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Dust ion acoustic waves propagation with degenerate ions and nonextensive electrons

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In this recent investigation we have studied the nonlinear wave propagation of dust-ion-acoustic (DIA) waves in an unmagnetized collisionless plasma system containing degenerate ions following only non-relativistic limits, nonextensive electrons, and negatively charged dust grains. This fluid model has been employed with the reductive perturbation method. The standard K-dV equation has been derived, and numerically examined. The basic features of the solitary waves (SWs) and shock waves (ShWs) are obtained from the solution of the K-dV and Burgers' equations. It has been found that depending on whether the parameter q and μ are less than or equal to (greater than) the critical value the DIA SWs and ShWs exhibit negative (positive) potentials by taking the effect of different plasma parameters in the plasma fluid into account. And because of the presence of coefficient of viscosity (η) the ShWs change the polarity. Dusty plasmas containing degenerate ions and nonextensive electrons with negative charged dust grains are the most interesting topics to the research which are only found in astrophysical objects like white dwarfs, black holes, neutron stars, etc. This analysis can be employed in understanding and treating the nature and the characteristics of DIA SWs and ShWs both in laboratory and space plasma.

I. INTRODUCTION

By now the study and analysis of the properties of dusty plasmas have become a popular and important topic of research. A particular field of study which has received a great deal of attention is that of dust-ion-acoustic (DIA) waves (e.g. DIA solitary and shock waves), and has been extensively studied both theoretically and experimentally. In this situation, the ion mass provides the inertia and the restoring force comes from the electron thermal pressure. The presence of DIA waves has been verified by the laboratory experiments [1, 2]. The linear properties of the DIA waves in an unmagnetized bounded [3, 4] plasma, as well as in magnetized [5] and inhomogeneous [6] dusty plasmas have also been studied. A number of authors have studied the DIA solitary waves (SWs) [7, 8] by using the dusty plasma model consisting of negatively charged static dust and single-temperature-electrons as well as ions. These SWs [9, 10] are formed due to delicate balance between nonlinearity and dispersion.

The electron-ion plasmas are thought to be generated naturally by pair production in high energy processes in the vicinity of several astrophysical objects as well as produced in laboratory plasmas experiments with a finite life time [11]. Because of the long life time of the positrons, most of the astrophysical [12] and laboratory plasmas become an admixture of electrons, positrons, and ions. It has also been shown that over a wide range of parameters, annihilation of electrons and positrons, which is the analog of recombination in plasma composed of ions and electrons, is relatively unimportant in classical, [13] as well as in dense quantum plasmas [14] to study the collective plasma oscillations. The ultradense degenerate electron positron plasmas with ions are believed to be found in compact astrophysical bodies like neutron stars and the inner layers of white dwarfs [14–17] as well as in intense laser-matter interaction experiments [18, 19]. Therefore, it seems important to study the influence of quantum effects on dense e-p-i plasmas. Several authors have theoretically investigated the collective effects in dense unmagnetized and magnetized e-p-i quantum plasmas under the assumption of low-phase velocity (in comparison with electron/positron Fermi velocity) [20–22]. In these studies, the authors have focused on the lower order quantum corrections appearing in the well known classical modes.

Now-a-days, a number of authors have become interested to study the properties of matter under extreme conditions [23–26]. Recently, a number of theoretical investigations have also been made of the nonlinear propagation of electrostatic waves in degenerate quantum plasma by a number of authors [27–29] etc. However, these investigations are based on the electron equation of state valid for the non-relativistic limit. Some investigations have been made of the nonlinear propagation of electrostatic waves in a degenerate dense plasma based on the degenerate electron equation of state valid for ultra-relativistic limit [30, 31].We are interested to study the dissipasion relation of the dust-ion-acoustic waves in a dusty plasma system where we added degenerate ion fluids [32–36], which is the most interesting elements of the astrophysical [37–41] The pressure for ion fluid can be given by the following equation

$$P_i = K_i n_i^{\alpha}, \tag{1}$$

where

$$\alpha = \frac{5}{3}; \quad K_i = \frac{3}{5}\left(\frac{\pi}{3}\right)^{\frac{1}{3}}\frac{\pi\hbar^2}{m} \simeq \frac{3}{5}\Lambda_c\hbar c, \tag{2}$$

for the non-relativistic limit [23–26] (where $\Lambda_c = \pi\hbar/mc = 1.2\times10^{-10}\ cm$, and $\hbar$ is the Planck constant divided by 2π).

Now-a-days, nonextensive [42] plasma has received a great deal of attention due to its wide relevance in

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in astrophysical and cosmological scenarios like stellar polytropes [43], hadronic matter and quark-gluon plasma [44], protoneutron stars [45], dark-matter halos [46] etc. Nonextensive plasmas associated with ion-acoustic waves, electron-acoustic waves, DIA waves or dust-acoustic (DA) waves, are investigated either by taking electron to be nonextensive [47–52], or ion nonextensive [53], or may both electron and ion nonextensive [54]. Eslami *et al.* [50] investigated the characteristics of the head-on collision of ion-acoustic (IA) SWs in a collisionless plasma and discussed the impacts of electron nonextensivity on the phase shifts of both the colliding SWs and ShWs. A generalization of the Boltzmann-Gibbs-Shannon entropy formula for statistical equilibrium was recognized to be required for systems subject to spatial or temporal long-range interactions making their behavior nonextensive. Owing to an increasing amount of experimental and theoretical evidence showing that the BGS formalism fails to describe systems with long range interactions and memory effects. In particular, this situation is usually found in astrophysical environments and plasma physics where, for example, the range of interactions is comparable to the size of the system considered. After, the rudimentary concept of nonextensive entropy, the nonextensive behaviour of electrons and ions (characterizing by a parameter q) have been successfully employed in plasma physics [55–58].

And the normalized electron density is given by

$$n_e = [1 + (q-1)\phi]^{\frac{1+q}{2(q-1)}} \tag{3}$$

where q is the nonextensive parameter and ϕ is the electrostatic wave potential [55–58].

It is important to note that $q = 1$ corresponds to Maxwellian distribution and $q \neq 1$ denotes the q distribution point to a class of Tsallis's velocity distribution [42]. By assuming ion nonextensivity, Tribeche [53] examined the basic features of the nonextensive DA SWs, where q is the electron nonextensive parameter. It has been found that depending on whether the parameter q is less or greater than critical value q_c, where μ is the equilibrium dust to ion ratio, the higher order DIA waves exhibit negative (positive) potential for $q \leq q_c$ ($q > q_c$).

Therefore, in our present investigation, we consider a dusty plasma system in absence of the magnetic field, but containing non-relativistic degenerate cold ion fluid, nonextensive electron, and negatively charged dust grains. The model is relevant to compact interstellar objects (e. g., white dwarf, neutron star, etc.). Recently, many authors [30, 31, 59–68], etc. have used the pressure laws (1) to (2) investigate the linear and nonlinear properties of electrostatic and electromagnetic waves, by using the non-relativistic quantum hydrodynamic (QHD) [69] by assuming either immobile ions or non-degenerate uncorrelated mobile ions. Very recently, Ashraf *et al.* [55–58] have investigated the nature of the DIA SWs by assuming inertial ions and nonextensive electrons and negatively charged stationary dust, and they inferred that both compressive and rarefactive type solitons are significantly modified by electron nonextensivity. Still now, there is no theoretical investigation has been made to study the extreme condition of matter for non-relativistic limits and effects of noextensivity on the propagation of electrostatic solitary waves (SWs) and shock waves (ShWs) in a dusty plasma system. Therefore, in our paper we have studied the properties of the SWs and ShWs considering a degenerate ion fluids, nonextensive electrons and negatively charged dust grains. Our considered model is relevant to compact interstellar objects (i.e. white dwarf, neutron star, black hole, etc.).

II. GOVERNING EQUATIONS

The dynamics of DIA SWs and ShWs in such dusty plasma system is governed by

$$\frac{\partial n_i}{\partial t} + \frac{\partial}{\partial x}(n_i u_i) = 0, \tag{4}$$

$$\frac{\partial u_i}{\partial t} + u_i \frac{\partial u_i}{\partial x} + \frac{\partial \phi}{\partial x} + \frac{K_1}{n_i}\frac{\partial n_i^\alpha}{\partial x} - \eta \frac{\partial^2 u_i}{\partial x^2} = 0, \tag{5}$$

$$\frac{\partial^2 \phi}{\partial x^2} = \mu n_e - n_i + (1-\mu), \tag{6}$$

where n_i is the ion number density of the species s normalized by its equilibrium value n_{i0}, u_i is the ion fluid speed normalized by $C_i = (n_{i0}c^2/m_i)^{1/2}$ with m_i being the ion rest mass and c being the speed of light in vacuum, ϕ is the electrostatic wave potential normalized by $m_i c^2/e$ with e being the magnitude of the charge of an ion, the time variable (t) is normalized by $\omega_{pi} = (4\pi n_{i0} e^2/m_i)^{1/2}$, and the space variable (x) is normalized by $\lambda_m = (m_i c^2/4\pi n_0 e^2)^{1/2}$. The coefficient of viscosity η is a normalized quantity given by $\omega_i \lambda_{m_i}^2 m_i n_{i0}$ [70], and the constant is $K_1 = n_{i0}^{\alpha-1} K_i/{m_i}^2 {C_i}^2$.

III. DERIVATION OF K-DV EQUATION

Now we derive a dynamical equation for the nonlinear propagation of the dust-ion-acoustic solitary waves by using (4 - 6). To do so, we employ a reductive perturbation technique to examine electrostatic perturbations propagating in the relativistic degenerate dense plasma due to the effect of dissipation, we first introduce the stretched coordinates [71, 72]

$$\zeta = \epsilon^{1/2}(x - V_p t), \tag{7}$$

$$\tau = \epsilon^{3/2} t, \tag{8}$$

where V_p is the wave phase speed (ω/k with ω being angular frequency and k being the wave number of the perturbation mode), and ϵ is a smallness parameter measuring the weakness of the dispersion ($0 < \epsilon < 1$). We then expand n_i, n_e, u_i, and ϕ, in power series of ϵ:

$$n_i = 1 + \epsilon n_i^{(1)} + \epsilon^2 n_i^{(2)} + \cdots, \tag{9}$$

$$n_e = 1 + \frac{1}{2}(1+q)\phi^{(1)} + \frac{1}{8}(1+q)(3-q)\phi^{(2)} + \frac{1}{48}(1+q)(3-q)(5-3q)\phi^{(3)} + \cdots, \quad (10)$$

$$u_i = \epsilon u_i^{(1)} + \epsilon^2 u_i^{(2)} + \cdots, \quad (11)$$

$$\phi = \epsilon\phi^{(1)} + \epsilon^2\phi^{(2)} + \cdots, \quad (12)$$

and develop equations in various powers of ϵ. To the lowest order in ϵ, using equations (9)-(12) into equations (4) - (6) we get as, $u_i^{(1)} = V_p\phi^{(1)}/(V_p^2 + K_1)$, $n_i^{(1)} = \phi^{(1)}/(V_p^2 + K_1)$, and $V_p = \sqrt{\frac{2}{(q+1)\mu} - K_1}$, called dispersion relation. To the next higher order in ϵ, we obtain a set of equations

$$\frac{\partial n_i^{(1)}}{\partial\tau} - V_p\frac{\partial n_i^{(2)}}{\partial\zeta} - \frac{\partial}{\partial\zeta}[u_i^{(2)} + n_i^{(1)}u_i^{(1)}] = 0, \quad (13)$$

$$\frac{\partial u_i^{(1)}}{\partial\tau} - V_p\frac{\partial u_i^{(2)}}{\partial\zeta} + u_i^{(1)}\frac{\partial u_i^{(1)}}{\partial\zeta} - K_1\frac{\partial n_i^{(2)}}{\partial\zeta} - K_1(\alpha-2)n_i^{(1)}\frac{\partial n_i^{(1)}}{\partial\zeta} = 0, \quad (14)$$

$$\frac{\partial^2\phi^{(1)}}{\partial\zeta^2} = \frac{\mu(1+q)}{2}\phi^{(2)} + \frac{\mu}{8}(1+q)(3-q)(\phi^{(1)})^2 - n_i^{(2)} \quad (15)$$

Now, combining (13-15) we deduce a K-dV equation

$$\frac{\partial\phi^{(1)}}{\partial\tau} + A\phi^{(1)}\frac{\partial\phi^{(1)}}{\partial\zeta} + B\frac{\partial^3\phi^{(1)}}{\partial\zeta^3} = 0, \quad (16)$$

where the value of A and B are given by

$$A = \frac{(V_p^2+K_1)^2}{V_p}[\frac{3V_p^2 - K_1(\alpha-2)}{2(V_p^2+K_1)^3} - \frac{\mu}{8}(1+q)(3-q)], \quad (17)$$

$$B = \frac{(V_p^2+K_1)^2}{V_p}. \quad (18)$$

The solitary wave solution of (16) is

$$\phi^{(1)} = \phi_m \mathrm{sech}^2\left(\frac{\xi}{\delta}\right), \quad (19)$$

where the special coordinate, $\xi = \zeta - u_0\tau$, the amplitude, $\phi_m = 3u_0/A$, and the width, $\Delta = (4B/u_0)^{1/2}$.

IV. DERIVATION OF BURGERS' EQUATION

To derive Burgers' equation, we first introduce the stretched coordinates [71, 72]

$$\zeta = \epsilon(x - V_p t), \quad (20)$$

$$\tau = \epsilon^2 t, \quad (21)$$

where meaning of the symbols are given in previous section.

The first order calculation is same as for K-dV equation derivation.

For the next higher order, we get the following equations

$$\frac{\partial n_i^{(1)}}{\partial\tau} - V_p\frac{\partial n_i^{(2)}}{\partial\zeta} - \frac{\partial}{\partial\zeta}[u_i^{(2)} + n_i^{(1)}u_i^{(1)}] = 0, \quad (22)$$

$$\frac{\partial u_i^{(1)}}{\partial\tau} - V_p\frac{\partial u_i^{(2)}}{\partial\zeta} + u_i^{(1)}\frac{\partial u_i^{(1)}}{\partial\zeta} - K_1\frac{\partial n_i^{(2)}}{\partial\zeta} - K_1(\alpha-2)n_i^{(1)}\frac{\partial n_i^{(1)}}{\partial\zeta} - \eta\frac{\partial^2}{\partial\zeta^2}u_i^{(1)} = 0, \quad (23)$$

$$0 = \frac{\mu(1+q)}{2}\phi^{(2)} - n_i^{(2)} + \frac{\mu}{8}(1+q)(3-q)(\phi^{(1)})^2 \quad (24)$$

Now, combining (22-24) we deduce Burgers' equation

$$\frac{\partial\phi^{(1)}}{\partial\tau} + A\phi^{(1)}\frac{\partial\phi^{(1)}}{\partial\zeta} = C\frac{\partial^2\phi^{(1)}}{\partial\zeta^2}, \quad (25)$$

where the value of A is same as for K-dV equation and the value of C is given by

$$C = \frac{\eta}{2} \quad (26)$$

The solution of (25) gives us a shock wave equation as

$$\phi^{(1)} = \phi_m[1 - tanh(\frac{\xi}{\delta})], \quad (27)$$

where the special stretched coordinates, $\xi = \zeta - u_0\tau$, the amplitude, $\phi_m = u_0/A$, the width, $\delta = 2C/u_0$, u_0 is the wave speed and the parameter η was chosen from standard value [70] for the system under consideration.

V. NUMERICAL ANALYSIS

From the figures 1-6 we have observed a 3D graphical representation and 7-8 represent two dimensional geometry. In figures 1-2 we have observed graphically that how the SWs potential structure, $\phi^{(1)}$ change with ξ and q when μ is less than the critical value ($\mu \leq 0.37$) or greater than the critical value of μ ($\mu > 0.37$). Similarly from 3-4 we have observed that how the SWs potential structure, $\phi^{(1)}$ change with ξ and μ when q is less than the critical value ($q \leq 0.50$) or greater than the critical value of q ($q > 0.50$). Figure 5 represents the effects of μ ($\mu \leq 0.37$) and q ($q \leq 0.50$) on the ShWs potential structures, $\phi^{(1)}$ with ξ and η. And similarly figure 6 represents the same when $\mu > 0.37$ and $q > 0.50$. Finally the figures 7-8 give us two dimensional graphical presentation from where we have confirmed the critical value of μ and q with respect to $\phi^{(1)}$.

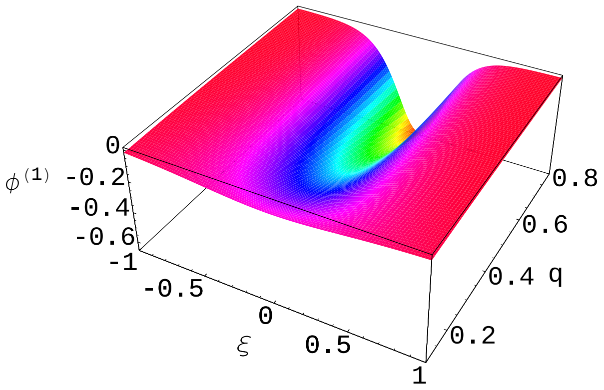

FIG. 1: Showing the effect of μ on the negative potential structure, $\phi^{(1)}$ with q when μ is less than or equal to the critical value ($\mu \leq 0.37$) for the electrostatic SWs obtained from (19).

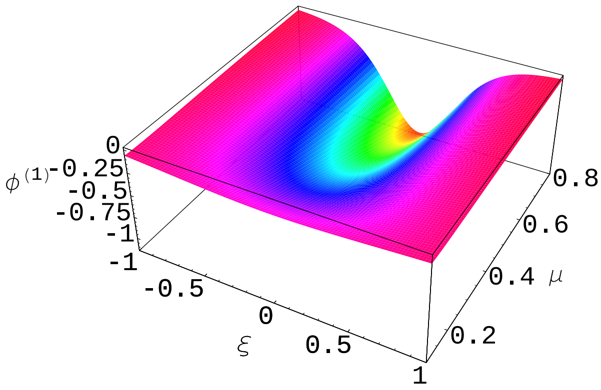

FIG. 3: Showing the effect of q on the negative potential structure, $\phi^{(1)}$ with μ when q is less than or equal to the critical value ($q \leq 0.50$) for the electrostatic SWs obtained from (19).

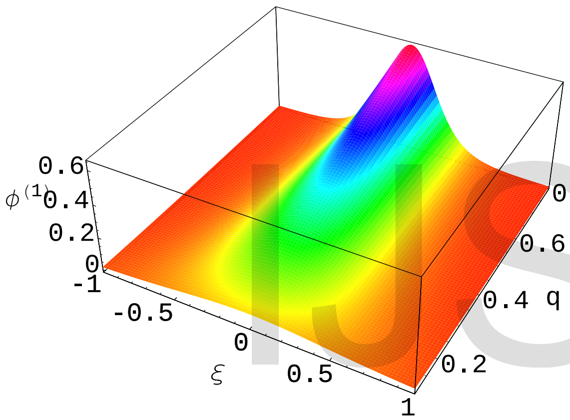

FIG. 2: Showing the effect of μ on the positive potential structure, $\phi^{(1)}$ with q when μ is greater than the critical value ($\mu > 0.37$) for the electrostatic SWs obtained from (19).

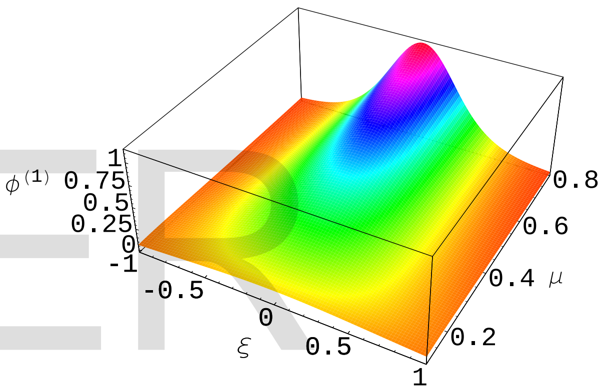

FIG. 4: Showing the effect of q on the positive potential structure, $\phi^{(1)}$ with μ when q is greater than the critical value ($q > 0.50$) for the electrostatic SWs obtained from (19).

However, the DIA SWs and ShWs investigation in our present work is valid theoretically. The results, which have been obtained from this investigation by observing figures 1-8, can be pinpointed as follows:
(i) We have observed the negative nonlinear waves (SWs and ShWs) potential exists if $\mu \leq 0.37$ and $q \leq 0.50$,
(ii) We have observed the positive nonlinear waves (SWs and ShWs) potential exists if $\mu > 0.37$ and $q > 0.50$,
(iii) The amplitude and width of SWs and ShWs increase with both μ and q.
(iv) With the increase of the phase speed of plasma species density of ions, the amplitude of nonlinear waves do not change significantly.
(v) The potential of SWs does not change polarity in any condition.
(vi) The potential of ShWs changes polarity because of the presence of η. So it can be said that viscosity plays an important role in the study of the nonlinear shock wave potential structures.
(vii) For our this model the critical values of μ and q are 0.37 & 0.50.
(viii) From our this theoretical study it has also been clear that the degenerate ion fluids has no effect on the potential structure where μ, q and η have effects.
(ix) It may be added here that the dissipation (which is usually responsible for the formation of the shock-like structures is not essential for the formation of the SWs structures.

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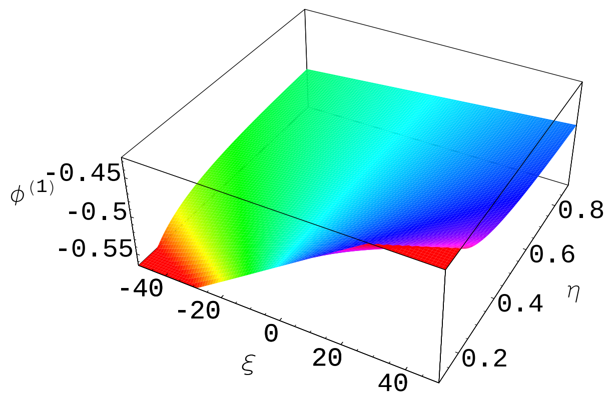

FIG. 5: Showing the effect of η on the negative potential structure, $\phi^{(1)}$ with μ (when μ is less than or equal to the critical value ($\mu \leq 0.37$)) & q (when q is less than or equal to the critical value ($q \leq 0.50$)) for the electrostatic ShWs obtained from (27).

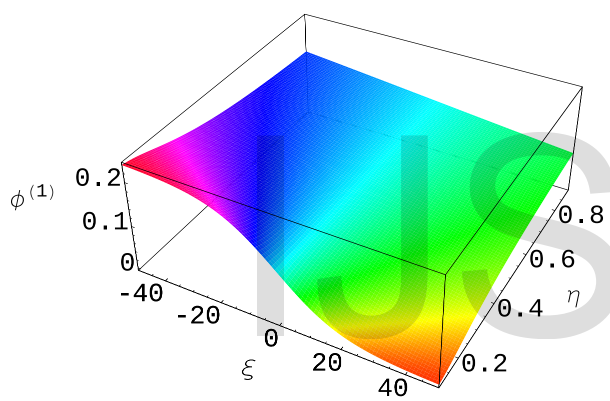

FIG. 6: Showing the effect of η on the positive potential structure, $\phi^{(1)}$ with μ (when μ is greater than the critical value ($\mu > 0.37$)) & q (when q is greater than the critical value ($q > 0.50$)) for the electrostatic ShWs obtained from (27).

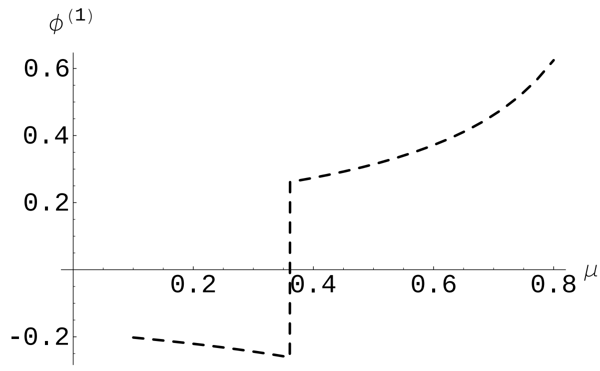

FIG. 7: Showing the effect of q ($q \leq 0.50$) on the potential structure, $\phi^{(1)}$ with μ in 2D.

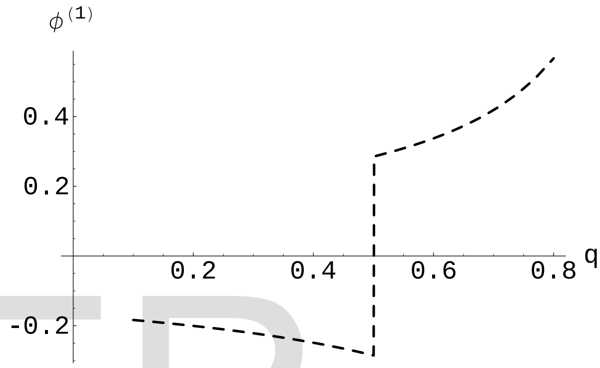

FIG. 8: Showing the effect of μ ($\mu \leq 0.37$) on the potential structure, $\phi^{(1)}$ with q in 2D.

VI. DISCUSSION

We have considered an unmagnetized dusty plasma containing non-relativistic degenerate cold ions fluid, nonextensive electrons and negatively charged dust fluids. We have examined the basic features of the electrostatic nonlinear structures that are found to exist in such dusty plasma.

We have shown the existence of compressive (hump shape) and rarefactive (dip shape) SWs and ShWs with negative and negative potential. It may be stressed here that the results of this investigation should be useful for understanding the nonlinear features of electrostatic disturbances in laboratory plasma conditions and space plasma. Our investigation would also be useful to study the effects of degenerate ion pressure in interstellar and space plasmas [73], particularly in stellar polytropes [43], hadronic matter and quark-gluon plasma [44], protoneutron stars [45], dark-matter halos [46] etc. We hope that our present investigation will be helpful for understanding the basic features of the localized electrostatic disturbances in compact astrophysical objects (e.g. white dwarfs, neutron stars, black hole, etc.) for space [74, 75] and also for laboratory [76–78] dusty plasmas. Further it can be said that the analysis of double layer structures, vortices, etc. in a nonplanar geometry are also the problems of great importance but beyond the scope of the present work. To conclude, we propose to perform a laboratory experiment which can study such special new features of the DIA SWs and ShWs propagating in dusty plasma in presence of degenerate ions and nonextensive electrons with negative charged dust grains.

VII. ACKNOWLEDGMENTS

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