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DEFORMATION EFFECT AND FIVE-FOLD CORRELATION TIME REVERSAL TEST IN NEUTRON RESONANCES USING ALIGNED ^{165}Ho

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ABSTRACT

We estimate the deformation effect cross sections for neutron resonances in aligned ^{165}Ho, and estimate the sensitivity of a five-fold correlation time reversal test carried out on a resonance that exhibits a deformation effect.

1. Introduction

Neutron transmission tests of time reversal invariance were proposed by a number of authors in the early 1980's[1]. The experiments are technically challenging because they require not only a polarized neutron beam, but also a polarized or aligned nuclear target. Nevertheless they have attracted considerable attention because of the large enhancements in sensitivity associated with compound nuclear resonances.

In 1988, Bunakov[2] proposed a test of parity (P) even time reversal (T) violation in the neighborhood of two interfering p-wave resonances of the same spin. A similar enhancement exists if a d-wave and s-wave resonance interfere[3]. Until now, however, no suitable resonances have been located in nuclei which can be aligned, and the only tests of time reversal violation in neutron transmission have been carried out with MeV energy neutrons[4,5].

In this paper we discuss how to use the deformation effect to identify resonances suitable for testing time reversal violation in the five-fold correlation. We focus specifically on polarized neutron transmission through aligned ^{165}Ho. In addition we estimate the sensitivity of the test to α_T, the ratio of the T-odd to T-even parts of the effective nucleon nucleon interaction.[6]

2. Five-Fold Correlation and Deformation Effect

The five fold correlation (FC) test involves searching for a P-even, T-odd term in the neutron-nucleus forward scattering amplitude of the form $f_T \vec{s} \cdot (\vec{I} \times \vec{k}) \vec{I} \cdot \vec{k}$. Here $\vec{s}$ is the neutron spin, $\vec{k}$ is the neutron momentum and $\vec{I}$ is the nuclear spin. The FC term only arises if the beam is polarized and the target is aligned. An aligned target will also have a P-even, T-even term in the forward scattering amplitude of the form $f_D(\vec{I} \cdot \vec{k})^2$, known as the deformation effect (DE). The DE will be present for both polarized and unpolarized neutron beams.

The FC and DE have characteristic angular signatures, $\sin 2\theta$ and $P_2(\cos\theta)$ respectively, where θ is the angle between the beam direction and the alignment axis. Searching for these angular signatures was the basis of the time reversal test of Ref. 5, carried out with a cryogenically aligned, rotating ^{165}Ho single crystal target.

The FC and DE involve coupling the angular momentum of the neutron beam to the $K = 2$ rank of the oriented target. Neither effect will be observable on a pure s-wave resonance. But if there is some d-wave admixture in an s-wave resonance, a deformation effect can be seen. In addition, if this d-wave admixture can interfere with a second nearby s-wave resonance, there will be sensitivity to time reversal violation. Spin assignments are known for a number of s-wave resonances in ^{165}Ho. Locating a d-wave admixture in any s-wave resonance therefore immediately opens up the possibility of a sensitive time reversal test. A p-wave resonance can in principle also exhibit a deformation effect, but no $l = 1$ resonances have been seen in ^{165}Ho, without which a time reversal test cannot be performed.

The large angular momentum barrier would appear to preclude the possibility of seeing d-wave admixtures. But as we now discuss, the deformation effect is a very sensitive probe of p- and d-wave neutron partial width amplitudes. We also note that the strong tensor force mixes s-wave and d-wave amplitudes, and can have a dramatic effect on low energy cross sections, enhancing for example, the $D(d,\alpha)\gamma$ capture cross section by orders of magnitude at energies of astrophysical interest[7].

3. Deformation Effect in an Isolated Resonance

General expressions for the polarized-beam, polarized-target cross section have been given by Alfimenkov *et al.*[8], Barabanov[9], and Gould *et al.*[3]. Following the notation of Ref. 3, the total cross section can be written as a sum over the polarization ranks k of the beam and K of the target:

$$\sigma_{tot} = \sum_{kK} \sigma_{kK} \tag{1}$$

with

$$\sigma_{kK} \quad \mathrm{Re}\left\{ 2\pi \lambda^{2} \sum_{\Lambda q} \hat{\Lambda} \langle \Lambda k 0 q | K q \rangle t_{kq}(s) t^{*}_{Kq}(I) \right. \\ \left. \times \sum_{J} g_J \sum_{ll'jj'} T_{Kk\Lambda}(l'j'ljJ) \left[\delta_{ll'} \delta_{jj'} - S_J(lj \cdot\cdot l'j') \right] \right\}. \tag{2}$$

Here, $t_{kq}(s)$ and $t^*_{Kq}(I)$ are the statistical tensors describing the orientation of the beam and target respectively, g_J is the spin statistical factor, $T_{Kk\Lambda}$ is a combination of angular momentum coupling factors and $S_J(lj \to l'j')$ is the S-matrix element describing the reaction. The deformation effect arises from the term σ_{02} corresponding to $k = 0$ and $K = 2$.

The angular momentum couplings are defined by $\vec{j} = \vec{l} + \vec{s}$, $\vec{J} = \vec{j} + \vec{I}$. For ^{165}Ho, $I^\pi = 7/2^-$ and s-wave resonances have $J^\pi = 3^-, 4^-$; p-wave resonances have $J^\pi = 2^+, 3^+, 4^+, 5^+$; and d-wave resonances have $J^\pi = 1^- ... 6^-$. For an s-wave resonance with d-wave admixture, the deformation effect arises from terms involving $l = 0$, $l' = 2$ and $l = 2$, $l' = 0$. The $l = l' = 2$ term will be negligible due to penetrability effects. For a p-wave resonance the deformation effect is due to the $l = l' = 1$ term.

Neglecting potential scattering, the S-matrix element for an isolated resonance is given by

$$S_J(lj \to l'j') = \delta_{ll'}\delta_{jj'} - \frac{i g_n^J(lj) g_n^J(l'j')}{(E - E_J) + i\Gamma_J/2}, \tag{3}$$

where $g_n^J(lj)$ is the neutron partial width amplitude, and E_J and Γ_J are the energy and total width of the resonance of spin J. Substituting equation 3 into equation 2, we find the deformation effect cross section for an isolated resonance is:

$$\sigma_{02}(J^\pi) = \pi \lambda\!\!\!^{-2} \hat{I} t_{20}(I) \frac{g_J \Gamma_J}{(E - E_J)^2 + \Gamma_J^2/4} C(J^\pi). \tag{4}$$

The coefficient $C(J^\pi)$ is given by

$$\begin{aligned} C(J^\pi) &= 4W(J\tfrac{1}{2}I2; I\tfrac{3}{2}) g_n^J(1\tfrac{1}{2}) g_n^J(1\tfrac{3}{2}) \\ &\quad -2W(J\tfrac{3}{2}I2; I\tfrac{3}{2}) \left[g_n^J(1\tfrac{3}{2})\right]^2 \end{aligned} \tag{5}$$

for $l = 1$ and by

$$\begin{aligned} C(J^\pi) &= 4W(J\tfrac{1}{2}I2; I\tfrac{3}{2}) g_n^J(0\tfrac{1}{2}) g_n^J(2\tfrac{3}{2}) \\ &\quad -2\sqrt{6}W(J\tfrac{1}{2}I2; I\tfrac{5}{2}) g_n^J(0\tfrac{1}{2}) g_n^J(2\tfrac{5}{2}) \end{aligned} \tag{6}$$

for $l = 0, 2$, where W is the usual Racah coefficient. The unpolarized resonance cross section is given by

$$\sigma_{00} = \pi \lambda\!\!\!^{-2} \frac{g_J \Gamma_J}{(E - E_J)^2 + \Gamma_J^2/4} \sum_{lj} \left[g_n^J(lj)\right]^2. \tag{7}$$

To proceed we need estimates of the unknown neutron amplitudes $g_n^J(lj)$. These are related to the neutron widths via $\Gamma_n^J(lj) = \left[g_n^J(lj)\right]^2$. We assume widths depend only on l, and estimate them from the strength functions S_l and level spacings

D_l. From the definition[10] $\langle g_J \Gamma_n^l \rangle = (2l+1) D_l S_l$, and taking $D_l \sim D_0/(l+1)$, $\Gamma_n = \Gamma_n^l V_l E(\mathrm{eV})^{1/2}$, $V_l \sim (kR)^{2l}$, and $g_J \sim \frac{1}{2}$, we find for ^{165}Ho:

$$\begin{aligned}
\Gamma_n(l=0) &= 1.7 \times 10^{-8} E(\mathrm{eV})^{1/2} \\
\Gamma_n(l=1) &= 2.3 \times 10^{-9} E(\mathrm{eV})^{3/2} \\
\Gamma_n(l=2) &= 2.2 \times 10^{-15} E(\mathrm{eV})^{5/2}.
\end{aligned} \tag{9}$$

For $l = 2$, we assume $S_2 \sim S_0$ in accordance with the giant resonance model. All other parameters are from Ref. 7.

The deformation effect cross section, equation (4), also depends on the ratio of the $j = l \pm 1/2$ neutron amplitudes. We parametrize this unknown ratio via the j-spin mixing ratio

$$x_j = g_n^J(l, j = l - 1/2)/[\Gamma_n^J(lj)]^{1/2} \tag{10}$$

where $-1 \leq x_j \leq 1$.

4. Cross Section Results

A recent high resolution study of ^{165}Ho at ORELA revealed many new weak neutron resonances, the first two at energies of 24.8 and 75.1 eV[11]. Figures 1 and 2 show transmission spectra in the vicinity of these resonances. They may be candidates for a time reversal violation study if they exhibit a deformation effect. The parameters of these resonances are listed in Table 1, along with the average neutron widths derived from equations (9). The resonances are seen to be three orders of magnitude weaker than average s-wave resonances, and more than one order of magnitude stronger than average p-waves. A Bayesian analysis of the type introduced by Bollinger and Thomas[12] indicates that with very high probability both are s-wave resonances, but we consider both possibilities for the purposes of estimating deformation effect cross sections from equation (4).

Figure 3 shows σ_{02} for the 24.8 eV resonance under the assumption that it is an s wave with the admixture of d-wave listed in Table I. We take $t_{20} = \sqrt{\frac{7}{8}}$, corresponding to 100% alignment along the beam direction ($\theta = 0°$). Two J values are possible, 3 and 4, and the ratio $|\sigma_{02}/\sigma_{00}| \sim 10^{-3}$ for both possibilities.

Figure 4 shows σ_{02} under the assumption the resonance is a p wave. Four J values are possible, but only $J = 3$ and 4 can be formed by mixed j. In all cases except $J = 2$, $|\sigma_{02}/\sigma_{00}| \sim 1$. Thus, the deformation effect is comparable to the total cross section. Clearly, deformation effect measurements are in general able to distinguish p-wave resonances from s-wave resonances with d-wave admixtures.

The small deformation effect associated with the d-wave admixture can be detected with a rotating aligned target and an unpolarized neutron beam. From the $P_2(\cos\theta)$ dependence, the effect changes sign going from 0° to 90°, leading to a 0° – 90° transmission asymmetry $\epsilon \sim n\sigma_{02}$ where n is the target thickness in atoms/b. The TUNL target corresponds to $n \sim 0.06$ atoms/b, leading to $\epsilon \sim$

1×10^{-3} for the 24.8eV resonance. On resonance asymmetries of order $\sim 10^{-4}$ have been achieved at LANSCE[13].

The effect will likely be easier to see in capture because of the absence of potential scattering background. Capture measurements are well suited to studying weak resonances and analyzing power accuracies of better than $\sim 10^{-3}$ have already been achieved at both LANSCE[14] and KEK[15].

5. Time Reversal Violation for s-d Mixing

If a ^{165}Ho resonance shows a small but non-zero deformation effect, then it is in all probability an s-wave with d-wave admixture, and, as such, is immediately suitable for a time reversal violation test with a polarized neutron beam. The FC cross section on top of a resonance is given by equation 5.11 of Ref. 3:

$$\sigma_{12} = -2\pi \lambda^2 \hat{t}_{10}\hat{t}_{20} \left(M_5 x_j + M_6 \sqrt{1 - x_j^2} \right) \frac{W}{E_s - E_d} \frac{\sqrt{\Gamma_n^s \Gamma_n^d}}{\Gamma^d} \qquad (11)$$

where E_d is the energy of the resonance showing a deformation effect (presumed weak), E_s is the energy of a neighboring s-wave resonance of the same J^π (presumed strong), M_5 and M_6 are numerical factors of order unity, $W \equiv |\langle s|H_T|d\rangle|$ is the time reversal violating matrix element coupling the two resonances, Γ_n^d and Γ_n^s are the total neutron widths of the d-wave and neighboring s-wave resonances, and Γ^d is the total width of the d-wave resonance. For purposes of estimating σ_{12} we take $W = 1$ eV, and take parameters for nearby resonances from Ref. 7. For the 24.8 eV resonance these are the 18.2 eV, $J = 3$ resonance, and the 12.8 eV, $J = 4$ resonance. These resonances are shown in figure 1 and the cross sections σ_{12} are shown in figure 5. We find peak values of $\sigma_{12}(J = 3) \sim \sigma_{12}(J = 4) \sim 60$ mb for the 24.8 eV resonance. This would correspond to a time reversal violating spin flip asymmetry $\epsilon \sim n\sigma_{12} \sim 4 \times 10^{-3}$.

In principle the time reversal experiment needs to be carried out in transmission with a neutron spin analyzer[1] to avoid difficulties from sequential T-even interaction terms. However, the sequential terms that mimic time reversal violation are all P-odd for the FC. If they can be shown by calculation or experiment to be negligible (likely the case for a d-wave resonance), then a FC measurement of σ_{12} via capture is possible. As for the deformation effect search, this will be more sensitive than a transmission measurement because of the absence of a potential scattering background.

Previous experiments[13] at LANSCE have measured parity violating longitudinal analyzing powers $P \sim \sigma_{10}/\sigma_{00}$ of order 10^{-3}, and a measurement of σ_{12}/σ_{00} at the 10^{-4} level is certainly achievable. A $\sim 10^{-4}$ bound on the analyzing power would correspond to a bound ~ 0.03 eV on W. From $\Gamma_T \sim 2\pi W^2/D \sim 2\pi 10^3 \alpha_T^2$, this implies a bound of 4×10^{-5} on α_T, the ratio of the T-odd to T-even parts of the $N - N$ effective interaction. The present limits[16] are $\sim 5 \times 10^{-4}$, so improvement of one to two orders of magnitude is possible, particularly if enhanced d wave admixtures are located.

6. Summary

We have estimated deformation effect cross sections for neutron resonances in an aligned ^{165}Ho target. For p-wave resonances, the effects are large. For s-wave resonances with d-wave admixtures, the effects are much smaller, but are still accessible to measurement, particularly in capture measurments of resonance total cross sections. Locating a deformation effect opens up the possibility of a sensitive test of time reversal violation.

7. Acknowledgements

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8. References

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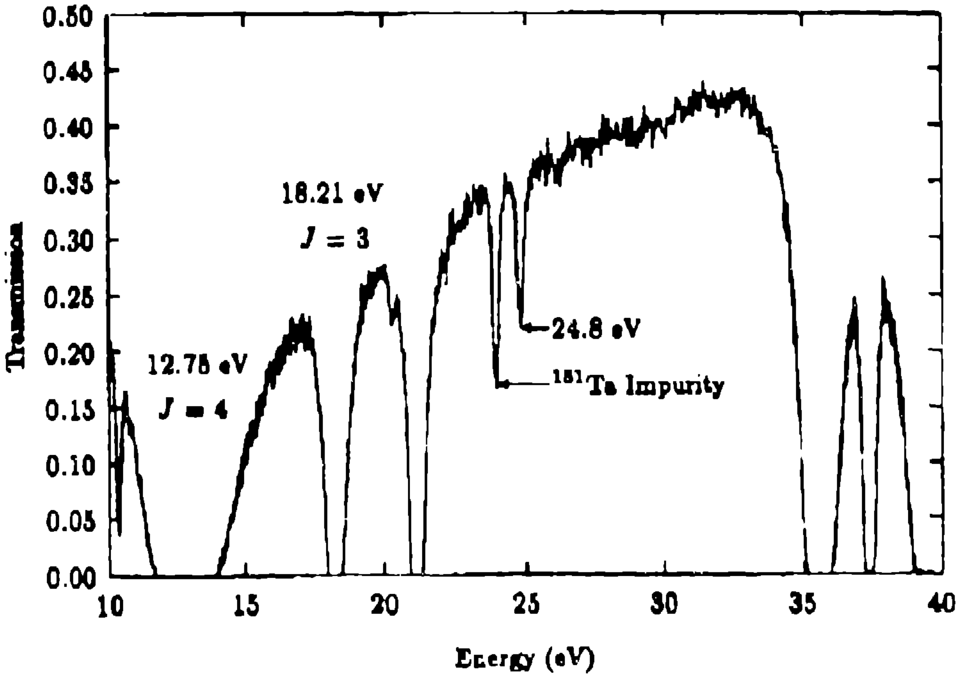

Figure 1: Transmission spectra of ^{165}Ho near the 24.8eV resonance

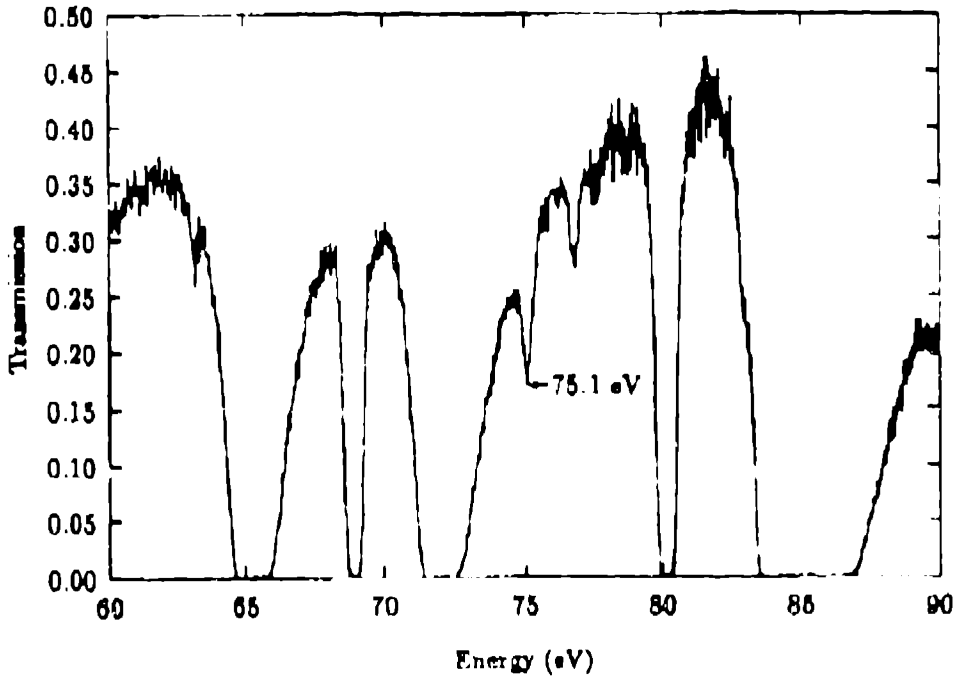

Figure 2: Transmission spectra of ^{165}Ho near the 75.1eV resonance

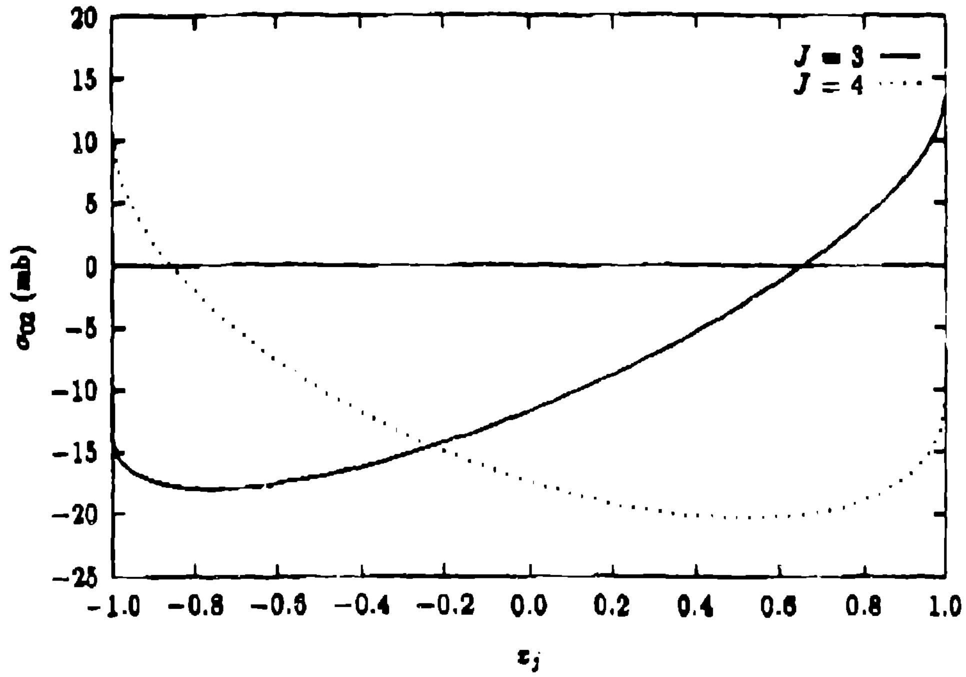

Figure 3: σ_{02} for the 24.8 eV resonance assuming it is *s*-wave with *d*-wave admixture

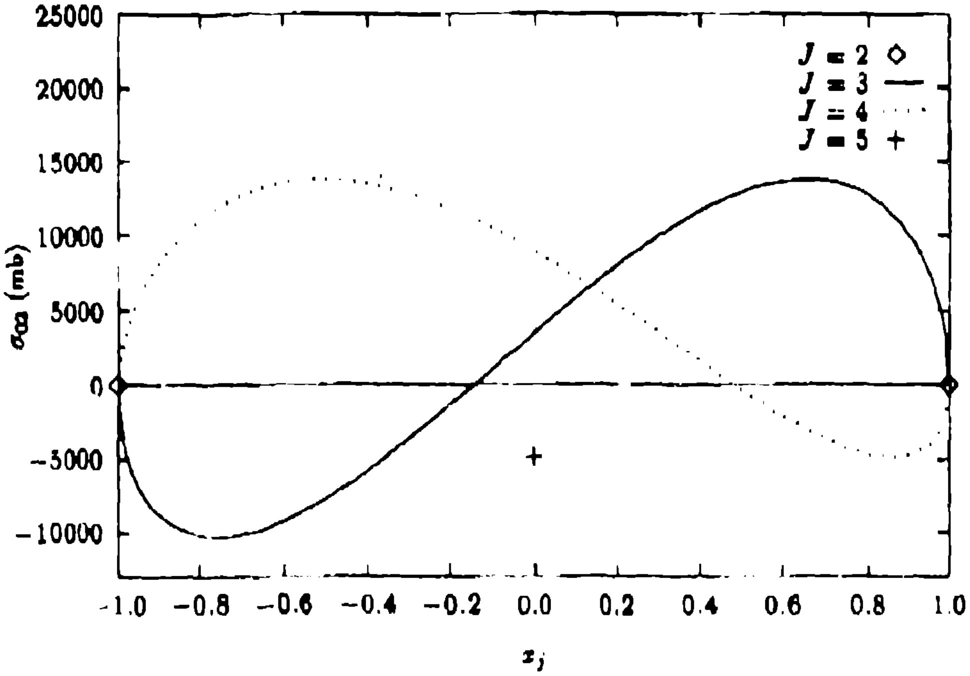

Figure 4: σ_{02} for the 24.8 eV resonance assuming it is *p*-wave

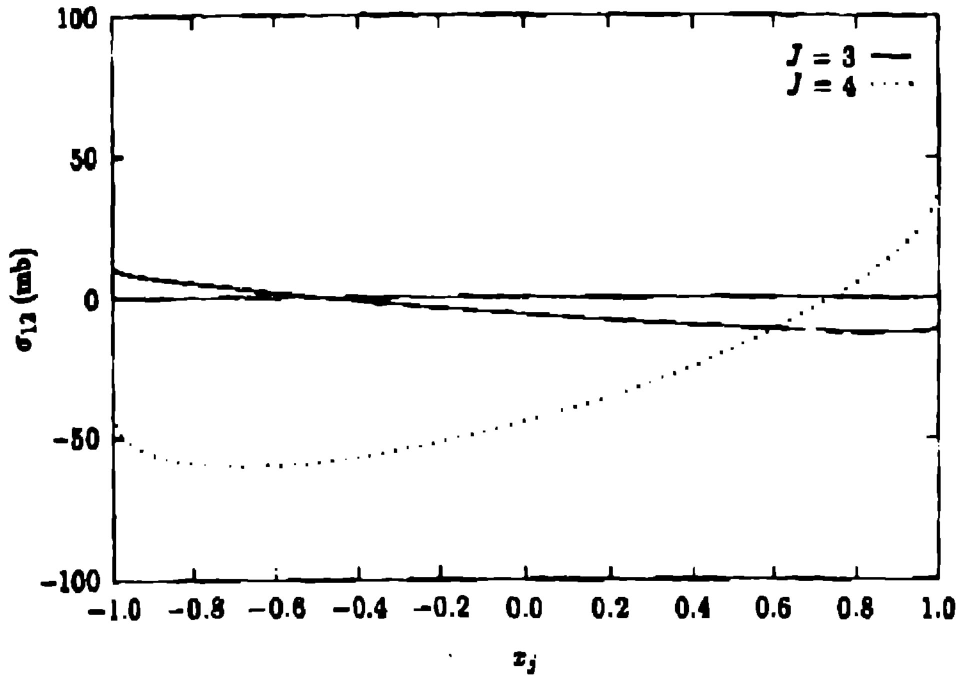

Figure 5: σ_{12} for the 24.8 eV s-wave resonance with d-wave admixture

	24.8 eV	75.1 eV
Experiment (meV)		
Γ_γ	88.4	70.0
$g\Gamma_n$	8.71×10^{-3}	5.08×10^{-2}
Average Widths (meV)		
$\Gamma_n^{l=0}$	8.25	14.3
$\Gamma_n^{l=1}$	2.85×10^{-4}	1.5×10^{-3}
$\Gamma_n^{l=2}$	6.5×10^{-9}	1.1×10^{-7}
Cross Sections (b)		
σ_{00}	10.3	25.1
σ_{02} $(s-d)$	2×10^{-2}	8×10^{-2}
σ_{02} $(p-p)$	14	34
σ_{12} $(s-d)$	6×10^{-2}	5×10^{-2}

Table 1: Resonance parameters, average widths, and peak cross sections σ_{00}, σ_{02} and σ_{12} for two resonances in ^{165}Ho.