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A Study of Inclusion of Centre of Mass Correlation for Even Nuclei

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ABSTRACT: The empirical success of the IBM for even–even nuclei encouraged its developers to expand it to odd– even and even–odd nuclei by the addition of one fermion. This odd-A version is known as the interacting boson– fermion model or IBFM. The IBFM Hamiltonian contains a boson term, a fermion term, and a third term representing the interaction (or coupling) between the bosons and fermion. As in the IBM, the IBFM can be discussed in symmetry limits, as in Eq. (1), in which the odd fermion is coupled to the valence bosons in either the U(5), SU(3), or SO(6) limits. The different limits can be related to particular cases in the collective model, such as the strong-coupling or weak-coupling limits.

The addition of an odd fermion greatly increases the number of possible parameters in this model; the number of possible states also greatly increases. For these reasons, the IBFM has been applied mainly to special cases, such as a nucleon in a single j level or in several j levels with the imposition of some boson–fermion symmetry. This model has also been used for studies of β -decay between odd–even and even–odd nuclei.

KEYWORDS: centre, mass, correlation, even, nuclei, momentum, energy, physics, light, particle

I. INTRODUCTION

In the harmonic approximation there are neither interactions between the different vibrational quanta, nor between the quanta and the quasi-particles. To this approximation the particles in an odd-mass nucleus move unaffected by the oscillatory field set up by the vibrations, and the resulting spectrum will consist of the intrinsic excitations (the quasi-particle states) and series of vibrational spectra associated with the intrinsic states. The combination of a particle state with angular momentum J and a vibrational state with angular momentum $R\lambda$ gives rise to an approximately degenerate multiplet with states of total angular momenta $I = R\lambda + J$, $R\lambda + J - 1$, ... $|R\lambda - J|$, i.e. a total of 2J + 1 or $2R\lambda + 1$ states. The energy of the multiplet relative to the intrinsic state is approximately equal to the corresponding phonon energy in the neighbouring even–even nuclei.[1,2]

Much of the experimental research on Coulomb excitation consists of determining the positions and γ -ray lifetimes of rotational levels. Their energies are most often obtained by measuring the γ -rays emitted when the nucleus reverts to the ground state, although it is also possible in some instances to observe from a thin target the spectrum of the inelastically scattered incident particles associated with the Coulomb excitation. When the incident particle is a proton or an α -particle it is usually only the first excited rotational level that can be reached. The most important type of excitation is electric quadrupole in nature. Thus, in even-even nuclei the excitation takes the nucleus from the 0+ ground state to the first excited state, the latter having a spin-parity of 2+ with only a few exceptions. The energy of the first 2+ state is known⁵ to be a smooth function of proton or neutron number, having broad minima in between the numbers 50, 82 and 126 (the 'magic' numbers or closed shells of the nuclear shell model) and rising to sharp maxima at the 'magic' numbers.[3,4]



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Even-even nuclei

The accumulation of a large amount of information⁶ on first excited states has been extremely useful for the understanding of collective motions. It has been natural to extend the studies to higher rotational states. If such states are connected to the ground state by electric quadrupole or E2 transitions it is possible in even-even nuclei to excite the second 2+ state with α -particles of higher energy than those used for forming the first 2+ state. This has been done by Stelson and McGowan⁷ in a number of medium-weight nuclei by means of ~ 10-MeV α -particle bombardment.[5,6] Rotational states of higher spin must be excited in a step-wise manner by multiple Coulomb excitation, i.e. through successive quadrupole excitations by a single bombarding particle. The probability for doing this with proton or α -particle beams is exceedingly small, but since the probability increases rapidly with the charge on the projectile there is a better chance for success if heavy ions are used. In experiments carried out at some researchers have bombarded Th²³² and U²³⁸ with ions of Ne²⁰, S³² and A⁴⁰ from a heavy-ion linear accelerator. Rotational states up to the sixth order (12+) in U²³⁸ and up to the fifth order (10+) in Th²³² were excited. For the lower states the spacing of levels in these two cases follows the J(J + 1) relationship of eq. (1) but good agreement with theory is achieved for the higher states of these rotational bands only if a correction term of the form $BJ^2(J + 1)^2$ is added to account for rotational-vibrational interactions. The constant *B* is related to vibrational energies. Figure 1 shows an internal conversion electron spectrum



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obtained by Stephens and Diamond³⁴ in the bombardment of Ho¹⁶⁵ with 60-MeV O¹⁶ ions. One section of an 'orange' spectrometer was used for the measurements which were taken at a resolution of 0.6%. The energy level scheme of Ho¹⁶⁵ deduced from these data is shown in Fig.



II. DISCUSSION

The lifetimes of rotational levels have been of considerable interest since they have given the strongest evidence in favor of the collective description. In the vicinity of closed shells the emission of γ -radiation is ascribed to the transition of a single particle from one orbit to another outside of a closed shell. [7,8]



Correlations

This subject is covered here where the single-particle transition probabilities are discussed. If low-lying nuclear states are collective in nature, as they are thought to be in regions far from the closed shells, the cooperative action of many nucleons should make it easier for the nucleus to change from one state to another with the emission of γ -radiation. Consequently the transition probability should be enhanced and the lifetime of a state should be shorter than that of a



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single-particle transition of the same energy and the same multipole order. Much of the work on lifetimes of rotational levels has been aimed at determining enhancement factors (the ratio of the observed transition probability to the calculated single-particle transition probability) which are measures of the extent to which the states are collective in nature.

In Coulomb excitation the lifetime of a rotational level is obtained indirectly. This follows from the fact that the crosssection for forming the state is proportional to the probability for raising the nucleus from its ground state to the first excited state. From the 'upward' E2 transition probability as given by the cross-section measurement the probability λ_{γ} for de-excitation of the level by γ -ray emission is readily obtained. λ_{γ} is simply the inverse of the mean γ ray lifetime of the state.[9,10]



Spin = 2, Parity = +

Some care, however, must be exercised, since fluctuations have been considered in only one order parameter, Δ_n . Indeed, it can be argued that neutron pair fluctuations should be significant in the cases studied: (i) indeed pairing is the strongest correlation – all even-even nuclei have 0⁺ ground states; and (ii) current studies of stably-deformed rare earth nuclei extend through the region of the pair phase transition where such fluctuations of the pair gap should be maximum. The importance of pair fluctuations, however, does not argue that fluctuations in other order parameters, e.g. the various deformations, are not important for nuclei. Indeed other such dynamic correlations should be important where the minimum potential energy is not well determined with respect to a particular order parameter.[11,12]



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III. RESULTS

Many of the states formed by Coulomb excitation also occur in the decay of radioactive isotopes. In such cases it is possible by means of fast coincidence techniques to measure the half-lives of these states when they are $\gtrsim 5 \text{ X}$ 10^{-11} sec. The total probability for decay of the level obtained from a direct lifetime measurement should agree with the sum of λ_{γ} , based on the Coulomb excitation result, and $\lambda_{i.c.}$ the probability for the emission of internal conversion electrons (assuming that no intermediate state exists). Combining such results therefore provides a means of determining the total internal conversion coefficient $\alpha_{exp} = \lambda_{i.e.} / \lambda_{\gamma}$. Analyses of this sort have shown that there are significant deviations between the experimental and theoretical internal conversion coefficients. From a plot of $\alpha_{exp} / \alpha_{th}$ versus N/Z Bernstein¹¹ has suggested that there is a systematic variation in this ratio between limits of 1.2 and 0.8 which may be related to dynamic effects in the nucleus.[13,14]



Most of the details of this spectrum of states can be reproduced within the Nilsson model based on either modifiedoscillator or Wood-Saxon potentials. One serious disagreement, however, remains between the empirical and theoretical spectra of states. The lowest empirical (+,1/2) and (+,-1/2) levels are predicted to have much larger alignments relative to the neighboring negative-parity levels than observed. This feature, which is reasonably insensitive to the details of the parameters of the calculations, also is present in empirical spectra of states constructed from energy differences within a specific nucleus. The physical basis of this discrepancy is not known.

With the pairing interaction between the valence neutrons, the calculations yield the decay energy of 18 keV of the ground state. The decay spectrum obtained by including only the [d3/2] 2 configurations is shown by the dashed line. In this case, the peak is shifted by 0.55 MeV from the unperturbed peak at 1.498 MeV. The peak is further shifted downwards by the di-neutron correlations due to configuration mixing, and gets closer to the threshold energy[15,16]



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IV. CONCLUSIONS

The rather unusual (and very slow) $\beta^{-}\beta^{-}$ -decay mode is energetically possible for several even-even nuclei, and kinetically possible to observe in those cases where the separating odd-odd nucleus of higher energy prevents normal β^{-} -decay, see Fig. 3.6 V. It has recently been observed for some such cases, e.g. $3482Se \rightarrow 3682Kr + 2\beta + 2v^{-}$

The half-life of about 1.7×10^{20} y can be observed because small amounts of the noble gas Kr can be physically isolated from large amounts of ⁸²Se (9% natural abundance), and then measured. Studies of $\beta\beta$ -decay are of importance for evaluation of neutrino properties.[17,18]

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