New supersymmetric quartet of nuclei: $^{192,193}$Os-$^{193,194}$Ir

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Abstract. We present evidence for the existence of a new supersymmetric quartet of nuclei in the $A \sim 190$ mass region. The analysis is based on new experimental information on the odd-odd nucleus $^{194}$Ir from transfer and neutron capture reactions. The new data allow the identification of a new supersymmetric quartet, consisting of the $^{192,193}$Os and $^{193,194}$Ir nuclei. We make explicit predictions for $^{193}$Os, and suggest that its spectroscopic properties be measured in dedicated experiments. Finally, we study correlations between different transfer reactions.

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INTRODUCTION

The $A \sim 190$ mass region is a particularly complex one, displaying transitional behavior such as prolate-oblative deformed shapes, $\gamma$-unstability, triaxial deformation and/or coexistence of different configurations which present a daunting challenge to nuclear structure models. Despite this complexity, the $A \sim 190$ mass region has been a rich source of empirical evidence for the existence of dynamical symmetries in nuclei both for even-even, odd-proton, odd-neutron and odd-odd nuclei, as well as supersymmetric pairs [1, 2] and quartets of nuclei [3, 4].

In this contribution, we present evidence for the existence of a new supersymmetric quartet in the $A \sim 190$ mass region, consisting of the $^{192,193}$Os and $^{193,194}$Ir nuclei, and study correlations between different one- and two-nucleon transfer reactions.

NUCLEAR SUPERSYMMETRY

Dynamical supersymmetries (SUSY) were introduced in nuclear physics in the context of the Interacting Boson Model (IBM) and its extensions [1]. The IBM describes collective excitations in even-even nuclei in terms of a system of interacting monopole ($s^\dagger$) and quadrupole ($d^\dagger$) bosons [5]. The bosons are associated with the number of correlated proton and neutron pairs, and hence the number of bosons $N$ is half the number of valence nucleons. For odd-mass nuclei the IBM was extended to include
single-particle degrees of freedom [6]. The ensuing Interacting Boson-Fermion Model (IBFM) has as its building blocks \( N \) bosons with \( l = 0, 2 \) and \( M = 1 \) fermion \( (a_j^\dagger) \) with \( j = j_1, j_2, \ldots \) [7]. The IBM and IBFM can be unified into a supersymmetry (SUSY) \( U(6/\Omega) \supset U(6) \otimes U(\Omega) \) where \( \Omega = \sum_j (2j + 1) \) is the dimension of the fermion space [1]. In this framework, even-even and odd-even nuclei form the members of a supermultiplet which is characterized by \( \mathcal{N} = N + M \), i.e., the total number of bosons and fermions. Supersymmetry distinguishes itself from other symmetries in that it includes, in addition to transformations among fermions and among bosons, also transformations that change a boson into a fermion and vice versa.

The concept of nuclear SUSY was extended in 1985 to include the neutron-proton degree of freedom [3]. In this case, a supermultiplet consists of an even-even, an odd-proton, an odd-neutron and an odd-odd nucleus. The best experimental evidence of a supersymmetric quartet is provided by the \(^{194,195}\)Pt and \(^{195,196}\)Au nuclei as an example of the \( U_\nu(6/12) \otimes U_\pi(6/4) \) supersymmetry [4, 8, 9, 10, 11], in which the odd neutron is allowed to occupy the \( 3p_{1/2}, 3p_{3/2} \) and \( 2f_{5/2} \) orbits of the 82-126 shell, and the odd proton the \( 2d_{3/2} \) orbit of the 50-82 shell. This supermultiplet is characterized by \( \mathcal{N}_\nu = 5 \) and \( \mathcal{N}_\pi = 2 \). The excitation spectra of the nuclei belonging to the supersymmetric quartet are described simultaneously by the energy formula

\[
E = A \left[ N_1(N_1 + 5) + N_2(N_2 + 3) + N_1(N_1 + 1) \right] + B \left[ \Sigma_1(\Sigma_1 + 4) + \Sigma_2(\Sigma_2 + 2) + \Sigma_3^2 \right] + B' \left[ \sigma_1(\sigma_1 + 4) + \sigma_2(\sigma_2 + 2) + \sigma_3^2 \right] + C \left[ \tau_1(\tau_1 + 3) + \tau_2(\tau_2 + 1) \right] + DL(L + 1) + EJ(J + 1). \tag{1}
\]

The coefficients \( A, B, B', C, D, \) and \( E \) are determined in a simultaneous fit of the excitation energies of the four nuclei that make up the quartet.

Recently, the structure of the odd-odd nucleus \(^{194}\)Ir was investigated by a series of transfer and neutron capture reactions [12]. In particular, the new data from the polarized \((d, \alpha)\) transfer reaction provided crucial new information about and insight into the structure of the spectrum of \(^{194}\)Ir which led to significant changes in the assignment of levels as compared to previous work [13].

The odd-odd nucleus \(^{194}\)Ir differs from \(^{196}\)Au by two protons, the number of neutrons being the same. The latter is crucial, since the dominant interaction between the odd neutron and the core nucleus is of quadrupole type, which arises from a more general interaction in the IBFM for very special values of the occupation probabilities of the \( 3p_{1/2}, 3p_{3/2} \) and \( 2f_{5/2} \) orbits, i.e. to the location of the Fermi surface for the neutron orbits [14]. This situation is satisfied to a good approximation by the \(^{195}\)Pt and \(^{196}\)Au nuclei, and thus also for \(^{193}\)Os and \(^{194}\)Ir. For this reason, it is reasonable to expect the odd-odd nucleus \(^{194}\)Ir to provide another example of the \( U(6/12)_\nu \otimes U(6/4)_\pi \) supersymmetry. Fig. 1 shows the negative parity levels of \(^{194}\)Ir in comparison with the theoretical spectrum in which it is assumed that these levels originate from the \( v3p_{1/2}, v3p_{3/2}, v2f_{5/2} \otimes \pi 2d_{3/2} \) configuration. The theoretical energy spectrum is calculated using the energy formula of Eq. (1) with \( A = 26.3, B = 8.7, B' = -33.6, C = 35.1, D = 6.3, \) and \( E = 4.5 \) (all in keV). Given the complex nature of the spectrum of heavy odd-odd nuclei, the agreement is remarkable. There is an almost one-to-one correlation between the experimental and theoretical level schemes [12].
The successful description of the odd-odd nucleus $^{194}$Ir opens the possibility of identifying a second quartet of nuclei in the $A \sim 190$ mass region with $U(6/12)_v \otimes U(6/4)_\pi$ supersymmetry. The new quartet consists of the nuclei $^{192,193}$Os and $^{193,194}$Ir and is characterized by $\mathcal{N}_v = 5$ and $\mathcal{N}_\pi = 3$. Whereas the $^{192}$Os and $^{193,194}$Ir nuclei are well-known experimentally, the available data for $^{193}$Os is rather scarce. In Fig. 2 we show the predicted spectrum for $^{193}$Os obtained from Eq. (1) using the same parameter set as for $^{194}$Ir. We note, that the ground state of $^{193}$Os has spin and parity $J^P = \frac{3}{2}^-$, which implies that the second band with labels $[7, 1], \langle 7, 1, 0 \rangle$ is the ground state band, rather than $[8, 0], \langle 8, 0, 0 \rangle$. The relative ordering of these bands is determined by the coefficients $A$ and $B + B'$. At present, we are carrying out a simultaneous fit of the excitation energies of all four nuclei that make up the quartet to see whether it is possible to reproduce the relative ordering in $^{193}$Os without affecting the successful description of $^{194}$Ir.

**CORRELATIONS**

The nuclei belonging to a supersymmetric quartet are described by a single Hamiltonian, and hence the wave functions, transition and transfer rates are strongly correlated. As
which gives predicted to be excited more strongly than the first excited value of 19.0 for SUSY and which can be tested experimentally.

and (4) are parameter-independent predictions which are a direct consequence of nuclear symmetry relations that exist between the wave functions of the even-even and odd-neutron nuclei of the supersymmetric quartet. It is important to point out, that Eqs. (3) and (4) are parameter-independent predictions which are a direct consequence of nuclear SUSY and which can be tested experimentally.

In a study of the $^{194}\text{Pt} \rightarrow ^{195}\text{Pt}$ stripping reaction it was found [15] that one-neutron transfer reactions can be described in the $U(6/12)_v \otimes U(6/4)_\pi$ supersymmetry scheme by the operator

$$P^{(j)}_v = \alpha_j \frac{1}{\sqrt{2}} \left[ (\tilde{\nu} v \times a^+_{\nu,j})^{(j)} - (\tilde{\nu} v \times a^+_{\nu,1/2})^{(j)} \right].$$

(2)

It is convenient to take ratios of intensities, since they do not depend on the value of the coefficient $\alpha_j$ and hence provide a stringent test of the wave functions. For the stripping reaction $^{194}\text{Pt} \rightarrow ^{195}\text{Pt}$ (ee $\rightarrow$ on) the ratio of intensities for the excitation of the $(1,0), L = 2$ doublet with $J = 3/2, 5/2$ belonging to the first excited band with $[N + 1, 1], (N + 1, 1, 0)$ relative to that of the ground state band $[N + 2], (N + 2, 0, 0)$ is given by [15]

$$R_j(\text{ee} \rightarrow \text{on}) = \frac{(N + 1)(N + 3)(N + 6)}{2(N + 4)},$$

(3)

which gives $R_j = 29.3$ for $^{194}\text{Pt} \rightarrow ^{195}\text{Pt}$ ($N = 5$), in comparison with the experimental value of 19.0 for $j = 5/2$, and $R_j = 37.8$ for $^{192}\text{Os} \rightarrow ^{193}\text{Os}$ ($N = 6$). The equivalent ratio for the inverse pick-up reaction is given by

$$R_j(\text{on} \rightarrow \text{ee}) = R_j(\text{ee} \rightarrow \text{on}) \frac{N_\pi + 1}{(N + 1)(N_\nu + 1)}.$$  

(4)

which gives $R_j = 1.96$ for $^{195}\text{Pt} \rightarrow ^{194}\text{Pt}$ ($N_\pi = 1$ and $N_\nu = 4$) and $R_j = 3.24$ for $^{193}\text{Os} \rightarrow ^{192}\text{Os}$ ($N_\pi = 2$ and $N_\nu = 4$). This means that the mixed symmetry $L = 2$ state is predicted to be excited more strongly than the first excited $L = 2$ state. This correlation between pick-up and stripping reactions can be derived in a general way only using the symmetry relations that exist between the wave functions of the even-even and odd-neutron nuclei of the supersymmetric quartet. It is important to point out, that Eqs. (3) and (4) are parameter-independent predictions which are a direct consequence of nuclear SUSY and which can be tested experimentally.
SUMMARY AND CONCLUSIONS

In conclusion, we have presented evidence for the existence of a second quartet of nuclei in the $A \sim 190$ region with $U_{\nu}(6/12) \otimes U_{\pi}(6/4)$ supersymmetry, consisting of the $^{192,193}$Os and $^{193,194}$Ir nuclei. The analysis is based on new experimental information on $^{194}$Ir. In particular, the ($\vec{d},\alpha$) reaction is important to establish the spin and parity assignments of the energy levels, and to provide insight into the structure of the spectrum of $^{194}$Ir. Given the complexity of the $A \sim 190$ mass region, the simple yet detailed description of $^{194}$Ir in a supersymmetry scheme is truly remarkable.

Nuclear supersymmetry establishes precise links among the spectroscopic properties of different nuclei. This relation has been used to predict the energies of $^{193}$Os. Since the wave functions of the members of a supermultiplet are connected by symmetry, there exists a high degree of correlation between different one- and two-nucleon transfer reactions not only between nuclei belonging to the same quartet, but also for nuclei from different multiplets [10, 11]. As an example, we studied the correlations between one-neutron transfer reactions for the Pt and Os isotopes, and predicted that the $L = 2$ mixed symmetry states in the even-even nucleus are populated much stronger than the first excited $L = 2$ state.

In order to establish the existence of a second supersymmetric quartet of nuclei in the $A \sim 190$ mass region, it is crucial that the nucleus $^{193}$Os be studied in more detail experimentally. The predictions for correlations between one-neutron transfer reactions in Pt and Os can be tested experimentally by combining for example ($\vec{d},p$) stripping and ($p,d$) pick-up reactions.

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