Breaking of Charge Independence of Nucleon-Nucleon Interaction and Bulk Properties of Nuclear Matter

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Abstract

The effects of charge independence breaking of nucleon-nucleon interaction on the bulk properties of nuclear matter are investigated. Our results indicate that at high densities, the inclusion of charge dependence in the nucleon-nucleon potential affects the bulk properties of nuclear matter. However, at low densities, this effect is not considerable. It is seen that the change of our results for the nuclear matter calculations due to the breaking of the charge independence increases by increasing density. It is shown that the energy contribution of the $^1S_0$ channel is sensitive to considering the charge dependence in the nucleon-nucleon interaction. It is indicated that the effects of charge independence breaking on the calculated equation of state of nuclear matter are ignorable.
1 Introduction

Nuclear matter is defined as an uniform system of interacting nucleons (we will consider equal number of neutrons and protons) without electromagnetic interactions. This is a good approximation for the conditions in the interior of a heavy nucleus. The nuclear matter is characterized by its saturation density \( \rho = 0.17 \pm 0.02 \text{fm}^{-3} \) and energy per nucleon \( (E = -16 \pm 1 \text{MeV}) \).

A central problem in nuclear many-body theory is the calculation of properties of nuclear matter using realistic models of nucleon-nucleon potentials. Recently, several realistic potentials are constructed which accurately fit the proton-proton and neutron-proton scattering phase shifts. These potentials contain terms which break charge independence \[1, 2\].

Charge independence breaking of the nucleon-nucleon interaction means that, in the isospin \( T = 1 \) state, the proton-proton \((T_z = +1)\), neutron-proton \((T_z = 0)\), or neutron-neutron \((T_z = -1)\) interactions are different, after electromagnetic effects have been removed. This is well established in the \(^1S_0\) state for the scattering lengths, \( a \), and effective ranges, \( r \), \[2\],

\[
\begin{align*}
    a_{pp} &= -17.3 \pm 0.4 \text{fm}, & r_{pp} &= 2.85 \pm 0.04 \text{fm}, \\
    a_{nn} &= -18.8 \pm 0.3 \text{fm}, & r_{nn} &= 2.75 \pm 0.11 \text{fm}, \\
    a_{np} &= -23.75 \pm 0.01 \text{fm}, & r_{np} &= 2.75 \pm 0.05 \text{fm}.
\end{align*}
\]

The charge dependence of nucleon-nucleon interaction can also be inferred from binding energy differences of the mirror nuclei \[3, 4, 5\].

The major cause of charge independence breaking in the nucleon-nucleon interaction
is the mass difference between the charged and neutral pions [6],

\[ m_{\pi^0} = 134.977 \text{MeV}, \]
\[ m_{\pi^\pm} = 139.570 \text{MeV}. \]  (2)

The charge dependence of nucleon-nucleon interaction due to the pion mass difference has been calculated in references [7, 8]. Within QCD, the charge independence breaking of nucleon-nucleon interaction is of course due to the differences in the up and down quarks masses and charges [9, 10].

The aim of present work is the investigation of the effects of charge independence breaking of nucleon-nucleon interaction on the properties of nuclear matter by employing the Reid-93 potential [1] in our calculations.

2 Nuclear Matter Calculations

For the Reid-93 potential, the proton-proton (pp), neutron-neutron (nn), and neutron-proton (np) interactions are different. Therefore, this potential depends on \( T_z \). This shows that in our calculations, we should consider explicitly the isospin projection \( T_z \).

The procedure of the method used in our calculations is fully discussed in references [11, 12, 13, 14, 15, 16, 17].

In this section, we present the results of our calculations for the various properties of nuclear matter with inclusion of charge dependence in the nucleon-nucleon interaction and then, we investigate the charge independence breaking effects on our results. For this purpose, we employ the Reid-93 potential in our nuclear matter calculations in two different cases as below.

1. Charge dependent case (CD-Reid-93):
We distinguish between the $pp$, $nn$, and $np$ interactions [1].

2. Charge independent case (CI-Reid-93):

We replace the $pp$ and $nn$ interactions by the corresponding $np$ interaction [1]. This means that we identify the nucleon-nucleon interactions with the $np$ interaction and therefore, the charge dependence is removed.

Then, we compare the results of these cases.

Our results for the total energy of nuclear matter as a function of density with the CD-Reid-93 (charge dependent case) and CI-Reid-93 (charge independent case) potentials are given in Figure 1. It is seen that the inclusion of charge dependence in the nucleon-nucleon interaction changes the total energy of nuclear matter, especially at high densities. At low densities ($\rho < 0.2\, fm^{-3}$), this effect is small. In order to clarify how the charge independence breaking (CIB) of nucleon-nucleon interaction affects the total energy of nuclear matter, we calculate the difference between our results for the charge dependent (CD) and charge independent (CI) cases,

$$\Delta E_{CIB} = E_{CD} - E_{CI}. \quad (3)$$

These results are presented in Table 1. We see that the change of total energy of nuclear matter due to the breaking of the charge independence increases by increasing density. In Figure 1, the results of EHMMP calculations with the Reid-93 potential [18] are also given for comparison. There is a good agreement between our results and those of EHMMP [18], especially at high densities.

In Table 2, the results of our calculations for the saturation density $\rho_0$, energy $E(\rho_0)$, and incompressibility $K_0$ of nuclear matter in the charge dependent case are compared with those of charge independent case and also with the results of EHMMP [18] and MPM
[19]. We see that for the saturation properies of nuclear matter, the inclusion of charge
dependence is a small effect. We also see that our results agree with the results of others.

We know that the contribution of one-body energy to the total energy of nuclear
matter is independent of the nucleon-nucleon interaction. Therefore, we investigate the
effects of charge independence breaking on the contribution of the potential energy of
various channels to the total energy. The contribution of the $^3S_1 - ^3D_1$ and $^1S_0$ channels
to the potential energy are plotted versus density in Figures 2 and 3, respectively. It
is seen that the $^3S_1 - ^3D_1$ energy contribution in both cases of charge dependent and
charge independent are identical. However, a significant difference is seen for the energy
contribution of the $^1S_0$ channel in those cases. This difference increases by increasing
density. It is also seen that the change of the energy of $^1S_0$ channel due to the inclusion of
charge dependence is repulsive. This shows that in the channel with isospin $T = 1$, the $np$
interaction is more attractive than the corresponding $pp$ and $nn$ interactions. The total
potential energy of nuclear matter in the charge dependent and charge independent cases
are shown in Figure 4. We see that at high densities, the charge independence breaking
of nucleon-nucleon interaction affects the potential energy of nuclear matter. But, at low
densities, this effect is negligible. The results of EHMMP with the Reid-93 potential [18]
are also shown in Figure 4. It is seen that our results are in a good agreement with those
of EHMMP [18].

The equation of state of nuclear matter is one of the most importance in astrophysics
and heavy-ion collisions. Our results for the equation of state of nuclear matter are given
in Figure 5. It can be seen that the results of charge dependent and charge independent
cases are nearly identical.
3 Summary and Conclusion

The calculation of properties of nuclear matter using a realistic nucleon-nucleon potential contained the charge dependence is of special interest in the nuclear many-body theory. In this article, we have calculated the various properties of nuclear matter such as the energy, saturation properties, and equation of state using the charge dependent Reid-93 potential. At high densities, a significant difference between our results for the energy of nuclear matter in the case of employing charge dependent nucleon-nucleon interaction and those of charge independent nucleon-nucleon interaction was observed. However, at low densities, this difference is small. This indicates that at high densities, the effects of charge independence breaking of nucleon-nucleon interaction on the properties of nuclear matter are considerable. It was seen that the energy contribution of the $^1S_0$ channel is considerably varied by inclusion of charge dependence in the nucleon-nucleon interaction, especially at high densities. It was shown that the change in the equation of state of nuclear matter due to the charge independence breaking is negligible. Finally, the agreement between our results and those of others was shown.

4 Acknowledgment

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Table 1: The change of total energy of nuclear matter due to the breaking of charge independence of nucleon-nucleon interaction as a function of density.

| $\rho (fm^{-3})$ | 0.05 | 0.1  | 0.2  | 0.3  | 0.4  | 0.5  | 0.6  |
|------------------|------|------|------|------|------|------|------|
| $\Delta E_{CIB}$ | 0.0823 | 0.1416 | 0.2773 | 0.4243 | 0.5684 | 0.7061 | 0.8207 |

Table 2: The saturation properties of nuclear matter in the cases of charge dependent (CD) and charge independent (CI). The results of EHMMP [18] and MPM [19] are given for comparison.

|          | $\rho_0 (fm^{-3})$ | $E(\rho_0)(MeV)$ | $K_0(MeV)$ |
|----------|---------------------|-------------------|------------|
| CD       | 0.272               | -13.81            | 224        |
| CI       | 0.277               | -14.08            | 233        |
| EHMMP    | 0.252               | -14.45            | —          |
| MPM      | 0.271               | -15.61            | —          |

Figure 1: The total energy of nuclear matter versus density in the charge dependent (full curve) and charge independent (dotted curve) cases. The results of EHMMP [18] (Dashed curve) are given for comparison.

Figure 2: As Figure 1 but for the $^3S_1 - ^3D_1$ energy contribution.

Figure 3: As Figure 1 but for the $^1S_0$ energy contribution.

Figure 4: As Figure 1 but for the total potential energy.

Figure 5: As Figure 1 but for the equation of state.
Potential Energy (MeV) vs. $\rho$ ($fm^{-3}$)
