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Standard Guide for Measurement of Electrophoretic Mobility and Zeta Potential of Nanosized Biological Materials[1]

This standard is issued under the fixed designation E2865; the number immediately following the designation indicates the year of original adoption or, in the case of revision, the year of last revision. A number in parentheses indicates the year of last reapproval. A superscript epsilon (ε) indicates an editorial change since the last revision or reapproval.

1. Scope

1.1 This guide deals with the measurement of mobility and zeta potential in systems containing biological material such as proteins, DNA, liposomes and other similar organic materials that possess particle sizes in the nanometer scale (<100 nm).

1.2 The values stated in SI units are to be regarded as standard. No other units of measurement are included in this standard.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.*

1.4 *This international standard was developed in accordance with internationally recognized principles on standardization established in the Decision on Principles for the Development of International Standards, Guides and Recommendations issued by the World Trade Organization Technical Barriers to Trade (TBT) Committee.*

2. Referenced Documents

2.1 *ASTM Standards:*[2]

E1470 Test Method for Characterization of Proteins by Electrophoretic Mobility (Withdrawn 2014)[3]

E2456 Terminology Relating to Nanotechnology

2.2 *ISO Standards:*[4]

ISO 13099-1 Colloidal Systems — Methods for Zeta-Potential Determination — Part 1: Electroacoustic and Electrokinetic Phenomena

ISO 13099-2 Colloidal Systems — Methods for Zeta-Potential Determination — Part 2: Optical Methods

ISO 13321 Particle Size Analysis — Photon Correlation Spectroscopy

3. Terminology

3.1 *Definitions*—Definitions of nanotechnology terms can be found in Terminology E2456.

3.2 *Definitions of Terms Specific to This Standard:*

3.2.1 *Brownian motion, n*—is the random movement of particles suspended in a fluid caused by external bombardment by dispersant atoms or molecules.

3.2.2 *dielectric constant, n*—the relative permittivity of a material for a frequency of zero is known as its dielectric constant (or static relative permittivity).

3.2.2.1 *Discussion*—Technically, it is the ratio of the amount of electrical energy stored in a material by an applied voltage, relative to that stored in a vacuum.

3.2.3 *electrophoretic mobility, n*—the motion of dispersed particles relative to a fluid under the influence of an electrical field (usually considered to be uniform).

3.2.4 *isoelectric point, n*—point of zero electrophoretic mobility.

3.2.5 *mobility*—see electrophoretic mobility.

3.2.6 *redox reaction, n*—a chemical reaction in which atoms have their oxidation number (oxidation state) changed.

3.2.7 *stability, n*—the tendency for a dispersion to remain in the same form for an appropriate timescale (for example, the experiment duration; on storage at 358K).

3.2.7.1 *Discussion*—In certain circumstances (for example water colloid flocculation) instability may be the desired property.

3.2.8 *van der Waals forces, n*—in broad terms the forces between particles or molecules.

3.2.8.1 *Discussion*—These forces tend to be attractive in nature (because such attractions lead to reduced energy in the system) unless specific steps are undertaken to prevent this attraction.

3.2.9 *zeta potential, n*—the potential difference between the dispersion medium and the stationary layer of fluid attached to the dispersed particle.

[1] This guide is under the jurisdiction of ASTM Committee E56 on Nanotechnology and is the direct responsibility of Subcommittee E56.02 on Physical and Chemical Characterization.

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[2] For referenced ASTM standards, visit the ASTM website, www.astm.org, or contact ASTM Customer Service at service@astm.org. For *Annual Book of ASTM Standards* volume information, refer to the standard's Document Summary page on the ASTM website.

[3] The last approved version of this historical standard is referenced on www.astm.org.

[4] Available from International Organization for Standardization (ISO), 1, ch. de la Voie-Creuse, CP 56, CH-1211 Geneva 20, Switzerland, http://www.iso.org.

3.2.10 *zwitterionic, n*—a molecule with a positive and a negative electrical charge.

3.2.10.1 *Discussion*—Amino acids are the best known examples of zwitterions.

4. Summary of Practice

4.1 *Introduction*—It is not the intention of this guide to spend any significant time on the theory of zeta potential and the routes by which a particle acquires charge within a system. Indeed it may be more appropriate to deal only with the movement or mobility of particles under an electrical field where conversion to zeta potential is not even attempted. The relevant text books (for example, see Hunter **(1)**[5]) should be consulted along with the more academic ISO references (ISO 13099-1 and ISO 13099-2). The IUAPC report **(2)** is also very useful, albeit fairly theoretical, but it does contain a section (4.1.2) entitled 'How and under which conditions the electrophoretic mobility can be converted into ζ-potential'. The Corbett and Jack paper **(3)** contains excellent practical advice for measurement of protein mobility and is recommended.

4.2 Test Method E1470 is based around a sole vendor's equipment, but this does not deal with the basis of the measurement or provide guidance in the practice of the measurement. It is one intention of this guide to address those deficits.

4.3 The following aspects need emphasis:

4.3.1 Zeta potential is a function of the particulate system as a whole – so the environment that the particle resides in (pH, concentration, ionic strength, polyvalent ions) will directly influence the magnitude and, in certain circumstances, the sign of the acquired charge. In particular, small quantities (parts per million) of polyvalent ions (for example calcium ions (Ca^{2+}), iron (III) ions (Fe^{3+})) or other impurities can significantly affect the magnitude of the zeta potential. It is obvious, but often ignored, that there is no such concept of the zeta potential of a powder.

4.3.2 The calculation of zeta potential from mobility measurement typically refers to the unrestricted mobility of a particle in suspension. In crowded environments (that is high concentration) particle-particle interactions occur and the movement may be hindered. In this circumstance, although a movement can be detected and measured, it may provide interpretation issues when a conversion to zeta potential is attempted.

4.3.3 Zeta potential tends only to be important in the sub-5 μm (and thus relevant to the sub-100 nm region considered in this text) region where van der Waals attractive forces are of a similar order of magnitude as inertial forces. Thus if sedimentation (function of size and density of the particle with respect to the medium it resides) is occurring or has occurred, the system is clearly not ideal for a zeta potential or mobility measurement. With significant settling the measurement of mobility is obviously compromised. The lower limit for measurement of electrophoretic mobility is in effect determined by the signal to noise which is a complex function of size, concentration and relative refractive index of the particulate system. An unambiguous statement of the lower size is therefore not possible.

4.3.4 Zeta potential and its (assumed) relation to system stability are reasonably well understood in aqueous systems. The classic examples are indicated in Thomas Riddick's text **(4)**. The obvious or stated link with formulation or product stability is not obvious for organic media where the counterions will be strongly bound to the particle surface and the position of the diffuse layer will be difficult to identify in an (effectively) insulating external medium. Again, what is often forgotten, is that conductivity is required in the 'background' solution (typically 0.001 $molL^{-1}$ sodium chloride (NaCl) is utilized) so that an electrical field can be correctly applied without effects such as electrode polarization (causing voltage irregularities) occurring. Mobility or zeta potential measurements should not be made in de-ionized water. In non-polar dispersant liquids, conversion of observed mobility to zeta potential may need some understanding of the position and thickness (single atom or molecule?) of the double layer, but this is not relevant to measurements in (aqueous) biological media.

4.3.5 It is mobility (movement) that is usually measured and the conversion to zeta potential relies on application of the Henry equation. (See also Fig. 1).

$$U_E = \frac{\varepsilon \zeta\, f(\kappa\alpha)}{6\pi\eta} \quad (1)$$

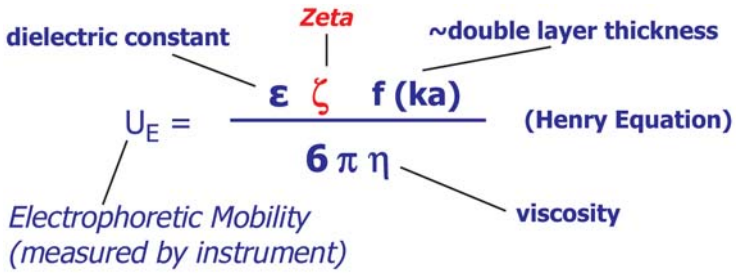

FIG. 1 Equation (1)

[5] The boldface numbers in parentheses refer to a list of references at the end of this standard.

where:

U_E = the electrophoretic mobility (measured by instrument),
ε = the dielectric constant of the dispersion medium,
ζ = the (calculated) zeta potential,
$f(\kappa\alpha)$ = Henry's function (see below), and
η = the viscosity of the medium (measured or assumed).

4.3.5.1 It is important to specify the units of measurement as failure to get these correct will lead incompatibility of units on the right and left hand side of the above equation. The normal SI units (metre, kilogram, second) are not often utilized in this area as they are too large for practical purposes (diffusion distances of one metre are not routinely encountered!) — see additional unit information in Ref. (**5**). We need to remember that the mobility and diffusion coefficient are a flux (and thus area) per unit time. The mobility will be scaled by the field (volts/distance). Ref. (**5**) recommended units for electrophoretic mobility are $m^2\ s^{-1}\ V^{-1}$. This can be expressed as $(ms^{-1})/(Vm^{-1})$ or a velocity per unit field. In practice, the electrophoretic mobility, U_E, has more convenient units of $\mu m^2/Vs$ Often mobilities are expressed in confused units (for example, the oft-utilized $\mu mcm^{-1}/Vs$ because this gives rise to mobility values in the convenient ±10 region). Mobilities expressed with a negative sign imply a negative zeta potential.

4.3.5.2 ε is the dielectric constant of the dispersion medium dimensionless/no units as it is a ratio of the relative permittivity of the material to vacuum whose relative permittivity is defined as 1.

4.3.5.3 f(κα) is usually referred to as "Henry's function" where α is the radius of the particle. κ is referred to as the Debye parameter and can be calculated from the electronic charge, Boltzmann's and Avogadro's constants, the absolute temperature and the ionic strength. The charged region around a particle falls to about 2 % of the surface charge at a distance approximately 3/κ from the particle. For ionic strength around 0.01 $molL^{-1}$ then 3/κ is around 10 nm and for ionic strength around 10^{-5} $molL^{-1}$ then 3/κ is around 280 nm (see Koutsoukos et al. (**6**)). 1/κ can be envisioned as the "thickness" of the electrical double layer (the Debye length) and thus the units of κ are reciprocal length. Thus f(κα) is dimensionless and usually assigned the value 1.00 or 1.50. For particles in polar media the maximum value of f(κα) is taken to be 1.5 (Smoluchowski approximation) and for particles in non-polar media the minimum value of f(κα) is 1 (Hückel approximation). It is the former that we are considering in this text. The literature does indicate intermediate values for f(κα) but in most biologically relevant media the value of 1.5 is the most appropriate.

4.3.5.4 In terms of viscosity, η, the SI physical unit of dynamic viscosity is the pascal-second (Pa·s), (equivalent to $N{\cdot}s/m^2$, or kg/(m·s)). Water at 293 K has a viscosity of 0.001002 Pa·s. The cgs physical unit for dynamic viscosity is the poise (P). It is more commonly expressed, particularly in ASTM standards, as centipoise (cP). Water at 293 K has a viscosity of 1.0020 cP.

NOTE 1—At room temperature (assumed 298 K) in water, all of the expressions are constants except for the (measured) mobility and the equation defers to:

$$\text{Zeta potential} = K^{*}\text{electrophoretic mobility},\ U_E \sim 12.85^{*}U_E \quad (2)$$

where the value of K (collective proportionality constant) is ~12.85 if the zeta potential is to be stated in mV and this falls out naturally from the Henry equation if the deprecated $\mu mcm^{-1}/Vs$ unit is used for electrophoretic mobility.

4.3.5.5 As well as movement under the constraint of an electric field, some degree of Brownian motion will also occur and may need to be considered. In biological media of relatively high ionic strength the Hückel model (f(κα) = 1) for zeta potential calculation is inappropriate and the value of f(κα) should be calculated from the measured size and the known ionic strength (or measured conductivity) (see Fig. 2).

4.3.6 Systems of positive charge tend to provide more measurement difficulties from a practical perspective than those of inherent negative charge. This is because most organic media including plastic sample cells are inherently negatively charged at neutral pH and may attract particles of opposite

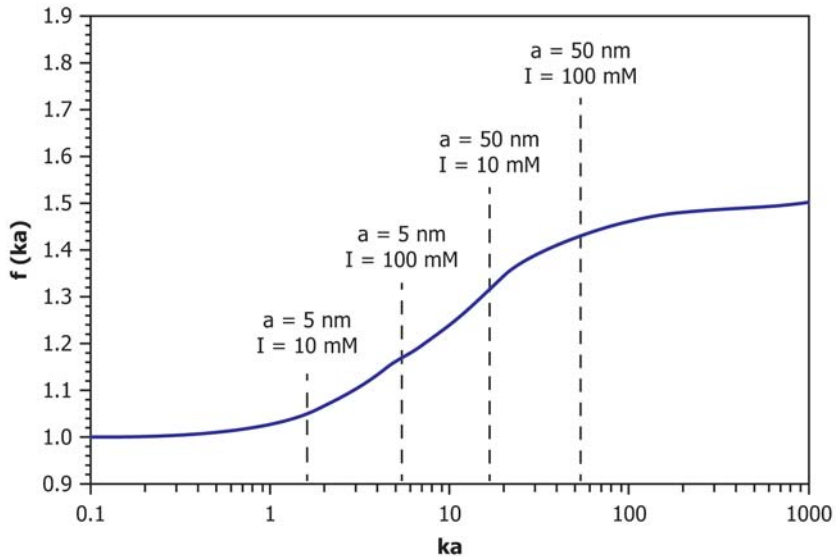

FIG. 2 Graphical Representation of the Henry Function and the κa Values for Four Example Particle Size and Ionic Strength Combinations

charge removing them from suspension and altering the wall potential. It is useful to have some form of automation for pH adjustment – for example a titrator. This eases the adjustment of pH and additive concentration.

4.3.7 It is of no value to state a zeta potential value without description of the manner in which it was measured together with vital measurement parameters. Zeta potential without a stated pH, ionic compostion, and electrolyte concentration value is close to meaningless.

4.4 *Biological Molecules and Entities*—Again, a few obvious points will need mentioning:

4.4.1 Many materials such as proteins contain charges and may be zwitterionic (contain both positive and negative charges). These molecules can be quite labile and may absorb and decompose readily under an electrical field at the electrode with the deposition of carbon (shown as electrode darkening) and gas evolution. This is a conventional redox reaction and is virtually impossible to eliminate if organic materials interact with or contact metal electrodes—the electrical field over the length of an adsorbed molecule is enormous in relation to that between the electrodes themselves. Protocols need to be aware of this possibility and seek to minimize it after appropriate investigation of the magnitude of the phenomenon. It may be virtually impossible to eliminate such decomposition for some molecules unless specific routes are taken—for example, isolation of the electrodes from the biological molecules with a porous membrane that allows ions but not larger molecules to pass through. Measurements taken quickly and at lower voltages in combination with a reduced electrode spacing (thus reducing the field) may also help in this regard but resolution will almost certainly be lost. Many hours are required in order for proteins to diffuse a few tens of millimeters; a distance between detection point and electrodes somewhat typical of many capillary based laser Doppler electrophoresis systems. It is the slow timescales associated with the diffusion coupled with measurement times of the order of minutes to tens of minutes associated with laser Doppler electrophoresis that is the enabling factor for the implementation of any diffusion barrier technique. Detection of aggregates by measurement in the forward scattering direction combined with visual inspection of (polished metal) electrodes for blackening will be good indicators of sample degradation. Obviously on a blackened oxide surface such 'deposits' will not be evident. The consequence in the measurement is typically a drift to more negative values and instability in the measurements themselves. Rapid measurements and those avoiding Joule heating may alleviate the problem somewhat but the only real solution is to prevent the protein interacting or adsorbing onto the electrode itself.

4.4.2 Biological materials may be in low concentration, may be small and are invariably of low relative refractive index (RRI) in comparison to inorganic particles and colloids. The practical aspects of this are that the scattered signal may be weak with the consequence that the mobility detected by a Doppler shift may be difficult to isolate from any background noise.

4.4.3 The availability of material may be small and thus representative sampling may need to be considered—is one drop really indicative of a bigger system? It is only possible to measure a few µL of sample with specific experimental set-ups as the electrodes need to be of a finite size and distance apart. In many instances a few millilitres of solution or suspension will make life easy, especially if flushing of a cell is needed, but this is not always available. If the material can be held as a 'plug' it may be possible to work with considerably less quantity.

4.4.4 Biological material is often contained in buffered solutions of relatively high ionic concentration. For example, phosphate buffered saline (PBS) is constituted of 0.0032 $molL^{-1}$ disodium hydrogen phosphate (Na_2HPO_4), 0.005 $molL^{-1}$ monopotassium phosphate (KH_2PO_4, 0.0013 $molL^{-1}$ potassium chloride (KCl), 0.135 $molL^{-1}$ NaCl, and is adjusted to pH 7.4. This has implications of Joule heating when voltage is applied across such a solution and the propensity of decomposition is increased in such scenarios—60 s between measurements is often recommended to allow appropriate cooling. Chloride ions often present as NaCl (say 0.9 $molL^{-1}$) can be aggressive to some electrode systems (especially the platinum group metals) and the electrode material may need investigation. The current passing through the measurement zone can be reduced by appropriate reduction of voltage or by reducing the distance between the electrodes but this is not a universal panacea.

5. Significance and Use

5.1 The magnitude of zeta potential of a system in aqueous media is often an indicator of formulation stability or a means to understanding protein charge of the system and this is the usual reason for measurement. Oft-quoted values of stability when a threshold of +30 mV or –30 mV is reached are common. This arises from Riddick's text (**4**) and it is worth reproducing his table in full:

Stability Characteristics	Average ZP, mV
Maximum agglomeration and precipitation	0 to +3
Range of strong agglomeration and precipitation	+5 to –5
Threshold of agglomeration	–10 to –15
Threshold of delicate dispersion	–16 to –30
Moderate stability	–31 to –40
Fairly good stability	–41 to –60
Very good stability	–61 to –80
Extremely good stability	–81 to –100

5.2 It is noted that –30 mV represents only 'moderate stability'—nowhere in Riddick's text (**4**) are these qualitative terms further defined: for example what is 'delicate dispersion?'. It is also noted that positive values greater than +5 mV are not noted in the table, the assumption being that it is the modulus rather than the sign of the charge that is responsible for the qualitative stability terms listed above. For smaller systems typically <1 µm, a higher magnitude of charge may be needed to confer stability in the system and nanometre-sized material may require in excess of 100 mV for adequate stability.

6. Reagents

6.1 *General:*

6.1.1 As each system is different, it is difficult to be specific about reagents. In many instances, though, an automated titrator is useful in order to add specific amounts of additive. It would be usual to have some route of pH adjustment via the