configurations of the decaying level and their amplitudes. The by far strongest configuration $\pi f_{7/2}\nu p_{3/2}$ is unimportant for the decay. The $\pi f_{5/2}\nu p_{1/2}$ configuration dominates the total transition element, although its probability is only 1%. In a few cases like this, that are extremely sensitive to small admixtures the γ-decay is not well reproduced. As Fig. 2(c) shows the by far strongest $\pi h_{9/2}\nu p_{1/2}$ configuration of the fed 4^+ level exhausts nearly the full transition element, leaving hardly any room for adjustments.

A few of the fitted matrix elements are shown in Fig. 3 and compared with the theoretical H7B elements. These are all nondiagonal elements. For this sample and in general the agreement is good for both magnitude and the trend as function of spin. No estimates of the uncertainties of the calculated interaction have been presented so far, nor are errors for the fit available, and it is therefore not clear how good the agreement should be. For the highest configurations, $\pi h_{9/2}\nu f_{7/2}$ and above, the agreement is slightly worse. But then the properties of these states are influenced by mixing with still higher unknown levels that cannot be considered in the fit.

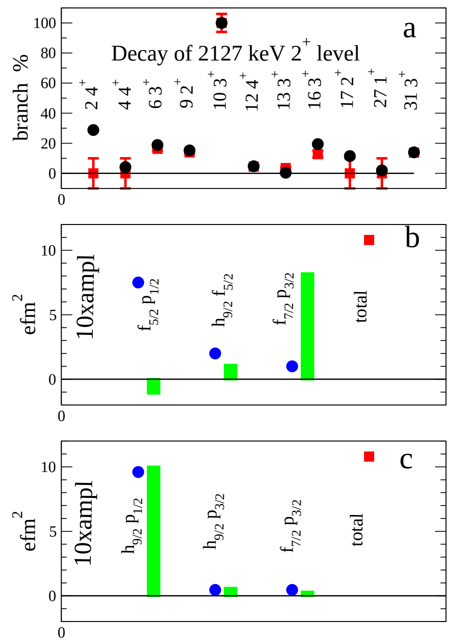

Fig. 2. Decay of the 2127 keV 2^+ level. (a) γ-branches to the indicated levels, black circles calculated from the fitted interaction, red squares experiment. (b), (c) Contributions to the transition matrix elements (blue, filled circles) of the indicated configurations of the decaying (b) and populated (c) state. The green bars give the amplitude ($\times 10$) of the configurations, the red square the total transition element.

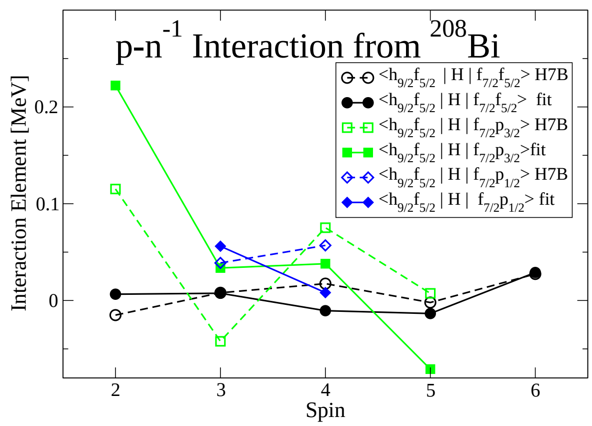

Fig. 3. Comparison of nondiagonal interaction elements for the indicated configurations. Fit: filled symbols, H7B interaction: open symbols.

5. Conclusions

150 diagonal and nondiagonal elements of the interaction between proton particles and neutron holes relative to ^{208}Pb could be fitted to measured properties of ^{208}Bi, because reliable and complete experimental data on level energies, spectroscopic factors, and γ-decay exist. Comparing these experimental elements of the Hamiltonian with theoretical elements is much more meaningful than just comparing some measured and calculated properties. The fitted and theoretical interaction are very similar, but the γ-branching changes dramatically in many cases. These matrix elements make shell model calculations of other nuclei in the region more reliable. More important, they can give hints how to improve the calculation of realistic interactions.

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