IKEDA, the partner for exploring the nuclear highland far from the valley of stability

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abstract

I have been collaborating with Ikeda since 1980's when I started the experiment with radioactive nuclear beams. He has been interested in explaining the halo structure and binding energy of ^{11}Li from the very beginning. From these studies, new basic concepts have been introduced, one of such important ideas is the soft resonance and cluster structure of halo nuclei. He also introduced the importance of the tensor forces on the halo formation, in particular for the correlation of two halo neutrons though s- and p- wave mixing. As an experimentalist, I have been trying to provide data to help him to develop these ideas.

Here, I present the recent progresses in experimental studies. One is the first measurement of the two-neutron transfer reaction of ^{11}Li to study the correlation between two halo neutrons. The other is a new on going experiment to obtain the direct evidence of the tensor forces in nuclei.

1. Prologue

1.1 Development of RIB experiments and Ikeda's idea

Radioactive nuclear beams (RNB) for study of nuclear structure were invented at Berkeley in mid-80th. [1] The use of this new beams in structure studies of nuclei far from the stability line provided several essential discoveries on structures of nuclei, immediately. Among them are neutron halos, neutron skins, and change of magic numbers. Then new types of developments in structure and reaction theories have been started. This wave of developments by RNB still continue not only in nuclear structure physics but also in cosmonuclear physics[2] and other applications.

Ikeda has been strongly contributing to these developments from the beginning. Immediately after the discovery of neutron halo in ^{11}Li, which has been confirmed by the large matter radius determined through the interaction cross section measurements and the narrow internal momentum distribution through the momentum distribution of ^{9}Li fragment, Ikeda introduced the cluster model of ^{11}Li, namely a nucleus ^{11}Li is modeled as ^{9}Li core and two halo neutrons. It is a natural model and immediately used in many calculations. The first model is the cluster shell model in which two neutrons are moving in a potential made by the interaction between a neutron and the core ^{9}Li. The subsystem n+^{9}Li (=^{10}Li) does not have bound state and the knowledge of the ^{10}Li was scares. One of the driving force of Ikeda's research on exotic nuclei has been the effort to understand the binding mechanism of such system.

While making models of ^{11}Li, Ikeda introduced the soft dipole resonance, a new excitation mode of halo nuclei. When he gave us the idea of soft resonance we were not sure how we can observe such phenomena. Fortunately, immediately after measuring the Coulomb dissociation cross sections, we found that the cross section is enhanced very much in ^{11}Li that is consistent with Ikeda's idea. [2]

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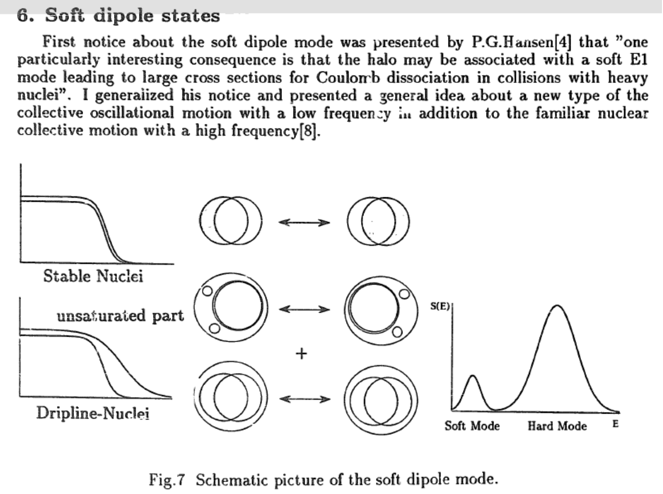
[2] I use the word "cosmonuclear physics" instead of "nuclear astrophysics" because these developments cover not only astrophysical object but also big bang and other cosmological physics.

The other important discovery was the new magic number *N*=16 in neutron rich nuclei as well as the disappearance of *N*=8 magic number in He, Li, Be isotopes. It is then connected to the development of the study of the tensor forces in nuclei.

Let us discuss two important physics that Ikeda has contributed in the following sub-sections.

1.2 Soft resonances

Immediately after the introduction of ^{11}Li neutron halo, the soft dipole mode of excitation has been introduced by Hansen [3]. Then Ikeda generalized this idea to a new collective excitation mode the soft dipole resonance. The statement can be seen in his paper as shown in Fig. 1.1. His main idea is that the resonance will split into two. One of them has a very low excitation energy. At first before his idea, we considered that the E1 resonance energy will simply be lowered due to the diffused surface by neutron halo. But Ikeda stated that is not the case. He considered that the oscillation between protons and neutrons inside the core should be separated from the oscillation of the core against the halo neutrons. From the cluster sum rule, the strength of this soft excitation is expected to be about the 10% of the main E1 excitation strength.



6. Soft dipole states

First notice about the soft dipole mode was presented by P.G.Hansen[4] that "one particularly interesting consequence is that the halo may be associated with a soft E1 mode leading to large cross sections for Coulomb dissociation in collisions with heavy nuclei". I generalized his notice and presented a general idea about a new type of the collective oscillational motion with a low frequency in addition to the familiar nuclear collective motion with a high frequency[8].

Fig.7 Schematic picture of the soft dipole mode.

Fig. 1.1 Idea of the soft resonance mode by Ikeda. [2]

The first evidence of the this mode of excitation was seen as large enhancements of the Coulomb dissociation cross sections of ^{11}Li on various target. [4] (Fig. 1.2) Then later 1.2 MeV exited state has been observed by proton inelastic scattering experiment. [5] The analysis of the angular distribution of the inelastic scattering is consistent with the E1 transition. This state has been observed by several other experiments such as charge exchange reaction of pions [6]. However the width or lifetime of this state has not been determined yet and still some doubt on the existence of the state remain, presently.

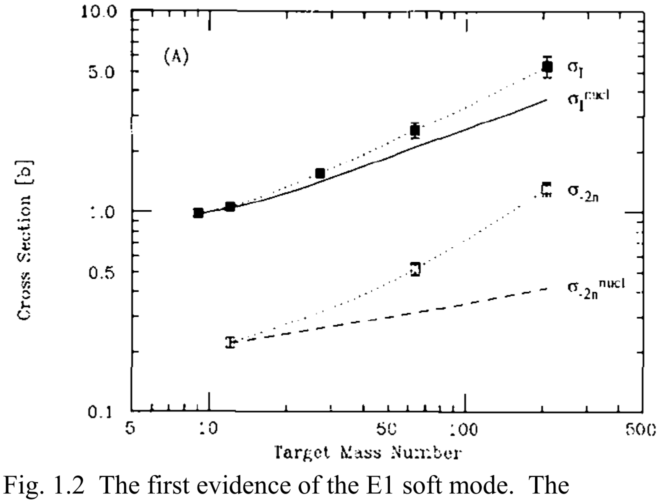


Fig. 1.2 The first evidence of the E1 soft mode. The Coulomb dissociation cross sections increases rapidly when the Z of target increases. [4]

The Ikeda's idea of the soft dipole resonance were extended theoretically for other multipoles and many theoretical works are under progress. It may also have some relation to the pigmy resonance studied for neutron skin nuclei.

1.3 Effects of tensor forces

While Ikeda works on understanding the binding of the ^{11}Li nuclei, he started from the cluster shell model and developed it to include correlations between halo neutrons. [2] Then he realized the importance of the continuum and the mixing of waves of different angular momentum, say p^2

and s^2 waves. He gave deep concern why p orbital and s orbital mixes almost equally in ^{11}Li. This question brought him up to the idea of two-particle excitations due to the tensor forces.

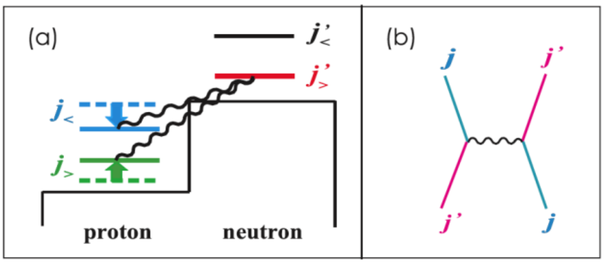


Fig. 1.3 The effect of the tensore forces on the single particle orbitals.

Th importance of the tensor interactions in neutron rich nuclei have been realized first by the change of magic numbers, in particular by the discovery of N=16 in O, F and possibly in B, C and N. [7] The relative shift of p-, s- and d- orbitals was studied by shell model and found that the tensor interactions may be an important ingredient. The figure 1.3 show the effect of the tensor forces on the different orbitals. The tensor forces are attractive between protons and neutrons in $j_>$ and $j_<$ states. In contrast, they are repulsive between protons and neutrons in $j_>$ and $j_>$ states (or $j_<$ and $j_<$ states). Where $j_>= l+1/2$ and $j_<=l-1/2$. When the number of neutrons in a $j_>$ state increases, the corresponding proton $j_>$ orbital become less bound and $j_<$ orbital become more bound, thus making the energy gap between $j_>$ and $j_<$ orbitals smaller. It is true also for neutrons when the number of proton changes.

In the case for N=16 the magic number appears due to the wide gap between $s_{1/2}$ and $d_{3/2}$ orbitals. When several protons are in $d_{5/2}$ orbital in the middle of the sd shell the gap between $d_{3/2}$ and $d_{5/2}$ of neutron is so called normal value. When the number of protons in $d_{5/2}$ orbital is small, the gap between $d_{3/2}$ and $d_{5/2}$ of neutron orbital become large. In addition, the s-orbital become lower due to the loosely bound nature of the neutron rich nuclei and thus comes close or even lower than the $d_{5/2}$ orbital. That is why large gap opens above N=16. This change of orbitals is also a part of the reason why N=20 gap disappears, namely gap between $d_{3/2}$ and fp orbitals become smaller.

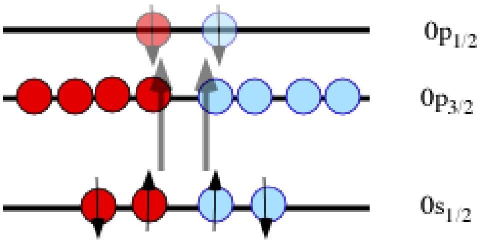


Fig. 1.4 two-particle two-hole excitation by the tensor foces. Transition occurs under the selection rule of $\Delta L=2$ and $\Delta S=2$.

Another important effect of the tensor forces has been known in the binding of the very light nuclei. It has been known that the major part of the biding energy of ^{4}He comes from the tensor forces. The other typical effect is the mixing of D-wave in deuteron. As seen in Fig. 1.4, the effect of tensor force appears as two-particle two-hole (2p-2h) excitation of p-n pair. The tensor forces requires the transition to be ΔL=2 and ΔS=2. That means transition occur for a pair of proton and neutron coupled to S=1 and between different parity states. Therefore the two-particle excitation between $s_{1/2}$ and $p_{1/2}$ is the important part of the wave function in deuteron and ^{4}He.

Recent ab-initio type study also confirmed that the tensor forces provide considerable amount of the binding energy in light nuclei. [8] Ikeda introduced the tensor forces for understanding the binding and the s-p mixing (mixing of $(\nu s_{1/2})^2$ and $(\nu p_{1/2})^2$ waves) in the ^{11}Li. A details of this consideration is published in [9] and also given in the talk of Myo in this conference. In addition he is working on making the versatile model of nuclei explicitly including the tensor forces, TOSM. [see Myo's talk]

2. Resent Search for Tensor Forces

Recently we have been working to observe the effects of tensor forces among other structure effects in ^{11}Li and also in stable nuclei. One is the correlation of two halo neutrons in ^{11}Li, in particular the s-p mixing (mixing of $(\nu s_{1/2})^2$ and $(\nu p_{1/2})^2$ waves) in halo neutron wave function and the other is the high-momentum components in the nuclear wave function.

2.1 Two neutron correlations in a halo nucleus ^{11}Li

It has been known that the two neutron transfer reactions are efficient tool to observe the correlation of neutron pairs in nuclei. Such a study is now possible for ^{11}Li(p, t)^{9}Li reaction at ISAC - 2 facility in TRIUMF. The ISAC-2 provide the reaccelerated beam of ^{11}Li up to 5*A* MeV in energy and 10^4 /s of intensity. An active target MAYA has been used to measure the differential cross sections of ^{11}Li(p,t)^{9}Li reaction at 3 and 5*A* MeV. The experimental system and a typical event is shown in Fig. 2.1.

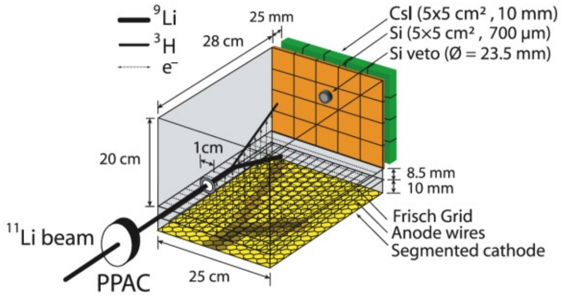


Fig. 2.1 Active target MAYA and the typical (p,t) reaction event data.

The obtained Q-value spectrum is shown in Fig. 2.2. From this we could also determine the mass of the ^{11}Li that had a some disagreement between reaction measurements and trap measurements, before. Our new value is consistent with the value obtained by trap experiments and resolved the discrepancy. [10] (See Fig. 2.3)

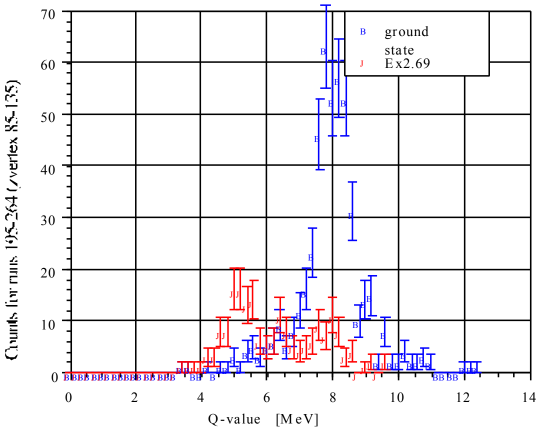


Fig. 2.2 The Q-value spectrum obtained by MAYA for ^{11}Li(p,t)^{9}Li reaction.

The differential cross sections are determined for the transitions to the ground state and the first excited state of ^{9}Li. The measured angular distribution is presented in Fig. 2.4. [11]

The cross section for transitions to the first excited state (Ex =2.69 MeV) is shown also in the figure. If this state were populated by a direct transfer, it would indicate that a 1^+ or 2^+ halo component is present in the ground state of ^{11}Li($3/2^-$), because the spin-parity of the ^{9}Li first excited state is $1/2^-$. This is a new information that has not yet been observed in any of previous investigations. A compound nucleus contribution should be small at the present energy, and in addition the angular distribution of compound decay should be essentially isotropic; hence the deep minimum and the peak observed in the angular distributions of the ground state and the first excited state indicate a limited compound nucleus contribution. However, before drawing a final conclusion as to the reaction mechanism can be made, detailed studies of coupled channels and sequential transfer effects need to be undertaken.

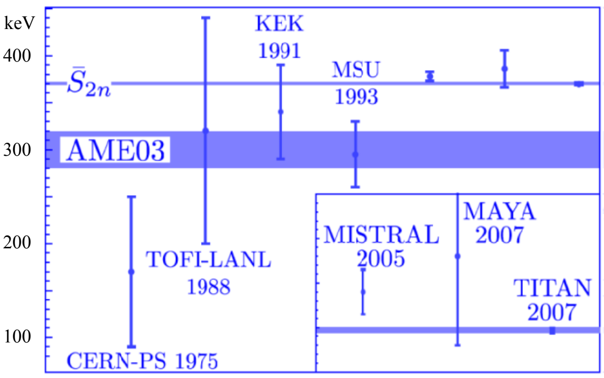


Fig. 2.3 Mass of ^{11}Li determined by different experiments.

Multistep transfer calculations to determine the differential cross sections to the ground state of ^{9}Li have been made. For these calculations several of the three-body models from Ref.[312], recalculated using the hyperspherical harmonic expansions [13] with projection operators to remove the $0s_{1/2}$ and $0p_{3/2}$ Pauli blocked states, have been used. In particular, the P0, P2 and P3 models from [12], which have percentage $(1s_{1/2})^2$ components of 3%, 31% and 45%, respectively were used. The corresponding matter radii for ^{11}Li are 3.05, 3.39 and 3.64 fm. For comparison, a simple $(p_{1/2})^2$ model based on the P0 case, but with no n-n potential to correlate the neutrons, was also investigated. All models here do not include an excitation of ^{9}Li core.

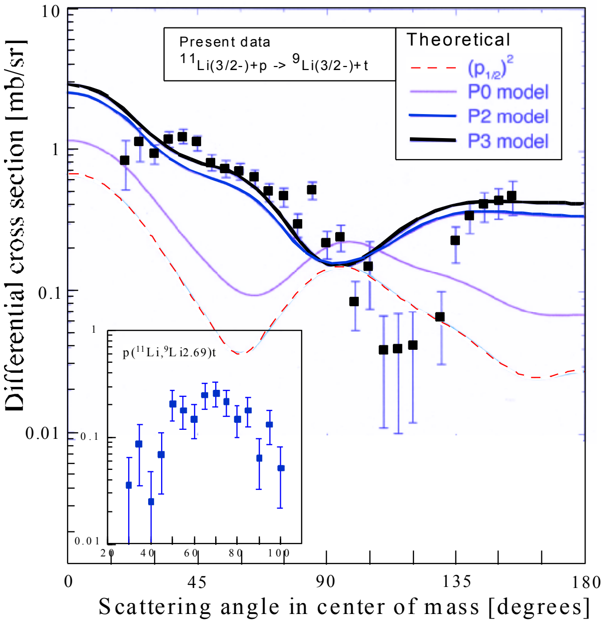


Fig. 2.4 Differential cross sections of (p,t) reaction to the ground state of ^{9}Li and to the first excited state (insert). Theoretical predictions using four different wave functions were shown by curves. See text for the difference of the wave functions.

The calculations reported here included the simultaneous transfer of two neutrons from ^{11}Li to ^{9}Li in a one step process, as well as coherently the two-step sequential transfers via ^{10}Li. The simultaneous transfers used a triton wavefuction calculated in the hyperspherical framework with the SSC(C) nucleon-nucleon force [14], and a three-body force to obtain the correct triton binding energy. The sequential transfers passed through both $1/2^+$ and $1/2^-$ neutron states of ^{10}Li, with spectroscopic factors given by respectively the s- and p-wave occupation probabilities for ^{11}Li models of [12]. The spectroscopic amplitudes for <d|t> and <^{10}Li|^{11}Li> include a factor of $\sqrt{2}$ to describe the doubled probability when either one of the two neutrons can be transferred. S and P wave radial states were used with effective binding energies of 1.0 and 0.10 MeV respectively; this ensured a rms radii of ~ 6 fm, which is the mean n-^{9}Li distance in the ^{11}Li models. The differential cross sections were obtained using the FRESCO code. [15]

Curves in Fig. 2.4 show the results of the calculations. The wave function $(p_{1/2})^2$ with no n-n correlation gives very small cross sections that are far from the measured values. Also the P0 wave function, with n-n correlation but with a small $(s_{1/2})^2$ mixing amplitude, gives too small cross sections. The results of the P2 and P3 wave functions fit the forward angle data reasonably well but the fitting near the minimum of the cross section is unsatisfactory. The results may be sensitive to the choice of the optical potentials as well as the selection of the intermediate states of two-step processes. Detailed analysis of such effects should be a subject of future studies.

In summary, transitions were observed to the ground and first excited state of ^{9}Li. Multistep transfer calculations were applied with different wave functions of ^{11}Li. It is seen that wave functions with strong mixing of p and s neutrons which includes three-body correlations, provides the best fit to the data for the magnitude of the reaction cross section. However the fitting to the angular shape is less satisfactory. The population of the first excited state of ^{9}Li suggests a 1^+ or 2^+ configuration of the halo neutrons. This shows that a two-nucleon transfer reaction as studied here may give a new insight in the halo structure of ^{11}Li. Further studies clearly are necessary to understand the observed cross sections as well as the correlation between the two-halo neutrons.

The energy of beam in this experiment is not around a few 10 MeV that is commonly believed to be best for DWBA analysis. The use of active target opens the possibility of the studies in other fragmentation RNB facility also. At RCNP in Osaka university, a fragment separator type RNB facility, EN course, is suitable for such studies at 20-30*A* MeV. This RNB separator has unique operation method compared with separaters in other places such as RIKEN, GANIL, and MSU. All of other separator use a wedge degrader to obtain the achromatic condition at the secondary target. It is a convenient and handy method to apply. However the magnification of the beam size at the secondary target increases when a thick degrader is used to obtain a low energy beam. Therefore the intensity of low energy beams in such facility is weak and thus a transfer reaction measurement is difficult in such a facilities.

The RCNP separator uses an uniform degrader in the separator. (Fig. 2.5) The adjustment of the achromatism at the secondary target requires a tuning of the dispersion of the magnet for each thickness of the degrader and so the adjustment is not as simple as a wedge degrader system. However an uniform degrader provides a constant magnification of the beam size independent of the thickness of a degrader. Therefore it is suitable to deliver a lower energy beams of 20-30*A* MeV. Several experiments of transfer reactions of neutron rich nuclei are in progress.

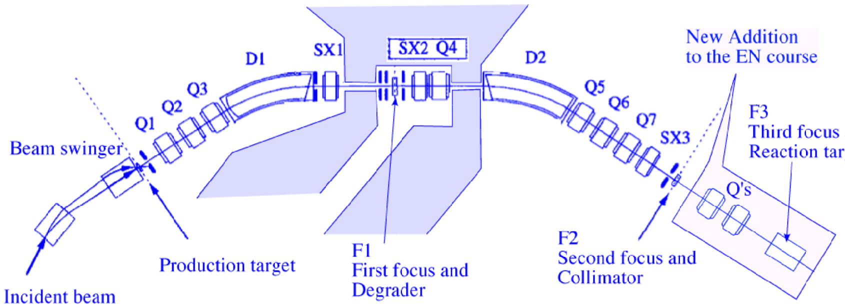


Fig. 2.5 The RCNP RNB separator suitable for the transfer reaction studies.

2.2 Direct observation of the tensor forces in high momentum components

As already mentioned, the importance of the tensor forces is clear; It is also a main component in nucleon-nucleon interactions. However except for very light nuclei, the tensor forces are incorporated only as perturbation effects in nuclear models. A direct experimental evidence of the tensor forces is not available. How can we study the specific effect of the tensor interactions on the nuclear structure experimentally?

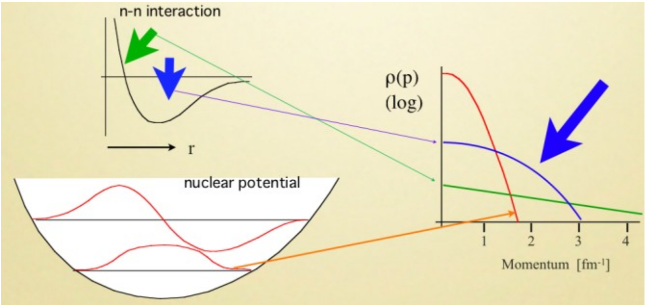


Fig. 2.6 The internal momentum distribution of nucleons for different component of wave functions.

The tensor forces in nucleon-nucleon interactions are generated by the pion exchange. It therefore has specific range that is longer than the short range core of nucleon-nucleon interaction and shorter than the size of nuclear potentials. It therefore has amplitude of this specific size or its conjugate momentum. (See Fig. 2. 6) The momentum distribution of nucleons inside the nucleus may have considerable amplitude at this specific momentum near 2 fm^{-1}.

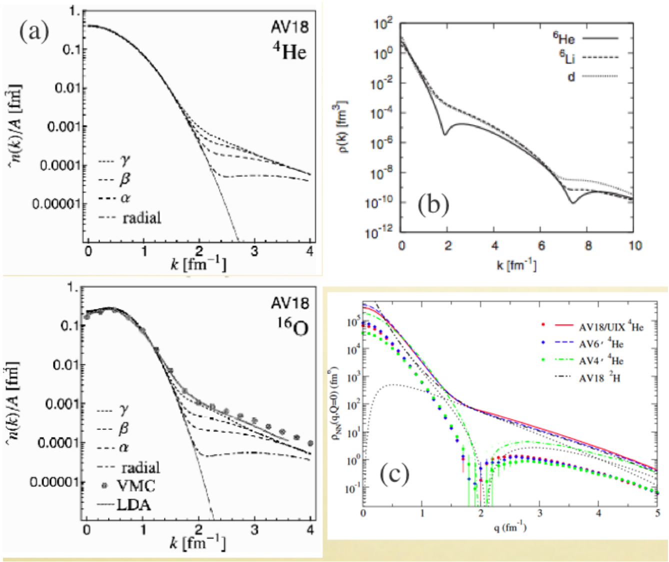


Fig. 2.7 The momentum distributions of nucleons by (a) UCOM [16], (b) Cluster shell model[17], and (c) VMC[18].

Several theoretical calculations of the momentum distribution have been reported as shown in Fig. 2.7. All calculations show the enhancement of the momentum distribution near 2 fm^{-1} and specifically for the nucleons in p-n pair. Therefore observation of such enhancement in nucleon momentum distribution would be a good direct evidence of the tensor interactions in nuclei. Detection of a high-momentum component is not easy in usual reaction such as (p, 2p) reaction at high momentum transfer. It is directly sensitive to the momentum distribution of internal nucleon but sensitive to all of the nucleon either small internal momentum or large internal momentum, where small momentum contribution is orders of magnitude larger. In such a condition rescattering effects of low momentum components may mix into the region of high momentum and thus difficult to isolate the high-momentum component.

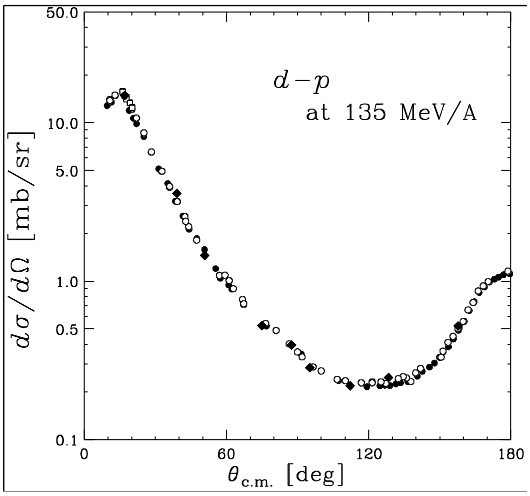


Fig. 2.8 Differential cross section of p-d elastic scattering. [19]

One of nucleon transfer reaction (p, d) is a appropriate reaction to study the high momentum nucleons. Let us see the reason why it is good. Figure 2.8 shows the differential cross section of p-d elastic scattering. The cross section falls off quickly for large momentum transfer at cm angles smaller than 120 degrees. However the cross section again increases for larger angles than 120 degrees. This part of the cross section is due to an exchange reaction as shown in Fig. 2.9 namely a pick up of the neutron in the target deuteron by an incident proton. Because of the momentum matching, only a high-momentum neutron that has momentum **P**= **P**$_d$ -**P**$_p$ is picked up. Where **P**$_d$ is the momentum of the out going deuteron and **P**$_p$ is the momentum of the incident proton. The impulse approximation give that the cross section of this pick up reaction to be,

$$\sigma_F = K \frac{P_d}{P_p} N(P_F) \left[\varepsilon_D + \frac{\hbar^2}{M} (\mathbf{P}_p - \mathbf{P}_d / 2)^2 \right]^2 \left| \left((r) \bullet e^{i(\mathbf{P}_p - \mathbf{P}_d \bullet r/2)} \right) \right|^2 .$$

As seen in the last term of the equation, the cross section is proportional to the square of the momentum component in the wave function φ(r) at momentum (**P**$_p$ - **P**$_d$•**r**)/2. The same is expected for (p, d) reaction at this momentum transfer domain.

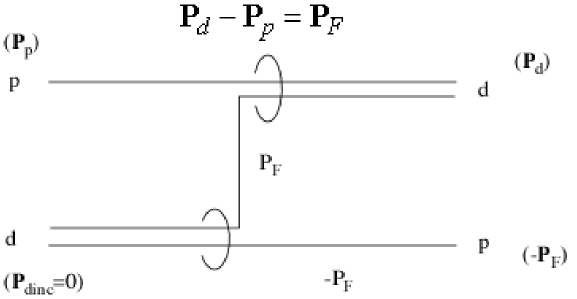


Fig. 2.9 The reaction mechanism of large angle scattering. The exchange of neutron.

In case of correlated nucleons in a nucleus, reactions may also go to other channels (p, pd) and (p, nd) for p-n pair and n-n pair, respectively. Those are cases where two nucleons were strongly correlated and running to the oposite direction in the nucleus. The partner of the picked up nucleon may come out from nucleus and thus making these quasi-free knock-out reactions. The advantage of these reaction is that one can distinguish the p-n pair for which the tensor correlation contribute and n-n pair for which the tensor correlation does not work. The momentum transfer (**P**$_p$ - **P**$_d$•**r**)/2 can be as high as 2 fm^{-1} when the incident proton energy is higher than several hundred MeV and one can map the momentum distribution of nucleons.

We have started such studies at RCNP using high resolution spectrometer Grand-RAIDEN with addition of recoil detectors for quasi-free scattering. Figure 2.10 shows the preliminary data of ^{16}O(p, d) scattering at 400 MeV proton incident energy and deuteron at 15 degrees, that is in the pick up reaction domain. Number of events are shown as a function of excitation energy of final state ^{15}O. An interesting phenomena is already seen. Ground state of ^{15}O is $1/2^-$ and is the $p_{1/2}$ hole state. The positive parity states in excited states are due to the single-particle excitation into sd shell. Therefore the excitation to the positive parity state in the direct pick up of neutron requires the sd shell admixture in the ^{16}O ground state. The transition to the ^{15}O ground state is the pick up of a $p_{1/2}$ neutron from the last single particle orbital in ^{16}O. A strong transition to the $3/2^-$ state is also seen, which is due to the pick up of $p_{3/2}$ neutron.

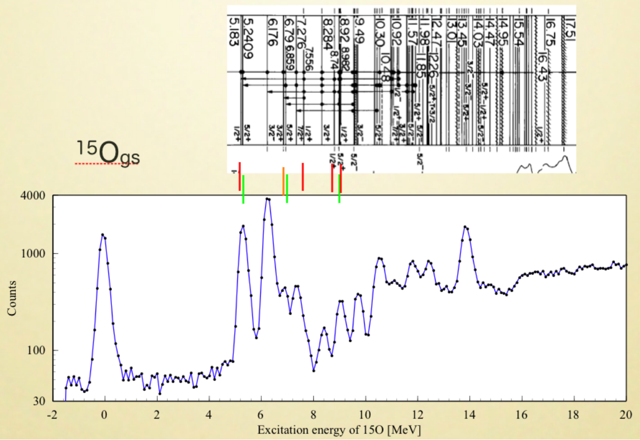


Fig. 2.10 Excitation yield of ^{16}O(p.d) reaction at 400 MeV incident. (On line data, preliminary)

An interesting observation is that the $1/2^+$ state is strongly excited with almost same strength as the ground state. It is not excited as strong at lower energy like 180 MeV incident beam energy. As shown in Fig. 2.11 this state can be produced by a pick up of neutrons in $s_{1/2}$ when two-particle two-hole state is excited. This is the very excitation expected by the tensor interactions. It, therefore, suggests that the relative amplitude of this 2p-2h component is larger for higher nucleon momentum and consistent with the tensor interaction.

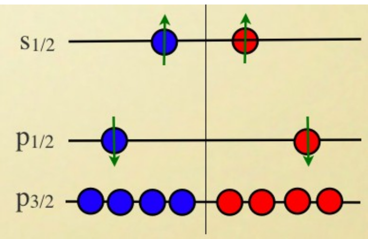


Fig. 2.11 The two-particle two-hole configuration in ^{16}O excited by the tensor interactions.

We definitely need a detailed analysis of the cross section and careful theoretical analysis before obtaining the conclusion.

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