Contribution of central and non-central components of N-N force in monopole elements

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In large-scale shell-model calculations, the monopole component of the Hamiltonian is an important ingredient for the study of the ground and excited states of nuclei. It sets the scale for excitation energies and plays a vital role in determining the evolution of shell-gap in the series of isotopes and isotones. The monopole contribution can be magnified as moving along the nuclear chart by changing the number of nucleons in the valence space, this highlight the physics of exotic nuclei compared to that of stable nuclei. It has been observed that the energies of nucleon orbit the "Single particle state" shifts as nuclei are farther from the region of stability and gaps between orbitals becomes larger or smaller in nuclei depending on the number of neutrons and protons available in valence space. The large value of spherical gap obtained from monopole gives the prerequisite knowledge of certain magic numbers and small spherical gap may be a route to the formation of deformed nuclei. This robust features of the monopole component generate keen interest to examine its behavior in light mass and heavy mass region. Interestingly, the particular component of the N-N interaction has prepotent role for the appearance or disappearance of magic numbers. To find the contribution of internal components of the nucleon-nucleon(N-N) force to the monopole, we examine the individual force centroids ($V_{jj'}^{\rho\rho'}$) or an angular momentum averaged two body matrix elements(TBME's).

$$V_{jj'}^{\rho\rho'} = \frac{\sum_J (2J+1) < jj'|V|jj' >_J (1+(-1)^J \delta_{jj'}\delta_{\rho\rho'})}{((2J+1)(2j'+1-\delta_{jj'}\delta_{\rho\rho'})}$$

where j, j' is the neutron and proton orbitals and ρ, ρ' is the type of particles.

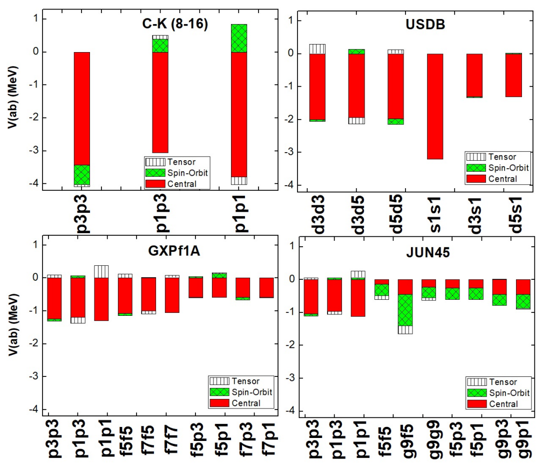

FIG. 1: Neutron-proton centroids ($V_{jj'}^{\nu\pi}$) for the central,spin-orbit and tensor part of the effective interactions CK(8-16),USDB, GXPf1A and JUN45 are plotted.

For the comprehensive study in light mass region and heavy mass region, we perform the calculation for the effective interactions CK (8-16), USDB, GXPf1A and JUN45 of the valence space p, sd, pf and pfg respectively [1]. The TBME's of central and non-central (spin-orbit and tensor) components are obtained from decomposing the TBME's of effective interactions by known spin-tensor decomposition technique[2]. The neutron-proton ($\nu\pi$) and neutron-neutron ($\nu\nu$) or proton-proton ($\pi\pi$) centroids ($V_{jj'}^{T=1}$) for the central, spin-orbit and tensor force of aforesaid interactions are shown in fig.1 and fig.2 respectively. The $V_{jj'}^{\nu\pi}$ centroids change significantly from $V_{jj'}^{T=1}$ centroids, plays a major role in monopole and shell evolution.

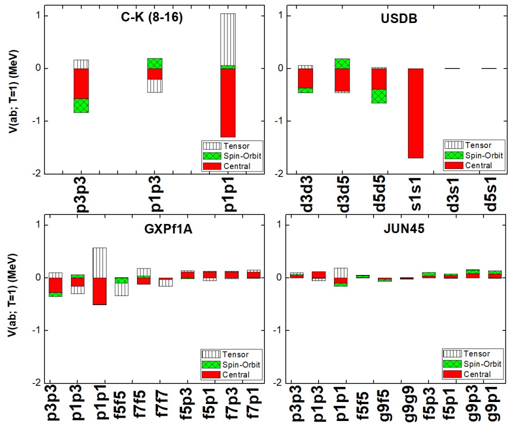

FIG. 2: Neutron-neutron or proton-proton centroids ($V_{jj'}^{T=1}$) for the central,spin-orbit and tensor part of the effective interactions CK(8-16),USDB, GXPf1A and JUN45 are plotted. scale of fig.2 is different from fig.1.

The central force has dominating monopole contribution for all employed interactions except some centroids of JUN45. The strength of central force is decreasing as we go from p-shell to pfg-shell, this may because of the increase of model space. The central strength is decreasing for high $'l'$ spin-orbit partners. i.e. spin-orbit partners ($p_{3/2}$, $p_{1/2}$) has more strength than the spin-orbit partners ($d_{3/2}$, $d_{5/2}$) and ($f_{5/2}$, $f_{7/2}$) of USDB and GXPf1A respectively. The central centroids of spin-orbit partners having same node ($V_{p3p3}^{\nu\pi}$, $V_{p3p1}^{\nu\pi}$ and $V_{p1p1}^{\nu\pi}$),($V_{d5d5}^{\nu\pi}$, $V_{d5d3}^{\nu\pi}$ and $V_{d3d3}^{\nu\pi}$), ($V_{p3p3}^{\nu\pi}$, $V_{p1p1}^{\nu\pi}$, $V_{f5f5}^{\nu\pi}$ and $V_{f7f7}^{\nu\pi}$) and ($V_{p1p1}^{\nu\pi}$ and $V_{p3p3}^{\nu\pi}$) in p-shell, sd-shell, pf-shell and pfg-shell respectively have approximately same strength except ($V_{f5f5}^{\nu\pi}$ and $V_{g9g9}^{\nu\pi}$) in pfg -shell, this discrepancy may because of missing spin-orbit partner in this region. In addition, the central strength is same for the centroids of spin-orbit partners between different node ($V_{d5s1}^{\nu\pi}$, $V_{d3s1}^{\nu\pi}$), ($V_{f5p3}^{\nu\pi}$,$V_{f5p1}^{\nu\pi}$ $V_{f7p3}^{\nu\pi}$, $V_{f7p1}^{\nu\pi}$) and ($V_{g9p3}^{\nu\pi}$, $V_{g9p1}^{\nu\pi}$) in sd-shell, pf-shell and pfg-shell respectively. The centroids of different node ($V_{s1d3}^{\nu\pi}$ and $V_{s1d5}^{\nu\pi}$) and ($V_{f5p3}^{\nu\pi}$, $V_{f5p1}^{\nu\pi}$, $V_{f7p1}^{\nu\pi}$ and $V_{f7p3}^{\nu\pi}$) of sd-shell and pf-shell respectively have less strength than the centroids of having same node, in line with the observation made in Ref.[3].
Although the non-central force has very small contribution in monopole but its contribution is significant in determining the shell gap of spin-orbit partners. The strength of spin-orbit force decreases from p-shell to pf-shell, but again increases in pfg-shell and has very large value of centroid $V_{g9f5}^{\nu\pi}$. The spin-orbit force of high spin ($V_{p3p3}^{\nu\pi}$, $V_{d5d5}^{\nu\pi}$) are more attractive than of low spin partners ($V_{p1p1}^{\nu\pi}$, $V_{d3d3}^{\nu\pi}$). Apart from spin-orbit force, the tensor force is repulsive for the same kind($j_>, j_>^{'}$) or ($j_<, j_<^{'}$), whereas attractive for the different kind($j_>, j_<^{'}$) or ($j_<, j_>^{'}$) [4]. The tensor force centroids of same kind $V_{p1p1}^{\nu\pi}$,$V_{p3p3}^{\nu\pi}$,$V_{f5f5}^{\nu\pi}$, $V_{f7f7}^{\nu\pi}$ of pf-shell and $V_{d3d3}^{\nu\pi}$,$V_{d5d5}^{\nu\pi}$ of sd-shell is repulsive and have lower strength for high spin $V_{p3p3}^{\nu\pi}$,$V_{f7f7}^{\nu\pi}$, $V_{d5d5}^{\nu\pi}$ than low spin $V_{p1p1}^{\nu\pi}$,$V_{f5f5}^{\nu\pi}$, $V_{d3d3}^{\nu\pi}$ centroids of spin-orbit partners. The centroids of different kind $V_{p1p3}^{\nu\pi}$,$V_{f5f7}^{\nu\pi}$ of pf-shell and $V_{d3d5}^{\nu\pi}$ of sd-shell is attractive and have reversed nature from spin-orbit partners of same kind. it is indeed the tensor force which may be responsible for the shell gap of spin-orbit partners as it is highly dependent on the spin direction.

The most significant changes in monopoles comes from central force, but besides the central force, the contribution from non-central force in the evolution of shell gap, spin-orbit splitting, disappearance or appearance of known magic numbers and change of the ordering of orbits is important. The detailed discussion of relevant result will be presented during symposium.

References

[1] S. Cohen et al., Nucl. Phys. 73,1(1965); B. A. Brown et. al. PRC 74, 034315(2006); M. Homma et. al. PRC69, 034335(2004); M. Homma et. al. PRC 80, 064323(2009.
[2] M.W. Kirson, Phys.Lett. B. 47, 110 (1973)
[3] X.B.Wang and G X Dong, J. Phys. G: Nucl. Part. Phys. 42,125101(2015).
[4] T. Otsuka et. al.,PRL 95, 232502(2005)