Spin dependent NN-potential for heavy-ion collisions in classical approaches

Isha B. Desai, S. S. Godre*
Department of Physics, Veer Narmad South Gujarat University, Surat, - 395007, INDIA
* email: ssgodre@yahoo.com

Introduction

Within the classical microscopic approximation, Classical Molecular Dynamics (CMD) [1], and a 3-stage CMD [2, 3] approach have been used for calculating heavy-ion fusion cross-sections for weakly and strongly bound nuclei. The nucleon-nucleon (NN) potential between all the nucleons, the configuration of the nucleon positions in the nuclei in their ground state and specification of other initial conditions are taken as central inputs to the CMD and 3S-CMD approaches for simulation of heavy-ion collisions. Thus, proper ground state (GS) configurations of the colliding nuclei and the form of NN-potential are important in these approaches. In these approaches, nucleons have been taken as point particles without spin and a soft-core Gaussian form for the NN-potential.

Using the same potential parameters, however, not all the generated nuclei are reproduced with the ground-state properties which agree well with experiments from light to heavy mass region [4]. Specifically, even for the light nuclei when the set of potential parameters are adjusted in such a way that the ground state properties of ^{4}He match with the experiments then this parameter set gives BE of ^{2}H and ^{16}O which are overestimated by about 100% due to the lack of spin and angular momentum (*l*) dependent terms in the NN-potential and zero-point motion of the nucleons in the nuclei.

Calculational Details

To overcome first of the above difficulties and to construct more realistic nuclei which can be used in CMD simulation of heavy-ion collisions requires more realistic NN-interaction. Therefore, to construct more realistic nuclei with correct ground-state properties we introduce spin-dependent potential terms in the NN-potential with spin being taken as an addition parameter for nucleons in classical sense only.

Out of the four exchange forces, we have presently chosen Majorana exchange force which is attractive for all four combinations of spin and isospin terms [5] which is shown in eq.(1). Usual Coulomb potential between charge particles is also added.

$$V_N\left(r_{ij}\right) = V_{NN}\left(r_{ij}\right) + V_{ST}\left(r_{ij}\right) \quad \ldots \quad (1)$$

where,

$$V_{NN}\left(r_{ij}\right) = -V_0\left(1-\frac{C}{r_{ij}}\right)\exp\left(\frac{r_{ij}^2}{r_0^2}\right) \cdots \quad (A)$$

$$V_{ST}\left(r_{ij}\right) = -V_1\exp\left(\frac{r_{ij}^2}{r_1^2}\right)N_{ST} \cdots \quad (B)$$

Here, $N_{ST} = -\left(\bar{S}_1\cdot\bar{S}_2-1\right)\left(\bar{T}_1\cdot\bar{T}_2-1\right)$

In the above equation S_1, S_2 are spin parameters and T_1, T_2 are isospin parameters, which have four combinations depending on parallel and anti-parallel spin & isospin and are represented as N_{ST} are shown as below:

1) N_{ST} = -1.3125 for S=1, T=0
2) N_{ST} = -0.5625 for S=1, T=1
3) N_{ST} = -1.3125 for S=0, T=1
4) N_{ST} = -3.0625 for S=0, T=0

In the case of NN-potential without spin, potential parameter set (WS1: V_0 = 466 MeV, C = 2.16 fm and r_0 = 1.4 fm) are adjusted for ^{16}O such that its GS properties match well with the experimental data. Similarly, potential parameter set of spin dependent NN-potential with spin as a parameter are (PS1: V_0 = 4620 MeV, C = 2.38 fm, r_0 = 1.2 fm, V_1 = -10 MeV and r_1 = 1.6 fm) are also adjusted for ^{16}O.

GS properties of the constructed nuclei ^{2}H, ^{4}He and ^{16}O in a variational approach with modification of the code STATIC [1] are taken as an example to compare both the NN-potentials.

We have developed a model of assigning angular momentum (*l*) and spin distribution in shell model like scheme in spin dependent NN-potential such that nucleons in different (*l*) state are less attractive than in the same (*l*) state. For heavier nuclei it might improve generation of GS properties which match well with expt data.

Results and Discussion

We have modified multiplication factor of Majorana exchange force such that it approximately matches with BE and R_{rms} of ^{16}O. Using the same set of potential parameters as mentioned above, the GS properties of ^{2}H and ^{4}He are also generated as given in the table-1.

Table 1: Ground-state properties for NN-potential with spin and without spin.

	Without Spin (WS-1)		With Spin (PS-1)		Expt.	
	BE (MeV)	R_{rms} (fm)	BE (MeV)	R_{rms} (fm)	BE (MeV)	R_{rms} (fm)
^{2}H	-2.6	1.25	-3.1	1.29	-2.23	2.11
^{4}He	-15.1	1.53	-22.5	1.57	-28.3	1.69
^{16}O	-127.4	2.61	-127.6	2.83	-127.5	2.73

For ^{4}He, BE is underestimated by 46% without spin and it improves to 20% with inclusion of spin. For ^{2}H, BE is overestimated by 17% without spin while by 38% with spin and for R_{rms} both nuclei give better value with spin than without spin NN-potential wrt expt values.

As ^{2}H is weakly bound nucleus and tensor force is not included in NN-potential with spin, therefore, matching BE with expt data is little challenging compared to ^{4}He and ^{16}O, as shown in Table 1.

NN-potential without spin (WS1) is shown as black solid line in fig. 1. Four combinations of Majorana exchange force (N_{ST}) in spin dependent NN-potential is also shown in fig. 1. From the values of N_{ST} and fig.1 we can say that most combinations are more attractive than (WS1) without spin. Only one combination in which spin and isospin both are parallel is less attractive than (WS1) without spin. We have slightly adjusted the values N_{ST} in such a way that GS properties of ^{16}O approximately match with the experimental values.

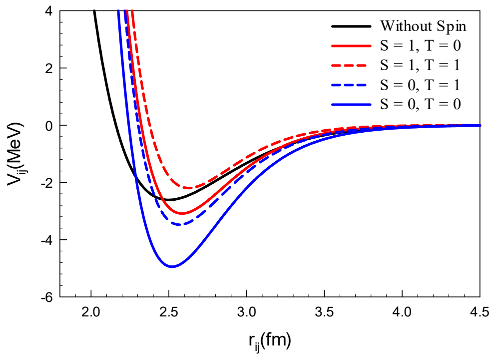

Fig. 1 Comparison of WS1 & PS1 NN-Potentials.

Conclusions

Using the above potential, a set of potential parameters are determined which simultaneously give good agreement with the experimental binding energy and rms radius for some of the light nuclei we have generated so far, i.e., ^{2}H, ^{4}He and ^{16}O nuclei. Higher mass nuclei are being constructed by assigning the angular momentum (*l*) quantum number as another parameter which is required in the Majorana exchange potential term. We expect the generated nuclei will have ground-state properties which are in better agreement with the experimental values as compared to those without the spin-dependent potential term. Inclusion of this spin dependent potential might give better description of the classical heavy-ion collision dynamics.

References

[1] S. S. Godre and Y. R. Waghmare, Phys. Rev. C **36**, 4 (1987)

[2] M. R. Morker, S. S. Godre, Proc. DAE Symp. on Nucl. Phys. **57**, 560 (2012)

[3] S. S. Godre, EPJ Web of Conf. **86**, 12 (2015)

[4] I. B. Desai and S. S. Godre, Proc. Int. DAE Symp. on Nucl. Phys. **54**, 196 (2009)

[5] P. Ring & P. Schuck, The Nuclear Many-Body Problem, Springer-Verlag New York In., (1980).