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Prof. Ikeda's important contributions to nuclear physics

D.M. Brink
Rudolf Peierls Institute for Theoretical Physics, Oxford, UK

Abstract
Professor Ikeda has made many fundamental contributions to nuclear physics, especially to the theory of Gamow-Teller giant resonances, to nuclear cluster physics, to hypernuclear physics, and to the physics of neutron-rich nuclei. He also has played an important role in the education of young researchers in Japan and on the contacts between theoreticians and experimentalists.

1 Introduction

It is a great pleasure and honor for me to be asked to introduce this day dedicated to Prof. Ikeda and to his many important contributions to nuclear physics. It is also a day to celebrate his 75th birthday. His influence extends beyond his published work. He has always encouraged physicists in different universities and institutes to collaborate on projects in nuclear physics. He has organized symposia at the Yukawa Institute in Kyoto each of which covered a topic in a developing field with in depth discussions. These meetings promoted collaborations in different institutes and contributed to important progress in that field. Ideas evolved through discussions.

One of Prof. Ikeda's earliest fields of research was the study of the Gamow-Teller giant resonance and its influence on low energy magnetic moments and beta-decay transition rates. It was followed by a major work on clustering in light nuclei. Later today Dr Mares will speak about Prof. Ikeda's contribution to hypernuclear physics. In the last few years there has been a lot of interest in the physics of neutron rich nuclei. Several talks today will speak about this new physics. The tensor force between nucleons is rather strong. What is the influence of the tensor force on the structure of nuclei? It is known that the exchange part of tensor force modifies the spin-orbit interaction in the shell model, especially in neutron rich nuclei? But are there other effects? This is an ongoing field of research and Prof Ikeda is actively involved. Several lectures will be devoted to this problem. My job is to introduce some of these topics.

2 Gamow-Teller giant resonances

Ikeda's studies of Gamow-Teller resonances began with two papers in collaboration with Fujii and Fujita in 1962 and 1963. The immediate motivation was a series of experiments on (p,n) reactions carried out with the Harwell cyclotron [1]. The Harwell group observed resonance peaks in the energy spectrum of neutrons in the forward direction with a number of targets ranging from deuterium to uranium. In their first paper Ikeda and his colleagues [2] suggested that they were giant resonances excited by the isospin operator. Lane and Soper [3] had already noted that isospin effects could persist even in very neutron rich nuclei and that isobaric analogue states could have a narrow width .

In their second paper [4] Ikeda and his colleagues argued that supermultiplet symmetry could also persist in heavy nuclei and that states in the same supermultiplet could be excited by the Gamow-Teller operator

$$Y_\pm = \sum_i \tau_{\pm i}\sigma_i. \tag{1}$$

In a nucleus with a neutron excess these operators can move a neutron from an occupied neutron state to an unoccupied proton state with similar quantum numbers. For an initial even nucleus with ground state spin 0^+ the T_- operator excites the isobaric analogue state with spin 0^+. The Gamow-Teller operator excites a final state with spin 1^+.

The operator $Y_\pm$ is the same as the one appearing in the theory of Gamow-Teller transitions in β decay. It had been known for a long time that measured magnetic moments deviated strongly from the predictions of the single particle model. β decays of the Gamow-Teller type associated with the operator $\tau\sigma$ were also delayed in comparison with values calculated from the single particle model. The papers of Ikeda et al established that there was an intimate connection between β decay and (p,n) reactions. The argument of Brown and Bolsterli [5] for the giant dipole resonance was invoked to explain the hindrance factor in the β transitions. The residual interactions remove some strength from the β decay matrix elements and transferred it to the GT giant resonance region. These arguments were elaborated in subsequent papers and resulted in a prediction that the β transitions are hindered by roughly a factor of 4.

The total strength is limited by the Gamow-Teller or Ikeda sum rule

$$S^N(GT) = S^N(GT^-) - S^N(GT^+) = 3(N - Z) \tag{2}$$

where $S^N(GT^\pm$ are the GT strengths of type $\beta^\pm$. It was discussed in [4] where the factor $3(N - Z)$ was introduced in a certain approximation. The expression (2) was used in a paper by Gaarde et al [6]. They also presented an experimental study of the Gamow-Teller resonance in ^{48}Sc using the (^{3}He, t) reaction. The first experiment which showed clear evidence for structure of the Gamow-Teller resonance in a (p,n) reaction was made by Doering et al in (1975) [7] in ^{90}Zr. They found a low energy component near the isobaric analogue state which was mainly due to a transition from the $g_{9/2}$ neutron state to the $g_{9/2}$ proton state. There was a broader higher energy component mainly due to transition from the $g_{9/2}$ neutron state to the spin-orbit partner $g_{7/2}$ proton state. Fujita et al have been able to make very detailed studies of the Gamow-Teller resonance in many nuclei using the (^{3}He, t) reaction [8].

3 Clustering in nuclei

The nucleus ^{8}Be is unbound for breakup into two α-particles but it has a very long lifetime. As a consequence it has a well defined 2α cluster structure. The two alphas in the quasi-bound state have a small overlap and, as a consequence the influence of the Pauli principle is small so that they retain their identity. There are two quasi-rotational excited bands in ^{16}O, a $K = 0^+$ band based on the 0^+ state a 6.06 MeV and a $K = 0^-$ band based on the 9.58 MeV 1^- state. These states are near the threshold for breakup into an alpha particle and ^{12}C in its ground state and Horiuchi and Ikeda argued that these are cluster states with an α+^{12}C structure. In 1968 Ikeda argued that alpha cluster structures could exist in in many nuclei and introduced the 'Ikeda diagram' to illustrate various possibilities. The diagram showed the threshold energy for breakup into the fragments and made the hypothesis that the cluster structures could exist for states with excitation energy near these thresholds. This is the 'Ikeda threshold rule'.

In the diagram these structures are illustrated as linear molecular states, but it does not imply a strictly linear configuration. For example the Hoyle state with excitation energy 7.656 MeV in ^{12}C should be imagined as a loose structure of 3αs rather than as a strictly linear structure. The Ikeda diagram has been enormously influential for both experimental and theoretical work on clustering in nuclei. On the experimental side it indicates the range of excitation energies where particular cluster structures might be expected to occur.

Another aspect of these cluster studies is that different structures can exist in the same nucleus. For example in ^{16}O the ground state has a shell model structure, some excited states with excitation energy in the range 6 - 10 MeV have an alpha $+^{12}$C cluster structure while states around 15 MeV can have a 4-α structure.

A study of ^{8}Be by Sugimoto, Ikeda and Toki [11] has shown that the tensor force influences the interaction between two clusters. It produces a repulsion when the clusters overlap which enhances the α clustering. If this is a more general effect it could explain why clustering is so strong in light 4-n nuclei.

4 Exotic nuclei

In 1988 Tanihata showed that very weakly bound nuclei had an unusually large matter radius and suggested that this was due to the large extension of the orbits of the weakly bound nucleons. The picture of a halo nucleus emerged with a tightly bound core with a halo of weakly bound nucleons. Prof Ikeda has studied a number of properties of neutron rich nuclei including the pygmy dipole resonance.

The giant dipole resonance is a collective mode in a nucleus in which the neutrons vibrate against the protons. It can be described by the Goldhaber-Teller model or the Steinwedel-Jensen model. The latter is a hydrodynamical model with a neutron and proton fluid which oscillate out of phase. It can predict the strength of the resonance and the A dependence of the resonance energy. In 1989 Ikeda, Suzuki and Sato suggested that a new kind of resonance could exist in halo nuclei in which the core and the excess neutrons vibrate against each other. They applied a modification of the Steinwedel and Jensen model to calculate properties of this new pygmy dipole resonance. Its strength is much weaker than the giant dipole resonance and it has a different excitation energy. It has been observed in a number of nuclei. A nice example is in ^{90}Zr studied recently at the ELBE accelerator by the group in Dresden [14]. The normal Giant dipole resonance has an excitation energy of 17 MeV. The pygmy dipole resonance is broad and has an mean excitation energy of about 9 MeV and a strength of about 4$\%$ of the normal GDR.

5 Tensor forces

The nucleon-nucleon tensor force due to pion exchange is very strong. It is responsible for the binding and quadrupole moment of the deuteron and gives large contribution to the binding energy of nuclei. The binding energy of ^{3}He is four times larger than the binding energy of the deuteron and 4He binding is a factor of 4 larger than the ^{3}He binding. A large part of this binding comes from the tensor force, but then in heavier nuclei it appears to saturate. The binding energy of ^{8}Be is just twice that of ^{4}He and the binding of 4-n nuclei like 12C, ^{16}O is almost proportional to the number of component α-particles. In heavier nuclei the tensor force appears to play a passive contribution, just giving a constant fraction of the binding of the binding energy. Later today Dr. Neff will explain that the tensor force produces short range tensor correlations between nucleons in a nucleus and that these correlations give an almost constant contribution to the binding energy per nucleon.

It has been known for a long time that the exchange part of the tensor force makes a first order contribution the the spin-orbit interaction in spin unsaturated nuclei [15] and can give a quenching or enhancement of the spin-orbit splitting in certain regions of the periodic table. It modifies the shell structure in neutron rich nuclei. For example ^{90}Zr is a good closed shell nucleus while ^{80}Zr is not and has a large deformation. The shell gap for neutrons and protons in ^{80}Zr is small. The (n,p) tensor force in ^{90}Zr increases the proton shell gap, making it a very good closed shell nucleus. A study on ^{23}F showed that there is a strong cancellation between the spin-orbit interaction and the tensor force which reduces the splitting between the d$_{5/2}$ and d$_{3/2}$ levels by a large factor.

The direct part of the tensor force involves the operators $\sum_i \mathbf{r}.\sigma$ and $\sum \mathbf{r}.\sigma\ \tau$ and has zero expectation value in a Hartree-Fock wave function, but a strong tensor force would lead to a parity violating phase transition. The tensor force in the nucleon nucleon interaction is not strong enough to produce this phase transition, but a charge-parity projected mean field theory (CPPHF) does have a phase transition. This effect has been studied by Ikeda, Sugimoto and Toki in a number of papers. In a study of ^{4}He [17] they find that there is a strong mixing between the s$_{1/2}$ and p$_{1/2}$ levels in which lowers the ground state energy but not by as much as might be expected. The reason is that the expectation value of the tensor potential increases the binding energy, but there is also an increase in the kinetic energy contribution and the two tend to cancel. The tensor force makes a big change in the wave function but does not give a large contribution to the energy.

Neff and Feldmeier [18] have shown that the tensor force produces strong short range tensor correlations in the nuclear wave function. With a phenomenological nucleon-nucleon wave function this contribution of the tensor force can be represented by an effective central force. This is a volume effect. The residual, long range part of the tensor force, studied in projected Hartree-Fock (CPPHF) is probably a surface effect which is important in light nuclei.

Prof. Ikeda has been involved in the tensor-optimized shell model [19] which is another approach to calculating the effects of the tensor force in light nuclei. The idea is to choose a subspace of the full shell model space in which the basis states are strongly coupled by the tensor force. This theory has been applied to study the effects of the tensor force in light halo nuclei. For example in ^{11}Li there are $s_{1/2}$ and $p_{1/2}$ single particle wave functions which have large components in the halo wave function. The studies in [19] and other works have indicated that blocking effects by the extra neutrons in this neutron rich nucleus can produce this effect.

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