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Superconducting state of metallic nanoclusters and Josephson tunneling networks

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ABSTRACT

Metallic nanoclusters form a new family of high temperature superconductors. In principle, the value of T_c can be raised up to room temperature. In addition, one can observe the Josephson tunneling between two clusters. One can build the nanocluster-based tunneling network capable to transfer a macroscopic supercurrent at high temperatures. Such a network can be synchronized and radiate as single junction.
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1. Introduction

This paper is concerned with superconducting state of metallic nanoclusters. Clusters represent finite Fermi systems (see, e.g. review [1]). We will describe also various properties of the cluster-based Josephson tunneling networks, which are capable to transfer macroscopic superconducting current, potentially at high temperatures. The analysis is based on our publications [2–5]; some new results will be also presented.

The structure of the paper is as follows. At first, we will describe the fundamental feature of metallic clusters, namely, the presence of the shell structure of their electronic spectra. The Cooper pairing appears to be realistic in nanoclusters, thanks to this key feature. Then we describe the pairing phenomenon and its manifestations. Afterwards, we will address the question of charge transfer through a tunneling network; such a transfer forms the bridge between pairing in an isolated cluster and macroscopic superconductivity in bulk materials. Finally, we will discuss the problem of synchronization in Josephson networks.

2. Clusters shell structure

Metallic nanocluster A_n is a set of atoms (e.g., Al_{56}, Zn_{23}) with its valence electrons become delocalized; the number of such electrons, N, is the main parameter for a given metallic cluster. For example, $N = 168$ for the cluster Al_{56}. These delocalized electrons form a finite Fermi system, and, therefore, clusters are characterized by discrete electronic energy spectra.

The quantum states of electrons in clusters are characterized by quantum numbers different from those for bulk solids. For spherical clusters the states are classified by the values of the orbital momenta "ℓ" and their projection "m", so that there is a well-known degeneracy $G = 2(2\ell + 1)$. As for the deformed clusters, the four-degenerate states (except those for $m = 0$; they are double degenerate) are classified by the projection of the orbital momenta "m".

The presence of shell structure in clusters was discovered in [6]. The energy shells are similar to those for atoms (s,d,..shells) and for atomic nuclei. The cluster geometry strongly depends on the degree of the shell filling. The dependence of the shape on the number of electrons is a remarkable feature of nanoclusters. If the shell is totally occupied (so-called "magic" clusters; they are similar to inert atoms), the cluster with a good accuracy displays the spherical symmetry (Fig. 1).

The properties of clusters are similar in many aspects to those in atomic nuclei. The shell structure of the spectra is also an important feature of nucleons. Correspondingly, the quantum numbers are similar. However, there are key differences between these two finite Fermi systems. First of all, we are dealing with different forces. For clusters, usual Coulomb forces cause the interaction; their screening is well studied. The second key difference is that clusters contain light (electrons) and heavy (ions) particles. As a

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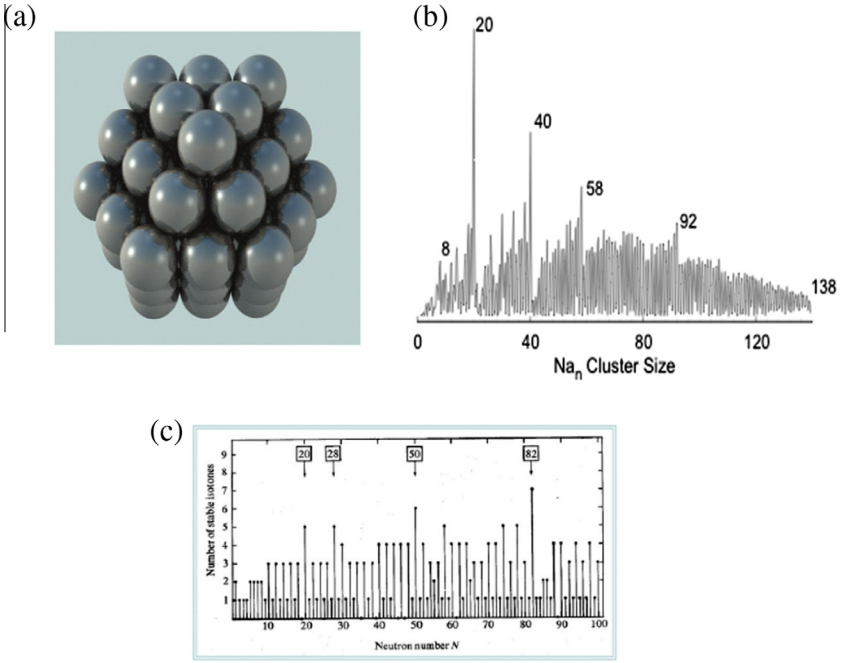

Fig. 1. (a) Cluster; the peaks in stability correspond to "magic" numbers: (b) in clusters; (c) in nuclei.

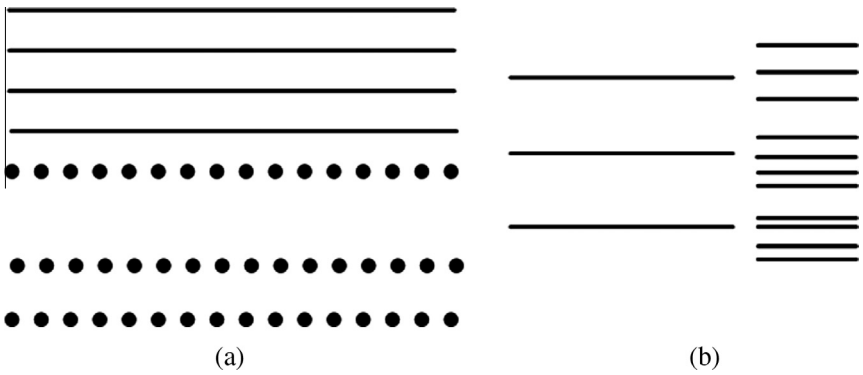

Fig. 2. Energy spectra for a "magic" cluster (a) and in the case of a nearly complete shell (b).

Fig. 3. Nano-based tunneling network.

result, one can employ the adiabatic Born–Oppenheimer approximation, which forms the basic to study molecules and solids. This approximation allows us to have the classification of energy levels, that is to introduce, e.g., the electronic and vibrational manifolds, and the electron–vibrational interaction. In other words, one can develop a microscopic description of metallic clusters.

One more important point. One can increase the size of the cluster and make continuous transition to the bulk solid. That is why the study of clusters allows to track the evolution from isolated atoms to solids. As a result, one can use with proper scaling some bulk parameters. As will be shown below, this feature is important for an analysis of superconducting state of nanoclusters.

The presence of the shell structure is a key ingredient leading to the pair correlation; it was discussed initially in [7,8]. As was demonstrated in our papers [2,3] and recent publications [9–11], the presence of the energy shells leads to an appearance of high temperature superconducting state. Let us turn into description of this phenomenon.

3. Superconducting state

3.1. General picture

As we know, the Cooper pairs in bulk superconductors are formed by electrons with opposite momenta and spins. For the nanoclusters of interest, the momentum is not a quantum number, and the pairs are formed by electrons with opposite projections of the angular momentum (m, $-m$). In many aspects, the picture of pairing is similar to that in atomic nuclei (see, e.g. [12]). However, there is a key difference and it is related to the mechanism of pairing. In clusters it is caused by the electron–vibrational coupling, i.e., the mechanism is similar to that in usual bulk superconductors.

The pairing strongly affects the cluster's energy spectrum, with the impact particularly strong for clusters with slightly incomplete shells, where the excitation energy in the absence of pairing can be rather small. A detailed theory will be described in the next section. It is essential that the strength of pair correlation varies for different clusters. Correspondingly, the critical temperature,