Role of Isospin in Heavy and Neutron-rich Nuclei

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Historically, the concept of isospin has evolved from the simple observation that neutron and proton are identical to each other except for the Coulombic charge. Starting from this humble beginning, isospin has been developed into an important and useful tool both in nuclear as well as particle physics. In fact, it became fundamentally important and forms an important pillar on which high energy nuclear physics rests. The low energy nuclear physics always considered isospin as an add-on quantum number, which is cosmetic in nature. Also, one always considered it to be important for light mass nuclei where Coulomb effect is small. However, over the years, isospin in low energy nuclear physics has continued to grow and is now considered as an essential ingredient of any theory. This thesis concerns the purity and applicability of isospin in heavy mass nuclei and/or, neutron-rich systems.

Isospin purity and mixing has been studied over last several decades by using various models like the Fermi gas model, shell model, hydrodynamical model, microscopic models etc. Isospin mixing was first calculated in 1956, for N=Z light nuclei by using the Fermi gas model and shell model. Both the approaches give a small mixing for the light nuclei, which rises rapidly with increasing mass number along the N=Z line. In 1962, these calculations were further extended for heavy mass nuclei having N>Z and it was concluded that isospin impurity decreases by a factor of $2/(N\text{-}Z+2)$ with neutron excess. This idea, however, became the backbone of the calculations presented in this thesis.

We present direct experimental evidences for the purity of isospin in heavy mass nuclei from two different approaches.

In the first approach, the evidence comes from analyzing the relative yields of neutron-rich heavy fragments emitted in heavy ion (HI) induced fusion-fission reactions [1-3]. There are only two HI reactions namely, ^{208}Pb(^{18}O, f) and ^{238}U(^{18}O, f), where three data sets are available. The reason being that the experimental data for these two reactions provide the yields of all the even-even fragments with the precision of one unit of Z, N and A. These data sets give us the fission fragment distribution, partition wise, for a number of partitions. Since, all the fission fragments also have N>Z, we consider the isospin to be pure in these fragments and it should remain conserved during the fusion-fission process.

It is tricky to assign the total isospin T to a nucleus. The third component of isosin T_3 is always fixed for each nucleus and is given by $(N\text{-}Z)/2$. However, there is no simple prescription to assign T to a nuclear state. We take the help of, what we call, the Kelson's conjectures in assigning isospin T to fragment nuclei. According to these conjectures, the neutron emission in fission favors the formation of excited states with T>T_3 which leads to the formation of isobaric analog states (IAS) in the final fission fragments. Thus, we make three isobars corresponding to each mass number and assign the isospin T to be the maxium of three T_3 values for that particular mass number. By using the conservation of isospin argument in the fission process, we calculate the partitionwise fission fragment distribution. Our results match quite well with the experimental data for both the reactions. One thing must be noted that we have not considered any shell effects or presence of isomers into our calculations. These effects are responsible for several fine structures in fission fragment mass distribution. Our calculations are rather simple and reproduce the fission fragment mass distribution quite reasonably. This supports the idea that the isospin is a reasonably good quantum number in heavy nuclei having N>Z and is approximately conserved in the fusion-fission process.

We, further, apply the same idea to thermal neutron-induced fission, ^{245}Cm(n^{th}, f) [4]. We could find only one set of experimental data for this kind of reactions which gives information on partition wise fission fragment distribution. Since the heavy nuclei with $N>Z$ are involved in this case also, we can apply the concept of isospin conservation as we have done for heavy ion induced reactions. In this case, we have experimental data available for the light mass fragments in 18 partitions. However, we perform our calculations only for the even-even fragments in the present formalism. Therefore, we consider only nine partitions with even-even fragments. We calculate the partition wise relative yields of fission fragments. Again, we found a good agreement between our calculated values and experimental data which further provide an evidence for isospin purity in neutron-rich systems. We have also predicted the fragment mass distribution for the heavier fragments and also for the most symmetric partition, Cd-Cd.

In the second approach, we provide another empirical evidence of isospin conservation by looking at the effect of isospin on fission decay widths [5, 6]. In this work, we consider a pair of reactions forming the same CN, one having projectile with isospin $T=T_3=-1/2$ and the other having projectile with isospin $T=T_3=0$. We have experimental data of fission cross-sections available for three such pairs of reactions, ^{209}Bi(p, f) and ^{206}Pb(α, f) leading to CN ^{210}Po, ^{185}Re(p, f) and ^{182}W(α, f) leading to CN ^{186}Os, and ^{205}Tl(p, f) and ^{202}Hg(α, f) leading to CN ^{206}Pb. The CN in these two reactions is the same but will be formed in two isospin states. We calculate the fission branching ratios from these two different isospin states of CN for all the three combinations. The difference between the fission branching ratios from different isospin states leads us to conclude that there is a definite isospin dependence in fission. In 1977, it was observed that at lower energies, fissility of CN formed in (α, f) reaction is smaller than (p, f) reaction while at higher energies, the inverse inequality occurs. It was considered as an anomaly. This anomaly was tried to be explained by taking angular momentum into account, but it could not be resolved. We, further, consider the data of fissility available for four cases, ^{209}Bi(p, f) and ^{206}Pb(α, f) leading to CN ^{210}Po, ^{208}Pb(p, f) and ^{205}Tl(α, f) leading to CN ^{209}Bi, ^{206}Pb(p, f) and ^{203}Tl(α, f) leading to CN ^{207}Bi and ^{197}Au(p, f) and ^{194}Pt(α, f) leading to CN ^{198}Hg. We calculate the fission branching ratios for two different isospin states of the same CN. Quite large difference between the fission branching ratios, further, provides an empirical evidence of isospin dependence in fission. It may be noted that our formalism is valid only for the CN processes. Therefore, as non-CN processes start making dominant contribution with the increase in energy, the fission branching ratios start showing an unusual behavior and become negative. This marks the onset of the region where non-CN processes begin to dominate the picture. These results strongly suggest that the CN remembers the isospin during its formation.

From all the results, we may conclude that isospin is a good and useful quantum number in heavy and neutron-rich systems. Our formalism may also be improved by considering various structure effects like shell structure or presence of isomers. We have performed the calculations only for the even-even fragments. These can be further extended to odd-odd and odd-A nuclei. Further experimental data are a must to confirm the claim of isospin conservation.

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