AC Electrokinetics and Nanotechnology

Meeting the Needs of the “Room at the Bottom”

Shaun Elder
Will Gathright
Ben Levy
Wen Tu
# Table of Contents

**The Theory** ......................................................... 1

- Dielectrophoresis .................................................. 1
- Electrorotation ..................................................... 3
- Traveling-Wave Dielectrophoresis ............................... 4

**The Fabrication** .................................................. 5

- Resolution ........................................................... 8

**Revolutionizing Science** ......................................... 9

- Mechanisms ......................................................... 11

**Toward the Future** ............................................... 14

- Scaling Laws ........................................................ 15
- Breaking the Barrier ............................................... 20

**In Summary** ....................................................... 24

- References .......................................................... 25
The Theory

The theory and application of AC electrokinetic techniques arose after the publication of Eigler and Schweizer’s 1990 paper about manipulation of a single Xenon atom on a silicon surface. Since then, AC Electrokinetic techniques such as dielectrophoresis and electrorotation have been utilized for manipulation, separation, and analysis of cellular-scale particles, DNA, and even nano-scale particles. The forces at work behind the functionality of the theories of AC electrokinetics are very general and can be applied to many areas of science. This paper will first thoroughly describe the theories and physics behind AC electrokinetics focusing on dielectrophoresis, electrorotation and traveling wave dielectrophoresis. Secondly, the techniques for making current devices, which actualize the theories, will be highlighted. Current electrokinetic devices are very diverse in use and are pushing the frontiers of science. Several such devices are detailed. Finally, we detail how this cutting edge field can be melded and shown to meet the needs of the fascinating world of nanotechnology.

Dielectrophoresis

Dielectrophoresis and electrorotation, which are collectively called AC electrokinetics, have been used in recent years to manipulate cellular- and nano- scale particles. This phenomenon occurs due to the interaction of induced dipoles with electric fields. Using these fields, particles can be attracted, repelled, and rotated by changing the nature of the field dynamics.

Consider a particle suspended in a non-uniform electric field shown in Figure 1. The applied field induces a dipole inside the particle. The interaction between the non-
uniform field and the induced dipole generates a force, which in turn induces some translation of the particle since the forces are not equal due to field gradient. If the particle is more conductive than the dielectric medium, which is shown in figure 1, the dipole aligns with the field causing attraction. If the particle is less conductive than the medium, then the induced dipole aligns against the field, causing repulsion of the particle [1].

![Figure 1 – Force diagram showing electrostatic fields and charges.](image)

The magnitude of the forces created is dependent on the magnitude of the induced dipole. The forces only respond the field gradients and are unaffected by field directions. Therefore, alignment of the field is unnecessary. Generating this force in an AC field with a set of electrodes can be advantageous in the reduction of electrophoretic (due to particle charge) forces. This type of manipulation of particles is called Dielectrophoresis. The force \( F_{\text{DEP}} \) [2] acting on an isotropic dielectric sphere is given by:

\[
F_{\text{DEP}} = 2\pi \varepsilon_r \varepsilon_0 \Re \left[ K(\omega) \right] \nabla B^2
\]
where $r$ is the particle radius, $\varepsilon_m$ is the permittivity of the suspending medium, $\nabla$ is the Del vector operator, $E$ is the rms. electric field and $\Re \left[ K(\omega) \right]$ the real part of the Clausius-Mossotti factor, given by:

$$K(\omega) = \frac{\varepsilon_p^* - \varepsilon_m^*}{\varepsilon_p^* + 2\varepsilon_m^*}$$

The particle moves to regions of highest field strength when $\Re \left[ K(\omega) \right]$ is positive (positive dielectrophoresis) and vice versa.

**Electrorotation**

If a polarizable particle is suspended in a rotating electric field generated by electrodes, the induced dipole will rotate in sync with the rotating field. But if the rotational velocity of the field is much faster than that of the time taken for the dipole to synchronize, then a gradient forms from dipole lag. This gradient induces a torque on the particle causing it to rotate with the field. This rotation is with the field at lags of less than $180^\circ$ and against the field otherwise. Field is induced by electrodes set $90^\circ$ apart as seen in Figure 2.

![Figure 2 – Schematic showing three different types of movement](image)
Torque $\Gamma$ on a spherical particle in a rotational electric field of magnitude $E$ is given by:

$$\Gamma = -4\pi r^3 \text{Im}[K(\omega)]E^2$$

$\text{Im}[K(\omega)]$ represents the imaginary component of the Clausius-Mossotti factor [3]. Notice that the torque on a particle is not a function of the gradient of the field like dielectrophoresis forces, but rather a function of the electric field itself. And since the dielectrophoresis force and electrorotational torque are functions of the real and imaginary component of the Clausius-Mossotti factor respectively, it is possible for a particle to experience both dielectrophoresis and electrorotation.

**Traveling-Wave Dielectrophoresis**

Traveling-wave dielectrophoresis is analogous to the linear version of electrorotation; instead of the electrodes being arranged in a circle, they are laid out linearly in a line. This setup of electrodes produces an electric field that waves and travels along the electrodes [4]. When the wave polarizes a particle (induces a dipole), the induced dipole moves with the electric field peaks, just as the particle dipole moves with the rotation of the electric field in the electrorotation case. This is shown in Figure 5 below. Similar to the electrorotational case, when the field moves too fast for the changing dipole, lagging occurs and the particle is forced to move linearly along the wave by forces caused by the dipole.
The force $F_{TWD}$ is quantified by [5]:

$$F_{TW} = rac{-4\pi \varepsilon_0 \sigma^3 H \mu \mathcal{K}(\phi) \mathcal{E}^2}{\lambda}$$

where $\lambda$ is the wavelength of the traveling wave.

**The Fabrication**

The primary means of patterning for fabrication of the electrodes is electron beam lithography (EBL). Electron beam lithography is a specialized technique for patterning with a feature size on the order of 50 nm [6].

Electron beam lithography has two primary advantages: high resolution and flexibility. Because the system is largely based upon the scanning electron microscope it has near atomic resolution and can be utilized on many materials in almost any pattern.

The drawbacks are high cost and slow speed of EBL. These drawbacks keep EBL from being used in large-scale processes. EBL is used primarily in niche markets such as
mask making for the integrated circuit industry and manufacturing research tools such as these electrodes for AC electrokinetics [7].

Below is a schematic of an EBL system. It is similar in structure to a SEM, and a few of the components will be briefly covered here.

![Typical EBL system](image)

**Figure 4 - Typical EBL system**

The first component is the electron source. There are two methods of expelling electrons from a material. A thermionic emission source is one in which a conductor is heated until the electrons have enough energy to overcome the work function of the material. A cold field emission source is one where electrons tunnel through the barrier, moved by a strong electric field. These two methods can also be combined to create a thermal field emission, or Schottky source. Of these methods, the cold field emission is rarely used in EBL due to its instability. The cold field emission technique is prone to atoms adsorbing onto the surface of the tip, which in turn affects the work function and therefore the tunneling current. Included is a chart of electron sources and their characteristics [6].
EBL systems also employ lenses. There are two types of electron lenses in use: electrostatic and magnetic as shown in Figure 5. A schematic cross-section of the magnetic lens is shown to the right. It features symmetric iron polepieces with copper winding in the center. The magnetic flux imparts a force on the electron optic axis, which focuses the beam [6].

The electrostatic lenses focus the beam by creating an electric field that will pull scattering electrons back towards the center. Because of they exhibit more aberrations electrostatic lenses are not often used, and when they are it is often in the gun region as a

<table>
<thead>
<tr>
<th>source type</th>
<th>brightness (A/cm²/sr)</th>
<th>source size</th>
<th>energy spread (eV)</th>
<th>vacuum requirement (Torr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>tungsten thermionic</td>
<td>~10⁵</td>
<td>25 um</td>
<td>2-3</td>
<td>10⁻⁶</td>
</tr>
<tr>
<td>LaB₆</td>
<td>~10⁶</td>
<td>10 um</td>
<td>2-3</td>
<td>10⁻⁸</td>
</tr>
<tr>
<td>thermal (Schottky) field emitter</td>
<td>~10⁸</td>
<td>20 nm</td>
<td>0.9</td>
<td>10⁻⁹</td>
</tr>
<tr>
<td>cold field emitter</td>
<td>~10⁹</td>
<td>5 nm</td>
<td>0.22</td>
<td>10⁻¹⁰</td>
</tr>
</tbody>
</table>
condenser lens to help draw electrons from the source. It is worth noting that electron lenses are almost exclusively converging lenses [7].

Similar techniques to those in electron lenses are used to deflect the beam. Just as with the lenses, magnetic deflectors are mainly used because they impart fewer aberrations. The electrostatic deflectors are used when response time is the most important. Deflecting the beam off axis will increase beam diameter and decrease resolution.

Resolution

The resolution of the system is determined by the theoretical beam size: [6]

\[ d = (d_g^2 + d_s^2 + d_c^2 + d_d^2)^{1/2} \]

The first component is the beam diameter at the gun, \( d_g = d_v / M^{-1} \) where \( d_v \) is the virtual source size and \( M^{-1} \) is the demagnification that occurs in the column. The \( d_s \) and \( d_c \) terms refer to spherical and chromatic aberrations respectively. Spherical aberrations arise from the predisposition of electron lenses to focus electrons on the outside of the lens more strongly than those on the inside. Its effect can be described by \( d_s = 1/2C_s a^3 \), where \( C_s \) is the spherical aberration coefficient of the final lens and \( a \) is the convergence half-angle of the beam at the target. Chromatic aberrations occur because low energy electrons are focused more strongly than high energy ones. This effect is described by \( d_c = C_c a DV / V_b \), where \( C_c \) is the chromatic aberration coefficient, \( DV \) is the energy spread of the electrons, and \( V_b \) is the beam voltage [7].

Advances in the technology of EBL has allowed for the reduction in the theoretical beam diameter and the improved resolution and control of the system.
Increasingly complicated electrode patterns can be created for greater control. Shown in Figure 6 are six possibilities for electrode configuration [8]. There are many others. For example, if the electrons are configured into an octopole cage, three-dimensional control can be exhibited. Though typical applications use the four-electrode configuration pictured in the upper right, other configurations have advantages that directly address fundamental difficulties in the system discussed later.

![Figure 6 – Possible electrode geometries](image)

**Revolutionizing Science**

AC electrokinetics is a new approach for manipulation of particles that can be employed as nanofabrication and MEMS processes are being developed and perfected. Molecular-sized and cellular-sized particles can be individually moved, rotated, or trapped, rather than mass-quantities. DNA has been investigated for decades using a simple electrophoresis mechanism in which charged DNA is separated as it diffuses through an agarose gel pulled by an electric field. This way particular DNA chains can be
selected according to their size. Dielectrophoresis is used at the micro- and nano-levels, as outlined above.

Applications of these techniques are being utilized to accomplish a variety of goals in modern science. In colloidal solutions, desired particles can be removed. Two particle types that have nearly the same characteristics can be separated with these devices. Isolation of a group of inaccessible cells at an exact concentration can be accomplished in order to process and classify the cells. Micro-motors can be activated to spin bacteria or make rotational measurements on particles. Electronic tweezers can be actuated using particle-manipulation technology. Nano-devices can replace common cell counters by separating viable and non-viable cells or classifying dyed and non-dyed cells. Lastly, and most importantly for medical interests, the breakthroughs in cell-manipulation can separate cancerous and non-malignant cells in vivo.

Historically, the general concepts have existed, but scientists had not had the capability to fabricate such devices. Electrode fabrication techniques were relatively crude up until the 1980’s. This limited the ability to manipulate beads and molecules because only large particles could be moved. Non-precise electrodes required larger electric fields to have an effect and non-uniformity of electric fields meant smaller particles (<500nm) were not accurately controlled. Thermal noise induced by the devices reduced the effectiveness to manipulate cells. Brownian motion would dominate the applied electric field and electrohydrodynamic motion in fluids would also disturb device function. With advances in nanofabrication procedures today, layers are more uniform and thinner; potentials are sharper and more exact, while device size minimization allows maneuverability into more locations.
Mechanisms

Dielectrophoresis is becoming a very general word in this field. Hundreds of nano-devices are being employed that adjust polarizable particles by inducing an electric field.

Trapping of DNA molecules will be discussed in order to exemplify the use of dielectrophoresis. Washizu et al. used a DEP FFF, dielectrophoresis field flow fractionation to separate and capture specific-sized macromolecules [12]. Molecules are swept through a chamber with parallel finger electrodes on the bottom. An AC current runs through those electrodes, which causes varying levitation of the charged DNA macromolecules. Large or small concentrations of DNA sent through the gauntlet of thin aluminum electrodes are stretched out and form bands above the fingers as shown in Figure 7. Individual DNA molecules can be seen in smaller concentrations by certain fluorescent spectroscopy techniques. More applicably, the solution can be dried when the bands are separated. The DNA molecules attach to the dry Aluminum electrodes. High concentrations can then be collected and, more importantly, lengths of DNA molecules can be measured because they are straight due to original stretching.
**Traveling wave dielectrophoresis (TWD)**, in some cases, uses a spiral shaped electrode to bring in the correct polarized particles to a central “clump” as the electric current travels on long electrodes. To demonstrate thoroughly the use of the TWD mechanism in a real-world application, trapping of human breast cancer cells using a device will be described. Traditional mask photolithography, coupled with a silicon molding procedure, created spiral microfluidic channels for which cells can traverse. Dielectrophoresis allows for the smart device to separate human breast cancer cells from T-lymphocytes and other cell types by polarization differences as shown in Figure 8. This traveling wave DEP, allows for higher throughput and continuous cell separation, whereas positive and negative DEP require stopping the experiment to collect the separated cells when necessary [9].
Electrorotation can be used to separate or orient any particle type. It employs conducting semicircular electrodes. In the case of polystyrene beads, an electrorotation experiment set up similarly to those of other types of particles, beads rotate at varying velocities depending on the frequency of electric field cycling. Coatings of these beads with various protein assays clearly affect their polarizability [10]. Particles’ shapes, sizes, densities, etc. affect how they respond to electrorotation. Results of the experiment by Genera Technologies Ltd. Cambridge, UK state “it is possible to determine the presence of particular proteins within a mixed sample by comparing the electrorotational spectra of complex beads with uncoated beads.” This is a way to investigate the effect of the coatings on the dielectric properties.

Figure 8 – Separating cancer cells
As mentioned earlier, to this date there are many experiments and real-world applications that use such micro-fabricated devices to manipulate molecules and cells. There are electronic applications in which carbon nanotubes are separated and/or aligned to make television screens. There are bacteria, cancer, and virus selection in vivo and in vitro that can capitalize on this aforementioned technology. The technology is being perfected in order to increase throughput, decrease size, and apply more types of scenarios all over the scientific world.

**Toward the Future**

The fundamental challenge facing the advancement of nanotechnology (the “room at the bottom” as it was initially coined) is the lack of precise tools for the manipulation of nano-scale particles. Two main methods are currently used for such manipulation and fabrication of nano-structures: self-assembly and scanning probe techniques.
Self-assembly methods have been studied extensively, relying on any number of properties and molecular interactions such as: hydrogen bonding, van der Waals, \( \pi-\pi \) stacking and hydro-phobic/philic interactions, etc. This “bottom-up” approach is very economical and efficient, but in the end, passive. Their yield can be drastically affected by macroscopic factors such as temperature and solution pH [11].

It is much more of a processing advantage to have active assembly methods that allow more robust designs. This “top-down” approach currently uses scanning probe techniques and is heavily researched to improve the field of molecular electronics. Scanning probe techniques, such as AFM and STM allow for external manipulation of nanoscale particles, down to single-atom placement with atomic scale resolution. Unfortunately, these techniques ultimately fail because, at present, it is impossible to run them in the massive parallel required for large production scale production.

Both techniques used today fall short of the ultimate goal for nanotechnological applications. AC electrokinetics and dielectrophoresis have the ability to offer the best of both worlds. With no mechanical motion, it is an efficient and extremely precise “top-down,” active approach to nanoscale assembly.

**Electrohydrodynamics and Dielectrophoresis: Scaling Laws**

Clearly, there is a strong desire to scale down electrokinetics toward the nano-regime. But there are significant barriers to overcome before this can happen perfectly, as other motion factors become prominent. As the size of the particle is reduced, the effects of Brownian motion start to become significant and will eventually dominate. This factor could be overcome by increasing the electric field in one of two ways:
increasing voltage or by reducing the system's characteristic sizes. The first is not reasonable as the voltages required are too high for a system to sustain. So the system must be scaled down. Most dielectrophoretic applications are liquid suspensions, especially of nano-scale particles, so other factors besides Brownian motion must be considered.[14] Most importantly, when generating such high electric fields, there will be a force on the suspending solution and thus induce motion in it too. This complication may actually be more severe than that of Brownian motion.

When considering hydrodynamics under intense electric fields, several factors have to be accounted for[13,15].

1) Electrothermal forces- Joule heating of the surrounding solution causes motion due to variations in conductivity.
2) Electro-osmosis- The device geometry induces a tangential electric field at the electrode-solution interface which causes a steady flow.
3) Gravity- Basic gravity actually serves as the strongest external force on a particle suspended in solution.
4) Buoyancy- Again, there exists the basic buoyant effects of a pressure differential that can induce flow.
5) Brownian motion- As aforementioned, random motion of particles due to heating energy.
6) Light-electrothermal- External light will heat the medium and cause flow similar to Joule heating.
Careful work has been done by Castellanos et. al. [13] to account for all these factors in addition to the dielectrophoretic force for a particle (latex sphere) in a simple electrode shown below:

*Figure 10 - Simple electrode used to determine scaling laws.*
In the above scenario, the characteristic length is 25µm, and scaling will be explored based on this dimension. For the above system, the equations governing all forces are:

<table>
<thead>
<tr>
<th>Force Type</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gravity</td>
<td>$0.5 \frac{a^2 \rho \Delta g}{\eta}$</td>
</tr>
<tr>
<td>Dielectrophoresis</td>
<td>$0.03 \frac{a^2 e (cV)^2}{r^4}$</td>
</tr>
<tr>
<td>Brownian displacement</td>
<td>$\sqrt{\frac{k_B T t}{3 \pi a \eta}}$</td>
</tr>
<tr>
<td>Electrothermal $(\varepsilon \omega / \sigma \ll 1)$</td>
<td>$5 \times 10^{-4} \frac{\varepsilon \sigma (cV)^4}{k_B r} \left</td>
</tr>
<tr>
<td>Electrothermal $(\varepsilon \omega / \sigma \ll 1)$</td>
<td>$2.5 \times 10^{-4} \frac{\varepsilon \sigma (cV)^4}{k_B r} \left</td>
</tr>
<tr>
<td>Buoyancy</td>
<td>$2 \times 10^{-2} \left( \frac{\partial \rho w}{\partial T} \right) \frac{\sigma (cV)^2 g r^2}{k_B \eta} t$</td>
</tr>
<tr>
<td>Light-electrothermal $(\varepsilon \omega / \sigma \ll 1)$</td>
<td>$3 \times 10^{-3} \frac{\varepsilon (cV)^2}{\eta} \left</td>
</tr>
<tr>
<td>AC electro-osmosis</td>
<td>$0.1 \Lambda \frac{a V^3}{\eta r} \frac{\Omega^2}{(1 + \Omega^2)^2} t$, $\Omega = \frac{\Lambda \omega \pi r}{2 \sigma \Delta \phi}$, $\Lambda = \frac{C_3}{(C_8 + C_{10})}$</td>
</tr>
</tbody>
</table>

*Figure 11 - Governing equations for a latex sphere in a simplified electrode.*
The above equations are quite complex, and the scaling relations can be difficult to easily grasp, so a series of graphs are provided to aid in interpretation of the above:

On the left is a particle with \( r = 0.25 \) \( \mu \text{m} \) and a solution with conductivity of \( 10^{-3} \) S m\(^{-1} \). (a) has a frequency of \( 10^2 \) Hz, (b) has a frequency of \( 10^5 \) Hz. Here it becomes clear that a small system size is needed, and the weak conductivity of the solution allows for a large area where DEP dominates. Furthermore, DEP is overridden by AC electro-osmotic forces at low frequencies. On the right, the same particle with a solution conductivity of \( 0.1 \) S m\(^{-1} \) can be seen. As expected, the region of functional DEP decreases. In the region where electro-osmotic forces dominate, with a high enough voltage, an electrolytic reaction will actually take place. In general, at high frequencies with small features, it is possible to get DEP to dominate.
The theory presented above allows for the manipulation of nano-scale particles if the characteristic features are small enough and high frequencies are supplied. And, a decrease in feature size minimizes the required frequency. Unfortunately, current e-beam lithography techniques do not allow the fabrication of electrodes small enough to manipulate true nano-particles. But, key breakthroughs have been made to combat this problem.

**Breaking the Barrier**

Long, thin structures have long been known to have enhanced polarizability, and much work has been done on such structures as DNA, nanowires, and nanotubes. These structures are easily manipulated by dielectrophoresis. With new experimentation, carbon nanotubes themselves have been used as the electrodes to achieve the electrode-size necessary to manipulate nanoparticles! The diameters of single-walled nanotubes are would definitely allow manipulation of nanoparticles one order of magnitude smaller than is possible currently. The figure below describe this scenario:

![Figure 13 - Schematic of carbon nanotube electrode.](image_url)
The governing equation for the electric field is as follows:

$$\bar{\nabla}(E_{\text{rms}}) \approx -2\left(\frac{V_{\text{rms}}}{\ln(4h/d)}\right)^2 \frac{1}{r^3} \hat{r}$$

The DEP force scales with $1/r^3$ for a nanotube-type electrode. It was mentioned above that DEP competes mainly with electrothermal forces within solution, and the governing equation for that force scales with $1/r$. Clearly then, DEP force will dominate over electrothermal forces (and Brownian motion) for the system.[16]

To test the theory above, Burke et. al.[15] has created such devices. Fabrication of a carbon nanotube electrode turns out to not be as difficult as it may have seemed at first. Nanotubes can be grown at select spots via chemical vapor deposition from lithographically defined catalyst sites. Here, photolithography is used to fabricate wells in photoresists where Fe-based catalytic mixtures are deposited. A gaseous mixture conducive to creating long, single-walled nanotubes (SWNT) is introduced and allows growth of the structure. The nanotubes are bound to the substrate (glass or silicon) by Van der Waals forces. Once this is done, SEM imaging is used to locate the nanotubes. Once located, optical lithography and sputtering can be used to fabricate traditional electrodes with electrical contact to the nanotubes. The final device is shown below:
The above device, and similar ones, was used to manipulate polystyrene nanoparticles of diameter 20 and 100 nm. The SWNTs were driven anywhere from 500 kHz to 5MHz, showing that higher frequencies are more conducive for DEP forces. Below is the result:

Figure 14 - SEM image of typical nanotube electrode.

Figure 15 - SEM image of nanoparticles attached to SWNT.
Control experiments were performed to eliminate other possible explanations, such as capillary forces, and there appears to be no other explanation for the above save DEP forces. Once “large” nanoparticle was seen to agree with theory, the device was pushed to see if it could manipulate 2 nm Gold nanoparticles. AFM was used to image this:

![AFM images](image)

*Figure 16 - AFM images (tapping and phase contact mode, respectively) of 2 nm Au nanoparticles on carbon nanotubes.*

As the above image shows, clearly the nanoparticles have been manipulated out of solution to the SWNT electrode. This research displays, for the first time, the use of an electrically active nanotube and the manipulation of 2 nm Au particles. Clearly, this is a step forward toward the use of dielectrophoresis for nanoscale assembly. It has overcome what has traditionally believed to be fundamental limits in size and widely opens the door for more research. AC electrokinetics is rapidly becoming a technique that can overcome the fundamental limitations in nanotechnology.
In Summary

AC electrokinetical theory presents a wide variety of techniques that can be employed; from the simple process of electrorotation to the “electrical highways” of Traveling Wave Dielectrophoresis. Each stands on solid physical and mathematical derivations, as outlined above. Fabrication to test these devices requires the use of an advanced lithography system known as E-beam lithography. The system’s astounding resolution capabilities are a direct product of the advanced technology making up the system. With this resolution, fascinating, and very practical devices are being fabricated each and every day to accomplish advanced research in everything from physics to biology. In medicine, these techniques are being used every day in vivo to test for cancerous cells and manipulate DNA. The number of applications is growing each day. But the biggest field standing to gain from AC electrokinetics, arguably, is the smallest one: nanotechnology. Here, the fundamental limitations of the current techniques prevent the field from any sort of mainstream viability. AC electrokinetics has been recently shown to overcome its own fundamental limitations with regards to manipulating nanoparticles. The advent of the nanotube electrode has opened the door; soon nanotechnology and electrokinetics will go hand in hand. All the “room at the bottom” will soon be bustling with atomic highways.
Sources


