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TITLE: THE INTERACTING BOSON MODEL AND MEDIUM ENERGY PROBES

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SUBMITTED TO: International Conference on Nuclear Structure, Reactions, and Symmetries, June 5-14, 1986, Dubrovnik, Yugoslavia

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THE INTERACTING BOSON MODEL AND MEDIUM ENERGY PROBES

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ABSTRACT

Medium energy electron and proton scattering are used to determine the quadrupole form factors for the Interacting Boson Model of Nuclei.

1. INTRODUCTION

The interacting boson model (IBM) has been successful in giving a unified description of energy spectra and transition rates of collective nuclei[1)]. However, there is now available very high quality electron scattering data which can determine the static and transition charge densities of nuclei down to very small distances[2)]. There are also high quality medium energy proton scattering data available on heavy nuclei, which, in conjunction with the electron scattering data, can determine the contribution of the neutron and proton degrees of freedom[3)]. Can the IBM describe these transition densities as well? This is the topic that we shall discuss in this paper.

2. MEDIUM ENERGY PROTON SCATTERING AND IBM

In order to address this question at all, we need to be satisfied that medium energy proton scattering is handled correctly. Electron scattering from nuclei can be analyzed with distorted wave Born approximation (DWBA). However for medium energy proton scattering coupled channel effects may be important[3,4)], especially for collective nuclei. Recently we have been able to calculate these coupled channel effects to all orders in a very elegant way[4,5)]. In the Glauber approximation the scattering amplitude for scattering a medium energy proton with momentum k from a nucleus in an initial state i to a final state f and transferring momentum $\vec{q}$ is given by

$$\langle f|F|i\rangle = \frac{k}{2\pi i}\int d^2b e^{i\vec{q}\cdot\vec{b}}(e^{i\phi(b)}\, U_{fi}(\vec{b}) - \delta_{fi}) \tag{1a}$$

$$U_{fi}(\vec{b}) = \langle f|e^{i\hat{\Psi}(\vec{b})}\ |i\rangle \tag{1b}$$

where $\vec{b}$ is the impact parameter, and $\phi(b)$ is the distorted wave. The transition operator $\hat{\Psi}(\vec{b})$ is a linear combination of the boson operators, and the quadrupole term is given by

$$\hat{\Psi}(\vec{b}) = \left[g(b)\ P + g_2(b)\ T\right] \cdot Y^{(2)}(\hat{b}) \tag{2a}$$

$$P_\mu = (s^\dagger\tilde{d} + d^\dagger s)^{(2)}_\mu \tag{2b}$$

$$T_\mu = (d^\dagger\tilde{d})^{(2)}_\mu \tag{2c}$$

$$g(b) = \frac{2\pi}{k}\ f\int_{\infty}^{\infty} dz\ \alpha\left(\sqrt{b^2 + z^2}\right) \tag{2d}$$

$$g_2(b) = \frac{2\pi}{k}\ f\int_{\infty}^{\infty} dz\ \beta\left(\sqrt{b^2 + z^2}\right) \tag{2e}$$

where P, T are boson operators acting on the monopole ($s^\dagger$) and quadrupole ($d^\dagger$) bosons in the nucleus, f is the average nucleon-nucleon scattering amplitude, and $\alpha(r)$, $\beta(r)$ are the IBM form factors to be discussed later. The salient point is the following. Since $\hat{\Psi}$ is a linear combination of the boson operators which are generators of the SU(6) dynamical symmetry[1)] of the IBM, the operator $e^{i\Psi(\vec{b})}$ produces a unitary transformation of the six bosons, $s^\dagger$, $d^\dagger_\mu$, $\mu = -2, -1, \ldots 2$ among themselves, and hence also among all the bosons in the nucleus. The transition matrix $U_{fi}(\vec{b})$ is then the SU_6 group representation matrix where g, g_2 are like rotation angles. That is, the transition matrix is a generalization of the Wigner D-function which is the group representation matrix of SU_2. Therefore this matrix can be calculated in closed form. For special limits of the quadrupole oscillator, the γ-unstable rotor, and the axially symmetric rotor, this transition matrix can be given in analytic form in terms of a hypergeometric power series[4]. For the more general case, the transition matrix can be calculated numerically[5]. Hence all coupled channels within the IBM model space are included in the scattering in a unified manner.

3. THE IBM ELECTROMAGNETIC QUADRUPOLE TRANSITION OPERATOR

Electron scattering from nuclei measures the static and transition densities of protons alone since neutrons carry no charge and the magnetic interactions are very small and are generally neglected. However the IBM is a truncation of the nuclear many-body problem and hence the IBM form factors will consist of both a direct part due to scattering from the <u>included</u> degrees of freedom, and an effective part due to the <u>excluded</u> degrees of freedom. Because neutrons and protons are probed differently in electron scattering, neutron and proton degrees of freedom should be distinguished as in IBM-2[1]. The electromagnetic quadrupole density operator is then given as

$$\hat{\rho}_{em,\mu}(r) = e \left[\alpha_{\pi\pi}(r)\, \hat{P}_{\pi,\mu} + \beta_{\pi\pi}(r)\, \hat{T}_{\pi,\mu} + \tilde{\alpha}_{\pi\nu}(r)\hat{P}_{\nu,\mu} + \tilde{\beta}_{\pi\nu}(r)\, \hat{T}_{\nu,\mu}\right] \quad (3)$$

The form factors $\alpha_{\pi\pi}$ and $\beta_{\pi\pi}$ include both direct and effective interactions of the electron with the valence protons, while $\tilde{\alpha}_{\pi\nu}$ and $\tilde{\beta}_{\pi\nu}$, of course, include only the effective interaction with the valence neutrons. We call these form factors generically IBM proton form factors since they are probed by electrons.

We use an IBM-2 Hamiltonian which reproduces the energy spectra and B(E2)'s of ^{154}Gd,[6]

$$H = \epsilon\hat{N} - \kappa\hat{Q}_\pi \cdot \hat{Q}_\nu + \sum_L \xi_L A_L^\dagger \cdot A_L \quad (4)$$

where $\epsilon = 0.52$ MeV, $\kappa = 0.075$ MeV, $\xi_1 = \xi_3 = 1.2$ MeV and $\xi_2 = 0.03$ MeV, where $A^\dagger_{LM} = (d^\dagger_\nu d^\dagger_\pi)^{(L)}_M$, $L = 1, 3$, and $A^\dagger_{LM} = (d^\dagger_\nu s^\dagger_\pi - d^\dagger_\pi s^\dagger_\nu)_M/\sqrt{2}$, $L = 2$. This last term pushes up the antisymmetric neutron-proton states. The quadrupole operators are $\hat{Q}_{\sigma\mu} = \left[\hat{P}_{\sigma\mu} + \chi\, \hat{T}_{\sigma\mu}\right]$, $\sigma = \pi, \nu$, where $\chi = -0.9$.

Using the eigenfunctions of this Hamiltonian we can then calculate the matrix elements of the quadrupole density operator given in (3) from the ground state to the measured excited states $J^\pi_i = 2^+_i$, $i = 1, 2, 3$. However since only three transition densities have been measured and we need to determine four form factors, we have assumed that the symmetric form factor $\alpha_{\pi\pi}(r) + \tilde{\alpha}_{\pi\nu}(r)$ has a Tassie form since this symmetric form factor dominates in the excitation of the first 2^+ state in deformed nuclei. This gives the fourth equation, and hence we can solve for the four form factors. The results for $\alpha_{\pi\pi}(r)$ and $\tilde{\alpha}_{\pi\nu}(r)$ are shown in Fig. 1. The form factor $\tilde{\alpha}_{\pi\nu}(r)$ is smaller than $\alpha_{\pi\pi}$ and peaks further out on the surface. This behavior is expected since $\tilde{\alpha}_{\pi\nu}(r)$ is entirely an effective form factor.

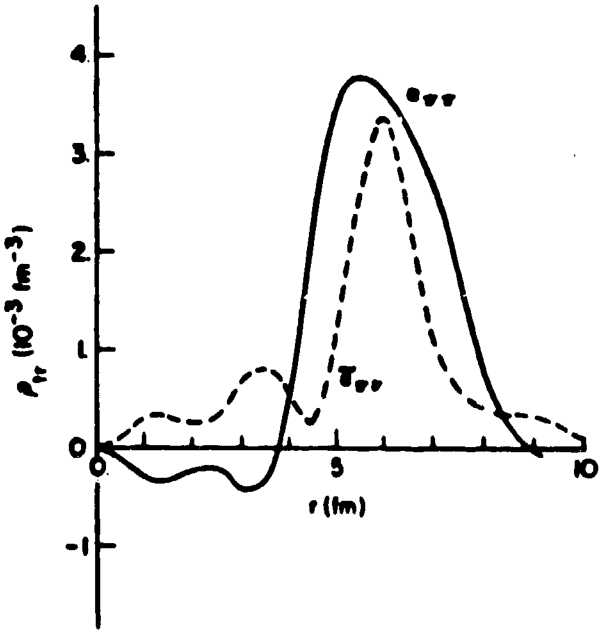

Figure 1. $\alpha_{\pi\pi}$ (solid line) and $\tilde{\alpha}_{\pi\nu}$ as a function of nuclear radius.

4. THE IBM HADRONIC QUADRUPOLE TRANSITION OPERATOR

Since hadronic probes are not elementary particles as is the electron, the hadronic form factors need not necessarily be the same as the electromagnetic form factors.[7] However we ignore this difference in this discussion for simplicity of exposition only.[7] Most importantly there are additional form factors because the proton does interact directly with the valence neutrons whereas electrons do not. For medium energy protons, in fact, the interaction with protons and neutrons is almost equal. For this reason IBM-1 may be adequate to describe proton scattering, but, of course, including coupled channel effects as outlined in section 2. The effective IBM-1 hadronic form factors to be used in Equation (2) will then be[7]

$$\alpha(r) = \alpha_{\pi\pi}(r) + \tilde{\alpha}_{\pi\nu}(r) - \Delta\alpha(r) \tag{5a}$$

$$\beta(r) = \beta_{\pi\pi}(r) + \tilde{\beta}_{\pi\nu}(r) - \Delta\beta(r) \tag{5b}$$

$$\Delta\alpha(r) = \left[N_\nu\left(\alpha_{\pi\pi}(r) - \alpha_{\nu\nu}(r)\right) + N_\pi\left(\tilde{\alpha}_{\pi\nu}(r) - \tilde{\alpha}_{\nu\pi}(r)\right)\right]/N \tag{5c}$$

$$\Delta\beta(r) = \left[N_\nu\left(\beta_{\pi\pi}(r) - \beta_{\nu\nu}(r)\right) + N_\pi\left(\tilde{\beta}_{\pi\nu}(r) - \tilde{\beta}_{\nu\pi}(r)\right)\right]/N \tag{5d}$$

where $N_{\nu(\pi)}$ is the number of neutron (proton) bosons and $N = N_\nu + N_\pi$. The neutron form factors $\alpha_{\nu\nu}$, $\tilde{\alpha}_{\nu\pi}$, $\beta_{\nu\nu}$, $\tilde{\beta}_{\nu\pi}$ are analogous to the form factors given in (3), but can only be probed in hadron scattering and can never be determined in electron scattering. Thus $\Delta\alpha(r)$ and $\Delta\beta(r)$ represent the average difference between proton and neutron boson form factors which can be determined by hadron scattering in IBM-1. As a first step we assume that $\Delta\alpha = \Delta\beta = 0$. and then α and β are determined from electron scattering and are shown in Fig. 2. We note that $\beta(r)$ is similar to the derivative of $\alpha(r)$. We take the IBM-1 Hamiltonian of Ref. 8 since the matrix elements of $\hat{P}$, $\hat{T}$ are almost equal to the matrix elements of $\hat{P}_\pi + \hat{P}_\nu$, $\hat{T}_\pi + \hat{T}_\nu$, of the IBM-2 Hamiltonian in (4), better than those of the IBM-1 Hamiltonian given by the prescription of Ref. 9 for reducing an IBM-2 Hamiltonian to an IBM-1 Hamiltonian.

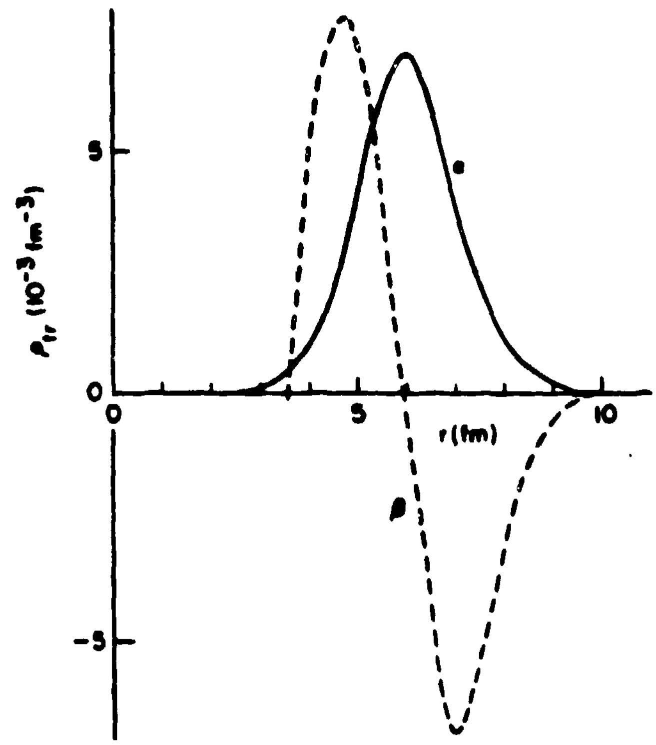

Figure 2. α and β as a function of nuclear radius for $\Delta\alpha, \Delta\beta = 0$.

5. RESULTS AND CONCLUSIONS

In Fig. 3 the differential cross sections for 650 MeV proton scattering on ^{154}Gd with $\Delta\alpha = \Delta\beta = 0$ are compared with the experimental cross sections measured at LAMPF.[10] For elastic scattering, the calculated cross section (solid line) agrees very well. For inelastic scattering the calculated cross section (dashed line) is about 20% too high for scattering to the first 2_1^+ state, but otherwise the minima and maxima are given very well. This result indicates that the proton scattering may be sensitive to the difference in neutron and proton degrees of freedom (i.e., $\Delta\alpha$ and $\Delta\beta$) which we ignored in going from electron scattering to proton scattering. Hence if on the average the proton form factors are larger than the neutron form factors ($\Delta\alpha, \Delta\beta > 0$), there will be a decrease in the cross section to the first 2_1^+ state.

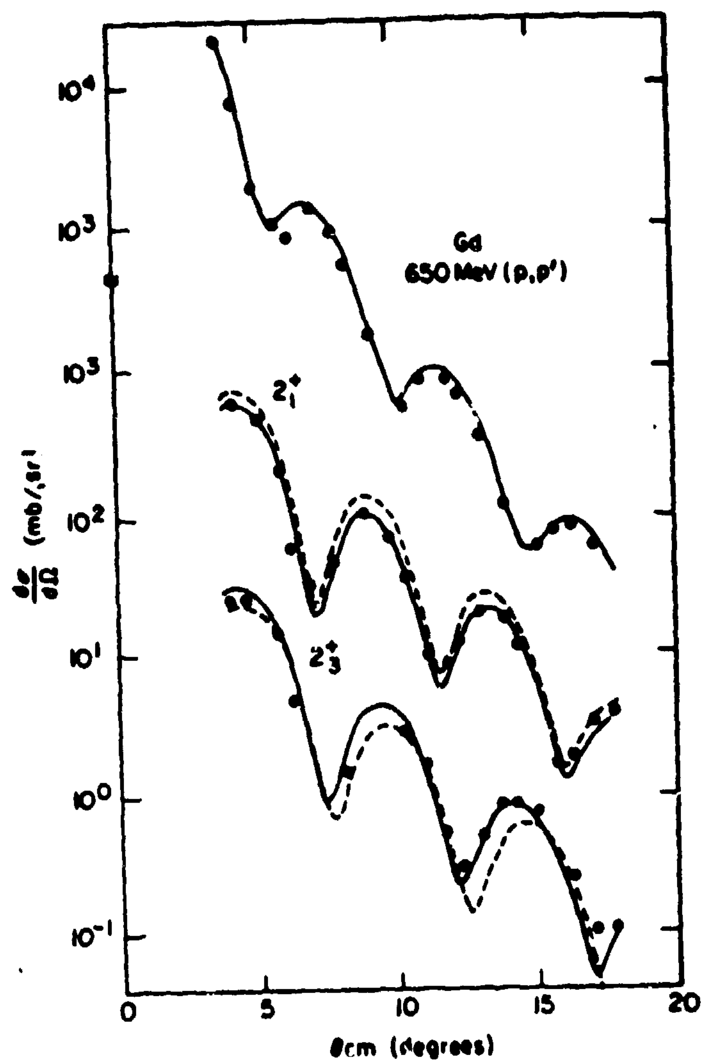

Figure 3. Elastic and Inelastic Proton Scattering in ^{154}Gd. For inelastic scattering dashed line is with $\Delta\alpha$, $\Delta\beta$=0 and full line with $\Delta\alpha$ = 0, $\Delta\beta$ = 0.5β. For elastic scattering solid line is for both.

For scattering to the 2_3^+ state the calculated cross section (dashed line) is about 20% too <u>low</u> and shifted forward about 0.4° in angle. However this state depends differently on $\alpha(r)$ and $\beta(r)$. A decrease in $\alpha(r)$ will decrease its cross section just as for the 2_1^+, but a drecrease in $\beta(r)$ will increase its cross section. In fact if we decrease the strength of $\beta(r)$ by a factor of two there is very good agreement for both states as shown by the solid line. Furthermore the scattering to the 2_2^+ state, which is the weakest state and is still being analyzed[10], depends on $\alpha(r)$ and $\beta(r)$ in a similar manner as the 2_3^+, but is even more sensitive to changes in $\beta(r)$. We are now in the process of determining $\Delta\alpha(r)$ and $\Delta\beta(r)$ from these cross sections which shall give us some information about the difference between the neutron and proton boson form factors. This means that we can successfully use electron and hadron scattering to determine the difference in neutron and proton form factors. Clearly in this study it will be helpful to have more systematic electron and proton scattering data to both the yrast and non-yrast 2^+ states on a series of Gd isotopes. Also fermion models of collective motion[11,12] can predict directly these form factors from a microscopic foundation.

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