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Plasma Shielding Effects On Nuclear Spectra: ^{18}Ne Application

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Abstract. In this study, the changes in the excited states of atomic nuclei in the plasma environment were investigated. Relevant interactions in plasma environments are illustrated by the more general exponential cosine scanned Coulomb (MGECSC) potential. Plasma effects on the single particle energy state and its effects on excited energy levels are investigated. For this purpose, single particle energy values were obtained by considering the modified Woods-Saxon potential due to the shielding effect of the plasma medium.

1 Introduction

The plasma medium is a very complex medium containing ionized gases, electrons, excited atoms, molecules and free radicals [1]. The most general classification of these is Debye and quantum plasma [2, 3]. Due to the shielding effect of plasma, the atomic systems in it are quite different from the atomic systems without plasma [4, 5]. In exciting atomic systems, the most suitable medium for radiation is the plasma medium. The effective potential that models the interaction in the core can be changed by modifications of the plasma shielding parameters. For the nucleus, the Coulomb interaction in the effective potential model is modified due to the plasma environment, and the more general exponential cosine scanning Coulomb (MGECSC) potential is considered due to the plasma shielding effect.

The effects of the plasma environment on the excited nuclear energy levels of the nucleus have not been studied before. Nuclear shell model calculations were used in this study for this purpose. As is known, the interaction between the nucleus and the valence nucleons provides the single-particle energy to be obtained [6, 7]. To explore the possible effects of plasma on nuclear energy levels, we focused on the plasma shielding of these interactions. Proton single-particle energy levels obtained using the Wood-Saxon potential were found to be sensitive to plasma shielding parameters (λ, a and b), and the localization of the levels of these single-particle energies to be used in shell model calculations were changed. In our shell model calculations, ^{16}O nucleus is assumed to be the inert core, and the active particles are assumed to be dispersed in $d5/2$, $s1/2$, and $d3/2$ single-particle orbits. The current and well-established USDB Hamiltonian [8] used in the shell model calculations is taken into account. As a result of replacing the Wood-Saxon potential with the plasma effects of the Coulomb term, plasma-dependent proton single particle energy values are obtained. Systematic calculations were made for the low energy levels of the ^{18}Ne isotope using different plasma-shielding parameters.

2 Materials and Method

The MGECSC potential is modelled the potential energy between two protons in ^{18}Ne nucleus, and given by Eq. (1) as [9–11]

$$V_{MGECSC}(r) = \frac{e^2}{r}(1 + br)\exp(-r/\lambda)\cos(ar/\lambda), \tag{1}$$

where e is the positive electron charge, a, b and λ are the plasma shielding parameters. While $a = 0$ case in MGECSC potential models the interactions in Debye plasma, a not equal 0 case is for the interactions in quantum plasma [12, 13].

The single-particle energies can be specified by allowing a central potential such as the harmonic oscillator, the Wood-Saxon, or the Yukawa-type potentials. Wood-Saxon potential is one of the appropriate choices for single-particle potential, which in turn provides a model for the necessary properties of the bound state and the continuous single-particle wave functions. In order to compute the single-particle energies, we have used WSPOT computer code developed by Brown [14]. Wood-Saxon parameters have been adjusted to give single-particle energies in USDB Hamiltonian for shell-model calculations as close as possible. The modification of the single-particle energies and two-body interaction matrix elements in SM calculations for proton-rich nuclei in the sd-shell has recently been proposed (USDB*) [15], and it has been found to give better results for ^{18}Ne compared to existing USDB Hamiltonian [16]. Accordingly, the related numerical parameters without plasma has been determined as $V_0 = -57.32$ MeV, $V_1 = -22.30$ MeV, $V_{so} = 18.765$ MeV, $r_0 = r_{so} = 1.2753$ fm, $a_0 = a_{so} = 1.0$ fm and $r_c = 1.275$ fm. The single-particle energy values obtained by using these parameters in the Wood-Saxon potential were calculated as 2.111, -3.207 and -3.927 MeV for $d3/2$, $s1/2$ and $d5/2$ orbitals, respectively, which is almost the same as ones used in USDB Hamiltonian. The total effective potential for the system is given below by Eq. (2).

$$U_{\text{eff}}(r) = \frac{V_0}{(1 + \frac{\exp(r - R_0)}{a_0})} + \frac{1}{r}\frac{d}{dr}\frac{V_{s0}}{(1 + \frac{\exp(r - R_{s0})}{a_{s0}})} \times \vec{\ell} \cdot \vec{s} + V_{\text{MGECSC}}(r)\,. \tag{2}$$

For the shell-model calculations, the well-known Hamiltonian, being ϵ_i values are the single-particle energy that is the interaction of the core nucleus with the valance nucleons, can be written in the following form in Eq. (3):

$$H = \sum_{ij}^{A} \epsilon_i a_i^+ a_j + \frac{1}{4} \sum_{ijkl}^{A} \langle ij \mid V \mid kl \rangle a_i^+ a_j^+ a_k a_l \, . \qquad (3)$$

The obtained single-particle energies are systematically used in USDB Hamiltonian, and then the excited nuclear energy levels of ^{18}Ne nucleus are computed by using nuclear shell-model. For the calculations, KShell [15] computer code has been used.

3 Results and Discussion

The physical observables of ^{18}Ne nucleus embedded in quantum plasma environments exhibit different behaviors because of plasma shielding effect compared to plasma-free medium. Three plasma shielding parameters have an influence on these behaviors: λ, b and a. In the calculations, certain ranges are used for the numerical values of these shielding parameters as $\lambda = 5$–500 fm, $b = 0.01$–0.2 fm^{-1} and $a = 0.1$–13. In Figure 1a, the change of $d5/2$, $s1/2$ and

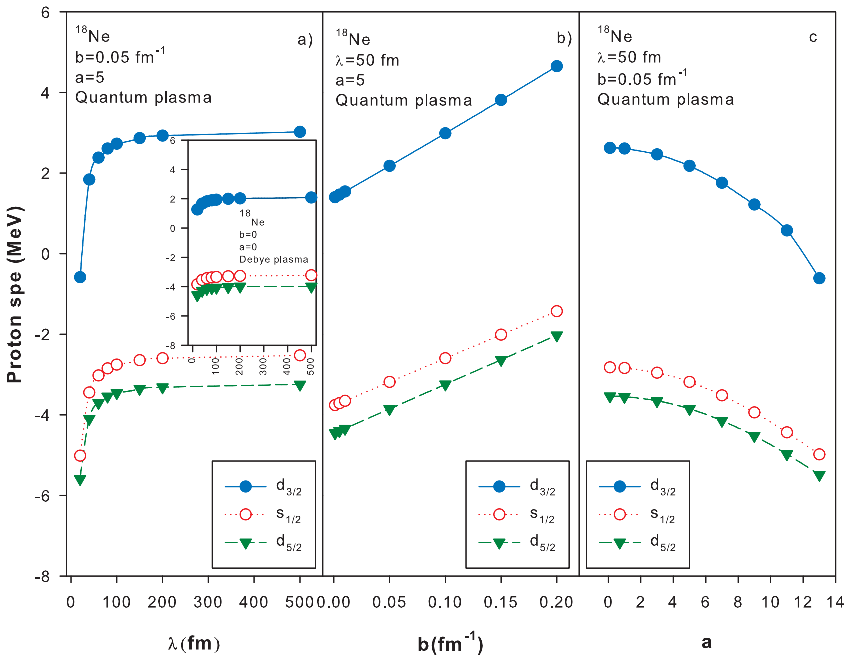

Figure 1. The change of the proton single-particle energy values of $d_{5/2}$, $s_{1/2}$ and $d_{3/2}$ levels in ^{18}Ne nucleus embedded in quantum plasma as a function of: a) λ (subfigure for Debye plasma); b) b; and c) a.

$d3/2$ levels for the proton single-particle energies of ^{18}Ne nucleus immersed in quantum plasma modeled by MGECSC potential with $a = 5$ and $b = 0.05$ fm^{-1} is presented as a function of lambda. As is seen in figure that the increment of lambda increases the proton single-particle energies dramatically to about 100 fm. The effective range of λ on the proton single-particle energy has been determined between 0 and 100 fm. In Figure 1b, the change of $d5/2$, $s1/2$ and $d3/2$ levels for the proton single-particle energy of ^{18}Ne nucleus immersed in quantum plasma modeled by MGECSC potential with $a = 5$ and $\lambda = 50$ fm is presented as a function of parameter b. As seen in the figure, the proton single-particle energies value linearly increases by increasing b. In Figure 1c, the change of $d5/2$, $s1/2$ and $d3/2$ levels for the proton single-particle energy of ^{18}Ne nucleus immersed in quantum plasma modeled by MGECSC potential with $\lambda = 50$ fm and $b = 0.05$ fm^{-1} is presented as a function of parameter a. As is seen in figure that the increment of a decreases the proton single-particle energies. However, unlike λ and b, the related increment versus larger values of a parameter tends to converge the $d5/2$–$s1/2$ levels closer to each other. Here it should be pointed out that it is evident that the effects of plasma shielding parameters on the proton single-particle energy values will indirectly cause shifts in the ground state and excited states of the nucleus.

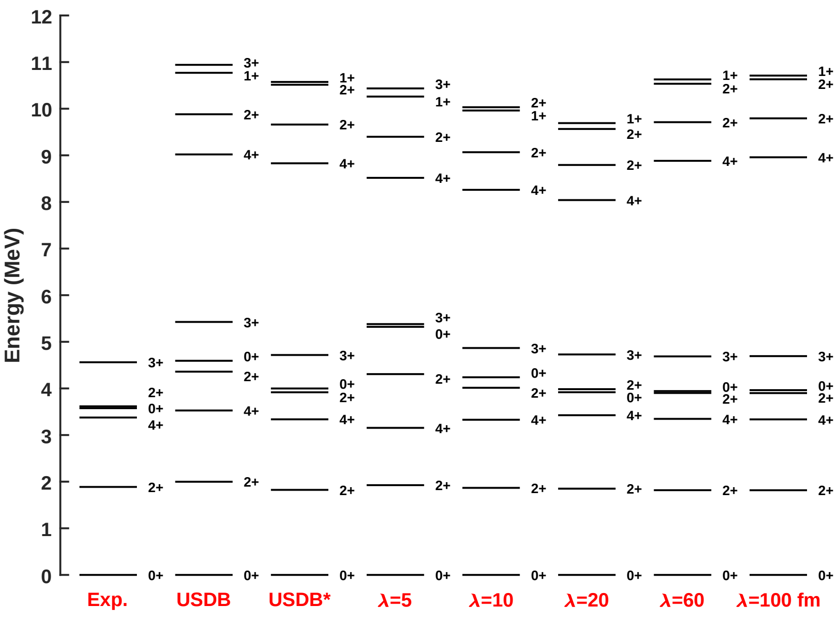

Figure 2. For different λ-values, the evolution of the excited state energies computed through the nuclear shell model of ^{18}Ne nucleus, with USDB* interaction, embedded in quantum plasma modeled by MGECSC potential with $a = 5$ and $b = 0.05$ fm^{-1}.

In Figure 2, the excited state energies of ^{18}Ne nucleus embedded in quantum plasma depicted by MGECSC potential with $a = 5$ and $b = 0.05$ fm^{-1} are represented for different λ-values. As seen, results obtained by modified USDB* Hamiltonian for proton-rich nucleus region are closer to experimental excited energy levels compared to that of USDB. With the inclusion of the plasma effect, when considering the low energy spectrum obtained for $\lambda = 5$ fm, it is observed that while 2_1^+ level runs up a little, 4_1^+ level goes down. Also, it has been observed that, 2_2^+, 0_2^+ and 3_1^+ levels go up significantly. Contrary to the expectation that all low level energies are expected to decrease because the gse for $\lambda = 5$ fm is lower than in plasma-free case, it has been determined that the energy of many low-excited levels increases. At higher excited energy levels, although a decrease in energies is observed, the 2_4^+ level is not observed, and 3_2^+ level is appeared.

In Figure 3, the excited state energies of ^{18}Ne nucleus embedded in quantum plasma environment described by MGECSC potential with $\lambda = 50$ fm and $b = 0.05$ fm^{-1} are demonstrated for different a-values. As plasma begins to take effect, when examining the low energy spectra up to $a = 13$, it is observed that 2_1^+ level enhances by 30 keV while the enhancement of 4_1^+ level is by 121 keV. Also, with the 2_2^+ level runs up by 81 keV and the 0_2^+ level falls

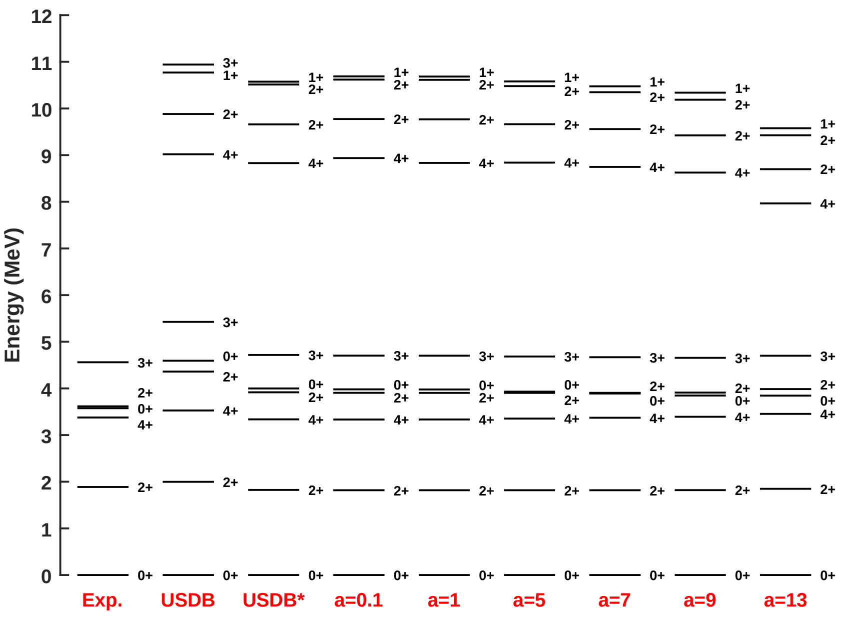

Figure 3. For different a-values, the evolution of the excited state energies computed through the nuclear shell model of ^{18}Ne nucleus, with USDB* interaction, embedded in quantum plasma environment modeled by MGECSC potential with $\lambda = 50$ fm and $b = 0.05$ fm^{-1}.

down by 135 keV, these levels were replaced at $a = 7$. When examining 3_1^+ level, it is observed that it shifts down by 56 keV up to $a = 11$ and then localizes to its first level at $a = 13$. As a result of the increase in quantum effects and reaching the value of $a = 13$, it is seen that the shift in low energy levels become clear and all levels enhance noticeably. At higher excited energy levels, all levels shift up with the onset of plasma effects.

In Figure 4, the excited-state energies of ^{18}Ne nucleus embedded in quantum plasma environment portrayed by MGECSC potential with $\lambda = 50$ fm and $a = 5$ are furnished for different b-values. With the onset of plasma effects, for $b = 0.001$ fm^{-1}, while all low energy states except 0_2^+ level from 2_1^+, 4_1^+, 2_2^+, 0_2^+ and 3_1^+ levels escalate very little, 0_2^+ level catches the 2_2^+ by falling down a little. As result of the increment of plasma effects by increasing b parameter, a slight downward shift in all levels except from 4_1^+ level is observed. While the 4_1^+ level does not shift at all, the 2_1^+, 2_2^+, 0_2^+ and 3_1^+ levels shift down by 40, 91, 206, and 137 keV. As well as these shifts, the 0_2^+ level settles below the 2_2^+ level by $b = 0.1$ fm. When examining the high energy part of the spectra, with attacking of plasma effects at $b = 0.001$ fm^{-1}, all levels shift down remarkably. As a result of increasing the intensity of plasma effects by b parameter, these

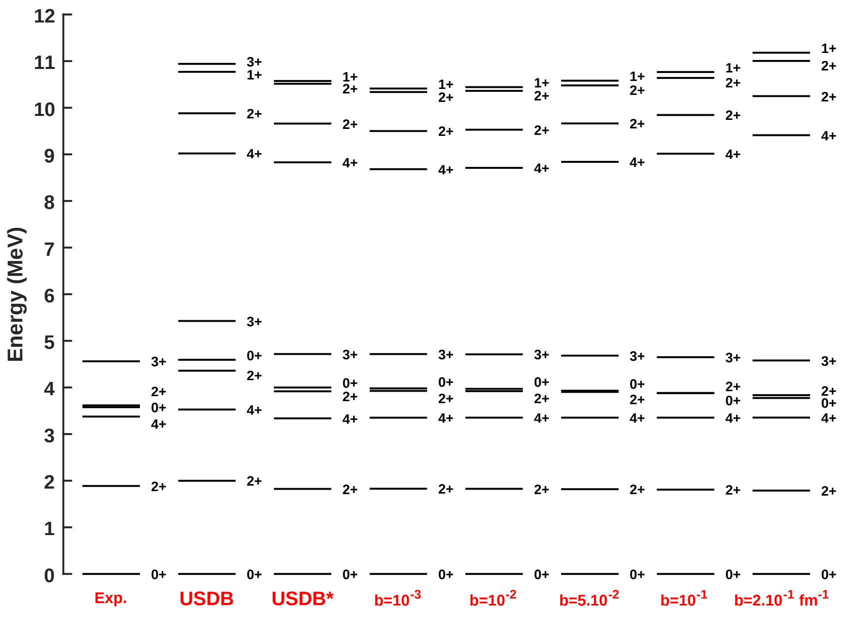

Figure 4. For different b-values, the evolution of the excited state energies computed through the nuclear shell model of ^{18}Ne nucleus, with USDB* interaction, embedded in quantum plasma environment modeled by MGECSC potential with $\lambda = 50$ fm and $a = 5$.

levels become to enhance ($\sim$ 700 keV) and the separation from the low excited region in the spectra is blatantly observed.

4 Conclusion

In this study, by considering ^{18}Ne nucleus embedded in quantum plasma, the effect on the nuclear excited energy levels are investigated. For this aim, the Coulomb interaction term in the Wood-Saxon potential has been modified due to the screening effect of the plasma. The Coulomb interaction between the ^{16}O inert core nucleus and the valance protons in ^{18}Ne nucleus is shielded by the plasma. As a result of this shielding effect to the system, the effective potential of the system changes. This change has affected the localizations of all nuclear levels, particularly the proton single-particle energies and energy levels. While the increment of λ and b parameters increases the proton single-particle energies, the increment of a parameter decreases.

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