Effect of Level Statistics on Local Magnetism in Nanoscale Metallic Grains

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Abstract

Effect of level statistics on local electronic states and local magnetism in nanoscale metallic grains with transition-metal impurity in the ballistic regime is studied. It is shown that the mean occupation of local electron and the local magnetic moment in nanoscale metallic grains with odd conduction-electrons are larger than those with even conduction-electrons. The effect of even-odd parity on the condition for the occurrence of local magnetic moment is also discussed, it is found that the critical value, \( \rho_d(0)U_c \), for the formation of local moment in nanoscale metallic grains is much smaller than that in bulks. The dependences of the local spin susceptibility on size and the Coulomb interaction are obtained. These results show that the level statistics plays an important role for the local magnetism, it distinguishes the properties of nanoscale metallic grains from those of clusters and bulks.

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1. INTRODUCTION

Nanoscale metallic grain, varying from a few nanometers to several hundred nanometers in size is complicated. It is neither few-body system as small cluster, in which the localization character of electronic states is dominant, nor an infinite system with translation invariance approximately as bulk, in which the band character of electronic states is predominant. When the size of grain, L, is comparable with the mean free path of the conduction electrons, two mesoscopic effects, the phase interference and the level statistics, play important roles for the low-temperature properties of nanoscale metallic grain. First, the average separation of the energy level, \( \delta_L \approx E_F/N \), is about 0.01 to 1K, here \( E_F \) is the Fermi energy and \( N \) the number of conduction-electrons, hence the quantum size effect including the size-dependence of energy levels and the level repulsion should also be considered at low temperature. Second, the grain size, \( L \), may be shorter than the phase coherence length \( L_\phi \), so the quantum interference of the phases of electron wavefunctions plays an important role. These two effects describe the quantum nature of many-electron interaction and single-electron properties in nanoscale and mesoscopic systems. These effects distinguish the physical properties of small metallic grains from those of bulks or clusters.

The magnetic properties of small clusters and disorder systems have attracted many authors’ attention\(^1\)\(^-\)\(^4\) in the past few years. The effect of size-dependence of the energy level on magnetism in small perfect clusters has been discussed by some authors (for example, see Refs. 1-2), the effect of the level statistics is not taken into account in such small perfect clusters with regular boundary since the effect of the statistical fluctuation of the levels on the magnetic properties is not as important as that of the size effect. When the grain size increases to a few nanometers and the disorder is taken into account, these mesoscopic effects take their positions. In the same time, an elastic scattering lifetime, \( \tau \), should be introduced for the propagation of conduction electrons in diffusive grain, the local magnetism will be affected by the disorder of metallic grains. This point is also not
interference effect on the spin magnetism of the conduction electrons in disordered mesoscopic metallic grains are studied. However, the local magnetism in nanoscale disordered metallic grains has not yet been studied systematically. Understanding this problem can provide insight the evolution of the local magnetism from clusters, grains to bulks at low temperature.

In the problem of local magnetism in ballistic grains, the quantum size effect of the levels plays a more important role than the quantum interference effect does. This effect manifests itself in the size-dependence of energy levels and the statistical fluctuation of energy levels. And the even-odd parity of the metallic grain modifies the electronic states, hence the local magnetism. In the present study, we find that the formation of local magnetic moment in nanoscale metallic grains with odd conduction-electrons is more easier than that with even conduction-electrons. We arouse an argument that there still exists a critical condition for the occurrence of local magnetic moment, it exhibits strong size dependence, however.

In this paper, we concentrate on the ballistic metallic grains with dilute transition metal impurities, the separation between impurities is much larger than the magnetic scattering length $L_s$, so that the impurities behave as isolated. The rest of this paper is organized as following: in Sec. 2, the formalism of the local magnetism in the ballistic grains is described; the results and discussions are given in Sec. 3 and the conclusion is shown in Sec. 4.

2. MODEL and FORMALISM

Magnetic impurity, such as transition-metal atom (Fe, Co, Ni, Mn, etc.), dissolved in nonmagnetic metallic host can be described by the Anderson impurity model. The Anderson model provides an essential description for the interaction between conduction electrons and the local electron. It explains the mechanism of the formation of magnetic moment in bulk metal and plays an important role in our understanding on the existence
valid in describing the physical process in metallic grains, and expressed in the following:

\[
H = \sum_{k\sigma} \epsilon_{k\sigma} c^\dagger_{k\sigma} c_{k\sigma} + \sum_{\sigma} [\epsilon_{d\sigma} d^\dagger_{\sigma} d_{\sigma} + \frac{U}{2} n_{\sigma} n_{\bar{\sigma}}] + \sum_{k\sigma} [V_{k} c^\dagger_{k\sigma} d_{\sigma} + h.c.] 
\]  

(1)

where \( c^\dagger_{k\sigma} \) creates the conduction (s) electron with state \( k \) and spin \( \sigma \), and \( \epsilon_{k\sigma} = \epsilon_{k} - \sigma \mu B \), denotes the free-electron dispersion under magnetic field \( B \); \( d^\dagger_{\sigma} \) creates a \( d \)-electron of the transition-metal impurity with the energy level \( \epsilon_{d\sigma} = \epsilon_{d} - g\sigma \mu B \), and \( U \) represents the on-site Coulomb interaction of the \( d \)-electrons; the hybridization matrix element between the conduction- and the \( d \)-electrons is \( V_{k} \). In the absence of the hybridization interaction, the retarded propagator of the s-electron is:

\[
G_{0,\sigma}(z + i\eta) = \frac{1}{z - H_{s} + i\eta} 
\]  

(2)

and that of \( d \)-electron is:

\[
D_{0,\sigma}(z + i\eta) = \frac{1}{z - H_{d} + i\eta} 
\]  

(3)

In the presence of disorder, the conduction electron in metallic grains is scattered by the nonmagnetic disorder potential \( v(r) \), it is assumed that the potential has vanishing average, and their correlation is \( \delta \)-like, i.e., \( \langle v(r) \rangle = 0 \) and \( \langle v(r) v(r') \rangle = \delta(r-r') \). Assuming the metallic grain is weak disordered, then the problem can be described in the framework of the perturbation theory. According to Altshuler et al. \(^6,^7\), after the average to the disorder configuration, the disorder effect may lead to a finite lifetime of the quasiparticles \( \tau \), \( 1/\tau = \pi \rho_{0} < v^{2} > \), where \( \rho_{0} \) is the density of states for the conduction electrons near the Fermi energy, then the propagator of the conduction electrons is rewritten after the disorder average to Eq.(2):

\[
G_{0,\sigma}(z) = 1/(z - \epsilon_{k} + i\frac{\hbar}{2\tau}) 
\]  

(4)

The propagator of the localized \( d \)-electrons is not affected by the nonmagnetic disorder:

\[
D_{0,\sigma}(z) = \frac{1 - \langle n_{\sigma} \rangle}{z - \epsilon_{d}} + \frac{\langle n_{\bar{\sigma}} \rangle}{z - \epsilon_{d} - U} 
\]  

(5)

According to Rice \(^8\), the physical meaning of \( 1/\tau \) in (4) is that the phase correlation among the plane waves for conduction electrons is lost in a distance \( l_{F} = v_{F} \tau \), \( v_{F} \) is the Fermi velocity. As a result, the averaged propagator is exponentially damped in the...
distance \( l \), this is the so-called weak localization resulting from the back scattering of electron wavefunction by the disorder potential interfering with itself. In the present paper, we concentrate on the metallic grain in the ballistic regime, i.e., the diffusive length \( l \) is much larger than the sample size \( L \), so the inverse of the lifetime, \( 1/\tau \), can be regarded as vanish, the propagator in Eq.(4) becomes the usual form of free conduction-, or \( s \)-, electrons.

The presence of the hybridization interaction will lead to self-energy corrections to the propagators of the \( s \)-electrons and \( d \)-electrons. By the perturbation theory, it can be shown that in the self-consistent mean-field approximation, the propagator of the \( d \)-electron is:

\[
D_{\sigma}(\omega) = D_{0,\sigma}(\omega)/[1 - \sum_{k} |V_{k}|^{2}G_{0,\sigma}(k,\omega)D_{0,\sigma}(\omega)]
\]

(6)

Accordingly, the density of states for local electrons in the ballistic grains is:

\[
\rho_{d,\sigma}(\omega) = \frac{1}{\pi} \frac{\Delta(\omega)}{D_{0,\sigma}(\omega) + \Delta^{2}(\omega)}
\]

(7)

where the Friedel’s halfwidth of the local electron [5] is:

\[
\Delta(\omega) = \pi \sum_{k} |V_{k}|^{2} \delta(\omega - \epsilon_{k\sigma} + E_{F})
\]

(8)

where \( \delta(\cdots) \) is the Dirac \( \delta \)-function. In the present work, we consider the situation at zero temperature. Therefore, the local electron occupation, \( n_{d} \), and the LMM, \( m_{d} \), in the impurity site can be obtained through the preceding density of states by the spectral theorem:

\[
n_{d}, m_{d} = \int_{E_{F}}^{\infty} d\omega \sum_{\sigma}(\sigma^{2}; \sigma)\rho_{d\sigma}(\omega)|_{B\to 0}
\]

(9)

in the absence of magnetic field.

The contribution of the spin susceptibility comes from the local electrons is obtained correspondingly. From Eqs.(7) and (9), one can get the expression of the spin susceptibility from local electrons at zero temperature:

\[
\chi_{d} = \frac{\partial m_{d}}{\partial B}|_{B\to 0} = \int_{E_{F}}^{\infty} d\omega [\frac{\partial \rho_{d\uparrow}(\omega)}{\partial B} - \frac{\partial \rho_{d\downarrow}(\omega)}{\partial B}]|_{B\to 0}
\]

(10)
terms of the instability of local spin susceptibility \(^9\), later we will show that it is difficult to do that for nanoscale metallic grains due to the broken of transition invariance and the level fluctuation.

3. Results and Discussions

With the above preparation, the effect of the level statistics on the local magnetism in nanoscale metallic grains is considered and the influence of the odd-even parity of conduction electrons on the LMM formation, the critical condition for the LMM formation and the size effect of the local spin susceptibility are discussed as the following.

3.1 Local Magnetic Moment in Metallic Grains

According to Eq.(9), the local occupation and the LMM in impurity site at zero temperature are obtained through the following expressions:

\[
n_{d}, m_{d} = \frac{1}{\pi} \int_{E_F}^{E_F} dw \sum_{\sigma} (\sigma^2, \sigma) \frac{\Delta_{\sigma}(w)}{(D_{0,\sigma}(\omega))^{-2} + \Delta_{\sigma}^2(w)}
\]

where

\[
\Delta_{\sigma}(\omega) = \pi V^2 \sum_{k} \delta(\omega - \epsilon_{k\sigma} + E_F)
\]

The main difference between the ultrasmall metallic grain and the bulk lies in the summation over the wave-vector \(K\) in Eq.(12). In bulk metal, the summation over \(K\) is quasi-continuous and can be become of integration over \(K\), the density of states \(\rho(0)\) of conduction electrons near the Fermi energy is almost a constant, the hybridizing width of the local electron is then: \(\Delta_{bulk} = \pi \rho(0)V^2\). However, in nanoscale metallic grains, the summation over \(K\) is discrete, so the hybridizing width of the local electron is:

\[
\Delta_{\sigma}(\omega) = \pi V^2 \sum_{i} \delta(\omega - \epsilon_{i\sigma} + E_F)
\]

As an approximation, \(|V_i|\) is taken to be independent of the level index. The average of this equation is taken over the disorder so that all the statistical information about the
of the unitary ensemble, since the present system does not preserve the time-reverse invariance in the presence of spin-flipped scattering \(^{10,11}\).

In nanoscale metallic grains, the eigenvalue energies of the conduction electrons are not equi-spacing levels as suggested by Kubo \(^{12}\) and Gorkov et al. \(^{13}\), rather, according to Wigner’s random matrix theory \(^{10,11}\), the energy level obeys certain distributions for the nearest-neighbour level correlation and the two level correlation, the distribution function of the nearest-neighbour levels of the similar ensemble is:

\[
P_n(\epsilon) = c_n(\frac{\pi \epsilon}{\delta L})^n e^{-\frac{\pi \epsilon^2}{(4\delta L^2)}}
\]

where \(c_n\) is the normalized coefficient, \(n\) is the ensemble symmetry parameter, here \(n = 2\), which corresponding to the unitary ensemble in the presence of spin scattering in the systems containing magnetic impurity and in magnetic field, and \(c_n = \pi/2\); \(P(\epsilon)\)\(d\epsilon\) represents the possibility of two nearest-neighbour levels of the conduction electrons with separation \(\epsilon\) near the Fermi energy. And the two-level correlation function of the unitary ensemble between levels \(\epsilon\) and \(\epsilon'\) is given by \(^{13}\):

\[
R_n(\epsilon - \epsilon') = 1 - \sin^2\left[\frac{\pi(\epsilon - \epsilon')}{\delta L}\right]/\left[\frac{\pi(\epsilon - \epsilon')}{\delta L}\right]^2
\]

where \(\epsilon\) and \(\epsilon'\) are two levels with arbitrary spacing in the ensemble. According to these two correlation functions, one can explore the effect of the level statistics on the physical quantities of the system, while as, these properties depend on the odd- or the even-parity of the conduction-electron reservoir in the systems. Let us consider the odd-parity case first.

In the case of odd-parity, it is assumed that the chemical potential coincides with the highest occupied level, \(\epsilon_{1\sigma} = E_F\), which is half-filled, therefore,

\[
\Delta_{odd}(\omega) = \pi V^2 \sum_i < \delta(\omega - \epsilon_{i\sigma} + \epsilon_{1\sigma}) >
\]

To a good approximation, one has \(^{14}\):

\[
\delta L \sum_i < \delta(\omega - \epsilon_i + \epsilon_1) > \approx R_n(\omega)
\]
Substituting Eqs.(16-18) into Eq.(7), one could obtain the density of states for local electrons in ultrasmall metallic grain with odd conduction electrons.

Next we consider the case of even-parity. In this situation, the chemical potential doesn’t coincide with the highest occupied level $\epsilon_0$. Assuming that the chemical potential lies in the half-way between the highest occupied level, $\epsilon_1$, and the first empty level, $\epsilon_0$, or $\mu = (\epsilon_1 + \epsilon_0)/2$, so the averaged hybridizing width of the local electrons for even-parity grains can be written as:

$$\Delta_{\text{even}}(\omega) = \pi V^2 \sum_i \frac{\delta}{\delta L} \left[ \omega - (\epsilon_{i\sigma} - \epsilon_{1\sigma}) + \frac{\epsilon_{0\sigma} - \epsilon_{1\sigma}}{2} \right]$$

The first term in the second line in Eq.(19) comes from the summation over energy index $i$ when $\epsilon_i = \epsilon_1$, the definitions of two-level correlation function, $P_n(x)$, and the distribution function of the nearest-neighbour, $R_n(x)$, are given in Eqs.(14) and (15), respectively. Since the averaged hybridizing width of the local electron with the conduction electrons depends on the energy $\omega$ through a complicated form, the integrals in Eqs.(18) and (19) can not be performed analytically, numerical calculation is thus performed for some typical systems and the results are shown in the following.

It is found that some features of local electronic states and the LMM in nanoscale grain are similar to that of bulk. The formation of the Friedel’s resonance states between the impurity electron and the conduction electrons through the hybridizing interaction and the splitting of the Friedel’s resonance states with up and down spins give rise to the LMM when the Coulomb interaction exceeds a critical value. With the increase of hybridizing interaction $V_k$, the impurity electron becomes more and more delocalized so that the mean occupation at impurity site and the LMM becomes small.

However, one striking difference of the LMM in nanoscale grain from that in bulk is that the critical Coulomb interaction $U_c$ for the occurrence of LMM in the grains with odd conduction electrons is much larger than that with even conduction electrons. The Coulomb-repulsion dependence of the LMM in metallic grain with odd- and even-parity is shown in Fig.1. The LMM of nanoscale metallic grains strongly depending on the parity originates from the level statistics, or the position of the chemical potential.
with respect to the occupied energy levels, especially to the highest occupied level. In the odd-parity grains, the broaden halfwidth of the local electron, $\Delta_{\text{odd}}$, is relevant to the two-level correlation function $R_{\text{nn}}$, which is only affected by a few levels close to the chemical potential. In the even grains, the halfwidth, $\Delta_{\text{even}}$, depends on not only the two-level correlation function but also the nearest-neighbour level distribution function $P_n$ due to strong level repulsion. Because of the strong level repulsion, only several levels below the chemical potential contribute to the density of states of the local electrons for the latter. For the systems with the same interaction parameters, the mean occupation of local electron and the LMM in odd-parity grains are larger than those in even-parity grains. This can be seen clearly in Fig.1. Therefore, unsmooth variation of the magnetic moment in nanoscale grain is expected when the electron number in the grain increases gradually.

For large Coulomb interaction, the differences of the local occupation and the LMM for odd- and even-grains become small. Curve 1 and 2, Curve 3 and 4 in Fig.1 approach the same values for the fact that when $U$ becomes large, the two levels of the resonance states are separated so large that the electron occupies the lower state. the local electronic state, hence the local moment, is almost not affected by the environmental electric field, so the local electronic states and the LMM become independent of the parity gradually.

Another one important effect of the level statistics is that the on-site Coulomb interaction necessary for the spin-splitting of the resonance states and the occurrence of the LMM is different for the odd-parity grain and for the even-parity grains. It strongly depends on the grain size. The general feature of the size-dependence of the critical Coulomb-strength for the occurrence of the LMM is shown in Fig.2. One finds that the critical on-site Coulomb interaction, $U_c$, increases when the grain size becomes large, and the $U_c$ in odd-parity grain is much smaller than that in even-parity grain.

As we all know, the condition for the occurrence of LMM in the Anderson model in bulk is $\rho_d(0)U_c = 1$ when the impurity level lies below the Fermi energy. However this condition no longer holds for nanoscale metallic grains. The critical value $\rho_d(0)U_c$ behaves
is much smaller than unity and increases with the size of grain. This can be explained in terms of the strong repulsion of the energy levels and the strong localization of the impurity electronic states in finite size system. The reason of the critical value, \( \rho(0)U_c \), in even grains is generally larger than that in odd grains is the same as that of \( U_c \).

The size-dependences of the mean local occupation and the LMM are shown in Fig.4. The main feature that the mean occupation and the LMM decrease as the increase of size is very similar to that of clusters so that the finite size effect is obvious. For the same metallic systems, it is more difficult for the occurrence of the LMM in the grains with even-parity than that with odd-parity. It also can be attributed to the fact that the resonance halfwidth of the former is larger than that of the latter. Delocalization character of the impurity electron becomes dominant when the grain size becomes large. The local occupation and the LMM approach constants (the bulk values) gradually are possibly expected when the size becomes very large. It was not found in the present size range \( (N \leq 3000) \), however. Similar situation also happens for the critical Coulomb interaction in Fig.2. It is believed that much large size grain should be considered for the present purpose.

### 3.2 Local Spin Susceptibility in Metallic Grains

We now turn to the local spin susceptibility of nanoscale metallic grains at zero temperature. It is reasonable to assume that the hybridizing width of the local electrons is independent of the magnetic field, so the expression of the local spin susceptibility is rewritten as:

\[
\chi_d = \frac{\pi}{2} \sum_{\sigma} \int_{E_F}^{E_F} d\omega \frac{\Delta(\omega)(\omega - \epsilon_d - U \lessgtr n_{\sigma})}{(\omega - \epsilon_d - U \lessgtr n_{\sigma})^2 + \Delta^2(\omega)}
\]

where the local spin susceptibility is measured in units of the square of the product of \( g \) factor and the Bohr magneton \( \mu_B \), i.e. \( (g\mu_B)^2 \). The behavior of the local spin susceptibility for the grains with odd- and with even-conduction electrons in accordance with the hybridizing width \( \Delta_{odd} \) or \( \Delta_{even} \) is then examined. The numerical results are shown in
It can be seen in Fig. 5 that the reduced local spin susceptibility, $\chi_d$, depends on the on-site Coulomb-interaction of the local electrons. As a comparison, the dependence of the LMM on size is also shown in this figure. Before the formation of LMM, $\chi_d$ decreases as the increase of the Coulomb interaction $U$. After the LMM occurs, $\chi_d$ increases with $U$. Detail calculation shows that the local susceptibility exhibits a finite discontinuity at the critical Coulomb strength for the occurrence of LMM. The reason of the decrease of $\chi_d$ below $U_c$ and the increase $\chi_d$ above $U_c$ lies in the different response of the local electron to external magnetic field. For smaller $U$ than $U_c$, there is no spin-splitting for local states, $\chi_d$ is positive, the local electron exhibits paramagnetic character. When $U$ approaches $U_c$, the LMM occurs and $\chi_d$ varies crucially, but doesn’t diverge as in bulk due to the finite size effect. It exhibits a finite discontinuity at $U_c$.

Fig. 6 shows the evolution of the local spin susceptibility with the increase of grain size. For the grain with small size, $\chi_d$ exhibits strong diamagnetic character, in which the LMM occurs. For the grain with large size, $\chi_d$ appears weak paramagnetic character since the LMM disappears. When the size becomes very large, the effect of odd-even parity becomes of unimportant.

In an earlier study $^{15}$, we found that if only the nearest-neighbour level distribution function was taken into account, the local magnetism would be much weaker than that in the present case. This can be attributed to the fact that when the two level correlation is absence, the impurity electron is more itinerant. The presence of the two level correlation will enhance the localization character of impurity electron. Also, the level statistic affects some other physical properties of metallic grains $^{16}$. Also the present method can be generalized to the nanoscale metallic grains in the diffusive regime, in which $1/\tau$ is finite and the fluctuations of LMM and local spin susceptibility are expected to be large.

4. CONCLUSION

The quantum correction arising from the level statistics effect to the local magnetic
still exists with the quality much smaller than that of bulk and depends on the size and parity of nanoscale grains.

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REFERENCES

1. G. M. Patsor, R. Hirsch and B. Muhlschlegel, Phys. Rev. Lett. 72, 3879 (1994); G. M. Pastor, J. Dorantes-Davila and K.H. Bennemann, Phys. Rev. B40, 7642 (1989).

2. B. V. Reddy, S. N. Khanna and B. I. Dunlap, Phys. Rev. Lett. 70, 3323 (1993). S. N. Khanna and S. Linderoth, Phys. Rev. Lett. 67, 742 (1991); J. Magn. Magn. Mater. 104-107, 1574 (1992).

3. H. Yoshioka, J. Phys. Soc. Jpn, 63, 405, (1994).

4. H. Mathur, M. Gokcedag and A. D. Stone, Phys. Rev. Lett. 74, 1855 (1995).

5. P. W. Anderson, Phys. Rev. 124, 41 (1961); Rev. Mod. Phys. B50, 191 (1978), and some references therein.

6. B. L. Altshuler and B. I. Shklovskii, Sov. Phys. JETP, 64, 127 (1986).

7. Y. Imry, Transport Phenomena in Mesoscopic Systems, ed. by H. Fukuyama and T. Ando, (Springer-Verlag Berlin Heidelberg, 1992), P205.

8. T. M. Rice, Metal-Insulator Transitions, Troisieme Cycle de la physique, Semmester d’hiver, 1983-1984. Zurich.

9. S. Doniach and E. H. Sondheimer, Green’s Functions for Solid State Physicists, (W. A. Benjamin, Inc. MA, 1974).

10. E. P. Wigner, Ann. Math. 53, 36 (1951); 62, 548 (1955); 65, 203 (1957); 67, 325 (1958).

11. K. B. Efetov, Adv. Phys. 32, 53 (1983).

12. R. Kubo, J. Phys. Soc. Jpn., 17, 975 (1962).

13. L. P. Gorkov and G. M. Eliashberg, Zh. Eksp. Teor. Fiz., 43, 1407 (1965).

14. R. A. Smith and V. Ambegaokar, Phys. Rev. Lett., 77, 4962 (1996).
16. A. Cerdeira, B. Kramer and G. Schon, eds. Quantum Dynamics of Submicron Structure, NATO ASI series, (Kluwer Academic Publishers, Dordrecht, The Netherlands, 1995).
Figures Captions

Fig.1. Coulomb-repulsion dependence of the mean occupation (Curve 1 and 2) and the local magnetic moment (Curve 3 and 4) in the ballistic metallic grains, parameters $\epsilon_d=-0.5$, $E_F=3.0$, $V=0.1$. Energy is in units of eV, magnetic moment is in units of $\mu_B$.

Fig.2. Size-dependence of the critical Coulomb-interaction for the occurrence of the local magnetic moment. Here $\epsilon_d=-0.5$, $E_F=8.0$, $V=0.1$. Energy is in units of eV.

Fig.3. Dependence of the critical value, $\rho_d(0)U_c$, for the occurrence of local magnetic moment on size. Parameters are the same as those in Fig.2.

Fig.4. Size-dependence of the mean occupation (Curve 1 and 2) and the local magnetic moment for odd-parity and even-parity metallic grains. $\epsilon_d=-2.5$, $E_F=8.0$, $U=6.0$, $V=0.1$. Energy is in units of eV. magnetic moment in units of $\mu_B$.

Fig.5. Dependence of the local spin susceptibility (Curve 2 and 4) and the local magnetic moment (Curve 1 and 3) on the Coulomb interaction for metallic grains with odd (N=101) and even (N=100) conduction electrons. $\epsilon_d=-0.5$, $E_F=3.0$, $V=0.1$. Energy is in units of eV, Susceptibility is in units of $(g\mu_B)^2$.

Fig.6 Dependence of local spin susceptibility and local magnetic moment on the size of metallic grains with odd and even conduction electrons. $\epsilon_d=-0.5$, $E_F=5.0$, $U=6.0$, $V=0.1$. Energy is in units of eV.
Local Occupation and Moment

Coulomb Interaction $U \text{(eV)}$

1, 3. $N=101$ (Odd)

2, 4. $N=100$ (Even)
Critical Value of \( p(0)U \)

- **N=Odd**
- **N=Even**

No. of Conduction Electrons (N)
Critical Coulomb Interaction

No. of Conduction Electrons (N)

1. N=Even
2. N=Odd
Local Spin Susceptibility

No. of Conduction Electrons (N)

1. N=Odd
2. N=Even