PAPER

CRIMINALISTICS

*Matthew R. Lockett,[1] Ph.D.; Katherine A. Mirica,[1] Ph.D.; Charles R. Mace,[1] Ph.D.;
Robert D. Blackledge,[2] M.S.; and George M. Whitesides,[1,3] Ph.D.*

Analyzing Forensic Evidence Based on Density with Magnetic Levitation*

ABSTRACT: This paper describes a method for determining the density of contact trace objects with magnetic levitation (MagLev). MagLev measurements accurately determine the density (± 0.0002 g/cm^3) of a diamagnetic object and are compatible with objects that are nonuniform in shape and size. The MagLev device (composed of two permanent magnets with like poles facing) and the method described provide a means of accurately determining the density of trace objects. This method is inexpensive, rapid, and verifiable and provides numerical values—independent of the specific apparatus or analyst—that correspond to the absolute density of the sample that may be entered into a searchable database. We discuss the feasibility of MagLev as a possible means of characterizing forensic-related evidence and demonstrate the ability of MagLev to (i) determine the density of samples of glitter and gunpowder, (ii) separate glitter particles of different densities, and (iii) determine the density of a glitter sample that was removed from a complex sample matrix.

KEYWORDS: forensic science, density-based measurements, analysis of contact traces, magnetic levitation (MagLev), quantitative analytical method, glitter, gunpowder

Common contact trace objects are used in forensic investigations to establish an association (i.e., link criminals to crime scenes and to victims). Most of these objects interact weakly with a magnetic field (i.e., are diamagnetic in nature)—hairs, fibers, paint chips, and fragments of broken glass. Glitter is another—less often exploited—contact trace material that has been used as associative evidence (1). Contact trace objects are characterized with tests that range in difficulty and expense, from visual or microscopic inspection to spectroscopic analysis. The density of an object is another physical parameter that could, in principle, be used to characterize a trace object. Measuring the density of an irregularly shaped object requires a displacement measurement to determine its volume. Volume measurements are difficult for small objects such as glitter particles, and thus, there exists a need for a method that makes it possible to determine the density of trace objects quickly and easily. Kirk developed a method for analyzing glass fragments that was both comparative and could be assigned a semi-quantitative value (2). This method, often called the "sink/float method," uses density columns that are prepared by mixing two organic liquids (e.g., bromoform and bromobenzene) in a specific ratio. Questioned and known glass fragments are placed together in the mixture, and the ratio of the organic liquids is adjusted until the two glass fragments are distinguished (i.e., one fragment floats to the top of the density column while the other sinks to the bottom). If the two glass fragments can be separated, then the glass samples could not have originated from the same source. If the two glass fragments cannot be separated (i.e., floated or sank together) and can also be suspended within the density column at a specific liquid ratio, then one could conclude both fragments could have originated from the same source and that their density corresponds to the density of the liquid mixture.

Magnetic levitation ("MagLev") of diamagnetic objects is a new method of determining density that is well-suited for analyzing contact trace objects: (i) it does not destroy the sample, (ii) it is readily calibrated with a series of density standards, and (iii) it is applicable to small and irregularly shaped particles. MagLev is a technique whose sensitivity can be adjusted to the application. With care, MagLev can distinguish between two diamagnetic objects whose densities differ by 0.0002 g/cm^3 (3). This technique involves placing diamagnetic samples into a container filled with a paramagnetic fluid, which is then placed between two permanent magnets. The vertical position of the sample, in the presence of the magnetic field, correlates with its density. The position of the sample is independent of mass or volume separately, and measurements of density by MagLev thus do not require standardized sample sizes (3,4). The MagLev device we use (8 cm × 6 cm × 12 cm) is both portable and inexpensive to fabricate (the NdFeB magnets cost ~$20 each) (3), and does not require additional external equipment. A MagLev-based density measurement can be obtained in a short period of time (seconds to minutes, depending on the size of the object).

[1]Department of Chemistry and Chemical Biology, Harvard University, 12 Oxford Street, Cambridge, MA 02138.

[2]8365 Sunview Drive, El Cajon, CA 92021.

[3]Wyss Institute for Biologically Inspired Engineering, Harvard University, 60 Oxford Street, Cambridge, MA 02138.

We used MagLev to determine the density of glitter samples of known density, glitter samples of unknown density, and smokeless gunpowder samples of unknown density. We determined that prolonged exposure to a solution of $MnCl_2$ (i.e., the paramagnetic solution used in our experiments) does not affect the density of a sample of smokeless gunpowder. We also determined that repeated measurements (i.e., repeated exposure to a solution of $MnCl_2$ and washing and drying steps) do not affect the density of a sample of smokeless gunpowder.

Experimental Design

MagLev Device

We establish the magnetic field in the MagLev system by aligning two NdFeB magnets (grade N50, 5 cm × 5 cm × 2.5 cm, Model #NB063-N50; Applied Magnets, Plano, TX) co-axially, 4.5 cm apart, with like poles facing each other. The relative position of an object in the vertical direction when placed in the MagLev device, its "levitation height," is reached when the gravitational (F_g) and magnetic forces (F_m) acting, in opposite directions, on the object have the same magnitude (3). We define the levitation height as "h" in Fig. 1. This position correlates, linearly, with the density of the sample. The analytical expression (and the associated assumptions and approximation) for correlating the levitation height of a sample with its density is described elsewhere (3). A detailed knowledge of the parameters involved in making this correlation (e.g., the density of the paramagnetic medium, magnetic susceptibility of the medium, the magnetic field at the surface of the magnets) or a comprehensive understanding of the physics of MagLev is not necessary and can be disregarded when density measurements are made with standards of known density.

Choice of Analytes

The objects commonly encountered in crime scenes (smokeless gunpowder, fibers, hair, glitter, etc.) are diamagnetic and thus interact weakly with an applied magnetic field. MagLev of these samples is achie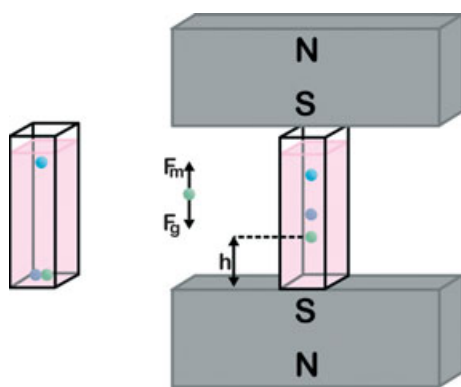ved by placing them in a solution containing a strongly paramagnetic ion. In a magnetic field gradient, suspended in a paramagnetic fluid medium, diamagnetic samples appear to be repelled from regions of high magnetic field; in actuality, the diamagnetic object displaces an equal volume of paramagnetic solution, and it is the attractive interaction between this paramagnetic volume and the regions of high magnetic field that result in MagLev. We and others have shown that a variety of aqueous solutions of paramagnetic salts (e.g., $MnCl_2$, $MnSO_4$, $GdCl_3$, $FeCl_3$, $CuSO_4$, etc.) and chelated paramagnetic ions (e.g., Gd(DTPA) and Mn(EDTA); both in aqueous and nonaqueous solutions) are suitable for MagLev (3–6).

Operating Procedure

In the MagLev experiments presented here, we placed each sample in a 1 cm × 1 cm × 4.5 cm cuvette containing $MnCl_2$ (chosen because the solutions are transparent and because manganese salts are inexpensive), capped the cuvette, and then inverted the cuvette several times to remove any bubbles that may have formed on the samples. We explored the benefits of using a degassed $MnCl_2$ solution, of adding a small amount of detergent (Tween 20, 0.1% (vol/vol)) to the $MnCl_2$ solution, and sonication of the prepared sample. The addition of detergent lowers the surface tension of the aqueous paramagnetic medium and reduces the interactions between hydrophobic objects, as well as their interactions with the walls of the cuvette. Bubbles that form on the walls of the cuvette and on the sample itself can be removed with sonication or by using a sample that has been degassed previously (e.g., the bubbles present on the sample are absorbed into the degassed solution). We found that the addition of a detergent to the $MnCl_2$ solution in addition to the brief sonication of the sample resulted in the most precise measurements; the samples were free of air bubbles by visual inspection. The presence of a bubble on a sample can greatly influence its overall density (e.g., the density of air is 0.00118 g/cm^3 at 25°C at standard pressure) (7).

We placed the cuvette between the magnets and took a photograph once the samples reached a stable levitation height (~3 min, Fig. 2). We used ImageJ, a freeware image-processing package available from the NIH (8), to determine the levitation height of each sample. Each photograph contained a ruler with millimeter markings, which we used as a reference when determining levitation height values. To analyze each image, we imported the color photograph into ImageJ and converted it into a gray scale image; we then adjusted the contrast using the "auto contrast" function and had the software outline the areas of high contrast with the "find edges" function; we then measured the distance from the bottom of the cuvette to the center of the outlined object manually, using the line tool of ImageJ. We compared the levitation height determined with ImageJ to measurements made by eye with the ruler in the photograph. We used density standard beads (purchased from American Density Materials Inc., Staunton, VA) to calibrate each measurement. The accuracy of each standard was ± 0.0002 g/cm^3. Polymers, of known density, may also be used in MagLev experiments as density standards.

FIG. 1—*Diamagnetic objects are placed in a paramagnetic solution, $MnCl_2$ in this work, and sink (purple and green spheres) or float (blue sphere) depending on the density of the object in comparison with that of the solution (left). The diamagnetic objects levitate, according to their density, when placed in a MagLev device that is composed of two magnets with like poles facing one another. The levitation height "h" of each object occurs when the gravitational force on the object (F_g) is canceled by the magnetic force (F_m) applied in the opposite direction.*

Glitter Samples

Glitter is a synthetic product, whose composition can range from tiny pieces of aluminum foil to multiple layers of plastic with (or without) an applied metal layer. Glitter is, in many ways, an ideal contact trace: it is nearly invisible, has a high
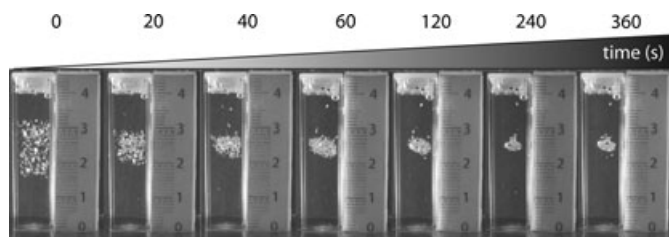
FIG. 2—*A sample of glitter (Mirror Crystalina I) was placed in cuvette containing an aqueous solution of 3.0 M $MnCl_2$, shaken to disperse the glitter throughout the solution, and placed in the MagLev device. A series of time-lapse photographs were taken to show the time required for a large number of glitter particles to reach the appropriate levitation height of 2.5 cm, determined by their density. A typical density measurement was performed with a smaller number of glitter particles than shown in these photographs; this large number of particles (~100) is for demonstration and ease of visualization. The objects above 4 cm are air bubbles at the top of the $MnCl_2$ solution.*

probability of transfer and retention, is highly individualistic, can be quickly collected and separated, small traces are easily characterized, and the measured properties of the glitter particles can be placed into a searchable database (9,10). Glitter particles can be characterized by a large number of methods: (i) visual inspection of color, shape, size, and morphology. This approach is problematic, however, as many glitter pieces do not contain dyes or pigments or have "color shifting" effects that vary with lighting and the angle of observation. (ii) The thickness of the glitter particles can be measured mechanically or spectroscopically. (iii) Attenuated total reflection Fourier transform infrared spectroscopy and Raman microspectroscopy provide insight into the chemical structure of the polymers and coatings used in glitter production (9).

Glitter particles, obtained from a commercial vendor, have density values ranging from 1.2–2.5 g/cm^3 (11). Density measurements of glitter particles could provide valuable insight when: (i) two pieces of glitter have a similar shape and color but have different densities, (ii) two pieces of glitter are composed of the same polymer base but differ in density because of the materials applied to them (organic dyes, polymeric materials, and metal particles), (iii) the heterogeneity of two glitter samples, determined from the range of observed levitation heights, is different.

Smokeless Gun Powder Samples

Smokeless powders are a class of explosive propellant, consisting of gelatinized nitrocellulose with double base powders containing nitroglycerin, which produce very little smoke upon deflagration (12). The decomposition of each of these compounds results in the release of nitrates and requires that a stabilizer be added, typically diphenylamine (13). The ratio of each of these materials, as well as methods of batch preparation, can result in density differences in smokeless gunpowder samples/batches. Smokeless powders are encountered in forensic science in the form of residues from gunshots or explosive devices (14). The shape and size of the powder particles have marked differences on the burning rate and power generation, with many powders being disk-, cylinder-, or ball-shaped. There are a number of analytical techniques that are used to narrow the number of brands of smokeless powders to one or a few; this process begins with morphological characterization and then proceeds to other types of physical and chemical characteristics (15).

Analysis of MagLev Data

We prepared stock solutions of $MnCl_2$ and used them throughout the experiments. The use of density standard beads ensured that minor changes in the relative $MnCl_2$ concentration were accounted for. The Results and Discussion section provides detailed information of the concentrations of $MnCl_2$ and the density of the standards used in each experiment.

We made seven measurements of levitation height for each sample. We measured the distance from the bottom of the cuvette to the vertical midpoint of each object to determine its levitation height. In a single measurement of levitation height, we placed three pieces of gunpowder or 10–20 pieces of glitter in the appropriate $MnCl_2$ solution. An excess of glitter was used to prepare Figs 2 and 3, for easier visualization. These figures are not representative of an actual experiment.

We placed a ruler, with millimeter markings, next to the cuvette containing the sample to make preliminary measurements of height and to aid in making height relationships by eye. We measured the levitation height of each object with the ImageJ software package. We determined the average height of the glitter (or gunpowder) samples, as well as their deviation from the mean, for each MagLev measurement. The standard deviations reported in this work were calculated with standard
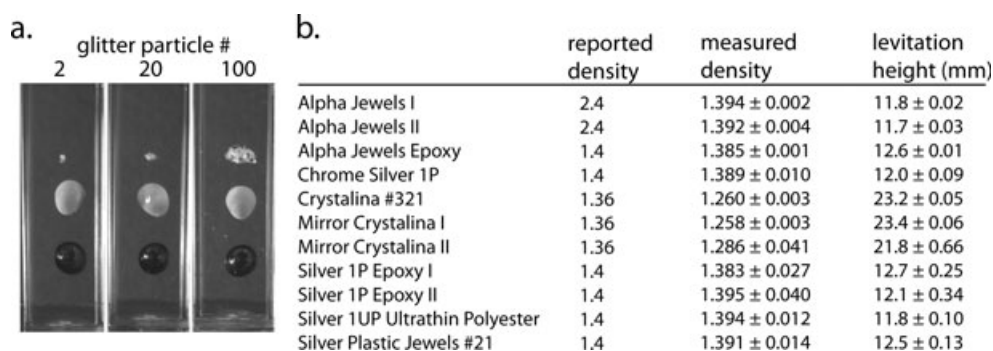

	reported density	measured density	levitation height (mm)
Alpha Jewels I	2.4	1.394 ± 0.002	11.8 ± 0.02
Alpha Jewels II	2.4	1.392 ± 0.004	11.7 ± 0.03
Alpha Jewels Epoxy	1.4	1.385 ± 0.001	12.6 ± 0.01
Chrome Silver 1P	1.4	1.389 ± 0.010	12.0 ± 0.09
Crystalina #321	1.36	1.260 ± 0.003	23.2 ± 0.05
Mirror Crystalina I	1.36	1.258 ± 0.003	23.4 ± 0.06
Mirror Crystalina II	1.36	1.286 ± 0.041	21.8 ± 0.66
Silver 1P Epoxy I	1.4	1.383 ± 0.027	12.7 ± 0.25
Silver 1P Epoxy II	1.4	1.395 ± 0.040	12.1 ± 0.34
Silver 1UP Ultrathin Polyester	1.4	1.394 ± 0.012	11.8 ± 0.10
Silver Plastic Jewels #21	1.4	1.391 ± 0.014	12.5 ± 0.13

FIG. 3—*(a) A sample of glitter (Crystalina #321) was levitated in a cuvette containing 3.0 M $MnCl_2$ and two density standards (1.350 and 1.450 g/cm^3; light and dark color, respectively). Each sample (containing 2, 20, or 100 pieces of glitter) was placed in the MagLev device, and photographs were taken after 360 sec. (b) Density values for each glitter sample were analyzed (measured density) and the density values reported by the manufacturer (reported density). The reported values are from seven independent measurements, with each measurement containing 20 pieces of glitter.*

error propagation methods (16), and account for each MagLev measurement.

Results and Discussion

MagLev as an Analytical Tool in Forensic Science

We measured the density of 11 samples of glitter, each of which was silver in color, by MagLev. We obtained glitter samples from Meadowbrook Inventions (Bernardsville, NJ) and Table 1 summarizes their properties. We levitated each sample of glitter in an aqueous solution of 3.0 M $MnCl_2$; we used density standard beads with densities of 1.350 and 1.450 g/cm^3 to extrapolate the density of each piece of glitter. Fig. 3a contains images of Crystalina #321 (Table 1) at 0 and 360 sec after the cuvette of glitter was placed in the MagLev device. We waited for approximately 3 min before obtaining photographs of the levitated glitter and gunpowder samples, based on the time series photographs obtained in Fig. 2.

The density of each glitter sample was measured using Mag-Lev, with a standard deviation of ± 0.001 g/cm^3—based on $n = 7$ independent measurements, with each measurement containing ~20 pieces of glitter—and compared with the density values provided by the manufacturer. The relative standard deviation for each glitter sample was <3.0%.

The measured densities for the 11 glitter samples can be broken down into three categories, when compared to the density values reported by the manufacturer: in high agreement with an average density difference of <0.05 g/cm^3, moderate agreement with an average density difference of >0.05 g/cm^3 but <0.10 g/cm^3, and low agreement with an average density difference of >0.10 g/cm^3. Seven samples were in high agreement with the reported density values, two samples were in moderate agreement, and two samples differed by more than 1.0 g/cm^3 from the reported density values (Alpha Jewels I and II). It should be noted that each of the density values measured by MagLev are less than those reported by the manufacturer, however, when rounded to an equivalent number of significant figures six of the 11 samples match.

TABLE 1—*Glitter samples that were analyzed with MagLev.*

Glitter Sample*	Thickness (μm)	Size (μm)	Shape
Alpha Jewels I[†]	25	204 × 204	Square
Alpha Jewels II[†]	25	635	Hexagonal
Alpha Jewels Epoxy[‡]	50	635	Hexagonal
Chrome Silver 1P[§]	178	635	Hexagonal
Crystalina #321[¶]	28–36	635	Hexagonal
Mirror Crystalina I[¶]	28–36	635	Hexagonal
Mirror Crystalina II[¶]	28–36	204 × 204	Square
Silver 1P Epoxy I[§]	25	102 × 102	Square
Silver 1P Epoxy II[§]	178	102 × 102	Square
Silver 1UP Ultrathin Polyester[§]	13	635	Hexagonal
Silver Plastic Jewels #21**	178	380 × 380	Square

*The composition of each glitter particle, as reported from Meadowbrook Inventions, Inc.

[†]Holographic glitter particles consisting of micro-embossed vacuum metalized (0.5% aluminum) polyethylene terephthalate (PET).

[‡]Holographic glitter particles consisting of micro-embossed aluminum copolymer particles.

[§]Metallic glitter particles consisting of vacuum metalized (0.5% aluminum) pigmented PET.

[¶]Iridescent glitter particles with a polyester/acrylic optical core and a polyester outer layer.

**Metallic glitter consisting of a copolymer.

We determined the density of a glitter sample, of unknown density, from commercial nail polish. We separated the glitter particles from the polish by dissolving 0.5 g of the product in 5 mL of acetone, which we then collected by passing the solution through a piece of Whatman 1 quantitative filter paper (GE HealthCare Life Sciences, Pittsburgh, PA). Griggs et al. (17) extracted shimmer particles from commercial make-up samples with a similar procedure. The density of the glitter contained in "New York Color starry silver glitter" (1.274 ± 0.034 g/cm^3) and "Sally Hansen diamond strength no chip nail polish" (1.276 ± 0.025 g/cm^3) was determined. To ensure that the extraction process employed successfully removed any polish residue from the glitter particles, and thus provided an accurate density measurement, we placed approximately 30 pieces of Alpha Jewels I glitter (1.394 ± 0.002 g/cm^3) into 0.25 g of Sally Hansen diamond strength nail polish and repeated the extraction and collection process. We compared the levitation height (i.e., the density) of the Alpha Jewels I glitter before and after acetone extraction and found the height of each sample to be within the standard deviation of the measurement. This method of extracting glitter from nail polish samples is, thus, an accurate means of obtaining density values from complex cosmetic matrices.

We determined the density of six smokeless gunpowder samples; the results are summarized in Fig. 4b. We levitated each sample in 4.0 M $MnCl_2$ (except for Hercules Red Dot, which we levitated in 3.0 M $MnCl_2$) with 1.450 and 1.800 g/cm^3 density standard beads. We investigated the effect of repeated exposure and/or prolonged exposure to an aqueous $MnCl_2$ solution, which is very acidic in nature with a pH of ~3.0, on the density of gunpowder samples. We placed Hercules Blue Dot samples into a solution of 4.0 M $MnCl_2$, and the density was measured every 24 h for a total of 7 days. The presence of density standards provided a means of accounting for evaporation of water from the solution and thus changes in the solution density. The change in the average density of the gunpowder after 7 days of exposure to aqueous $MnCl_2$ was 0.012 g/cm^3, which is within the standard deviation of the initial measurements.

The density of Hercules Blue Dot gunpowder is also not affected by repeated exposures to $MnCl_2$ solution. We levitated a sample of gunpowder for 10 consecutive measurements, to determine whether repeated exposure to $MnCl_2$ causes changes in the density of the sample. We placed the gunpowder into the $MnCl_2$ solution, levitated it in the MagLev device, removed it from the $MnCl_2$ solution, rinsed it with water, dried it with nitrogen, and repeated the process. The levitation height variation for

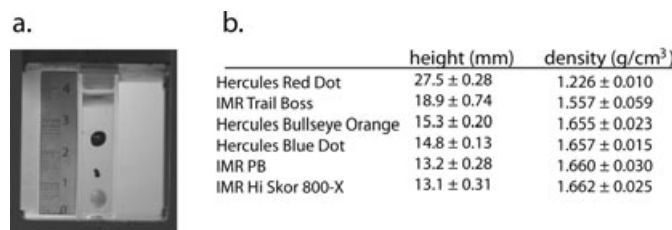|	height (mm)	density (g/cm³)
Hercules Red Dot	27.5 ± 0.28	1.226 ± 0.010
IMR Trail Boss	18.9 ± 0.74	1.557 ± 0.059
Hercules Bullseye Orange	15.3 ± 0.20	1.655 ± 0.023
Hercules Blue Dot	14.8 ± 0.13	1.657 ± 0.015
IMR PB	13.2 ± 0.28	1.660 ± 0.030
IMR Hi Skor 800-X	13.1 ± 0.31	1.662 ± 0.025

FIG. 4—*(a) A sample of gunpowder (Hercules Blue Dot) was levitated in a cuvette containing a 4.0 M $MnCl_2$ solution, and two density standards (1.450 and 1.800 g/cm^3; dark and light color, respectively) were placed in the MagLev device and a photograph taken after 360 sec. (b) The levitation height and corresponding density values for each gunpowder sample were analyzed. The reported values are from seven independent measurements, with each measurement containing three pieces of gunpowder.*

each measurement was within the standard deviation determined in Fig. 4b.

Density-Based Separation of Mixtures with MagLev

MagLev can also separate a mixture of objects by their density. We separated a mixture of glitter of similar size and shape (Mirror Crystalina I and Chrome Silver 1P), which were indistinguishable by eye as they have the same shape and size; the relative thicknesses of the two glitter samples are easily determined, however, with a light microscope (Fig. 5a). A mixture of multiple densities is readily separated in the MagLev device (Fig. 5b) and allows samples that are indistinguishable by eye (or via microscopy) to be separated. An added benefit of separation by MagLev is that samples can be readily sorted: a mixture is placed within the MagLev device, each sample reaches it appropriate levitation height based on density, the sample is removed from the magnet, and each discreet sample is collected before the mixture recombines (e.g., glitter is readily removed from the MagLev solution with a Pasteur pipette).

Sources of Error in a MagLev Measurement

There are a number of errors that can result in an inaccurate density measurement; therefore, care must be taken when performing a measurement with MagLev. Errors in solution preparation can result in measured density values that are higher or lower than expected.

Incorrect density measurements can also arise if the concentration of the paramagnetic solution changes over time (e.g., by solvent evaporation). Density standards afford an absolute measure of density and reduce incorrect readings caused by variations in the concentration of ions in the paramagnetic solution. An added benefit of using density standards is that measurements made in different laboratories and under different experimental conditions (i.e., temperature, humidity, etc.) are comparable.
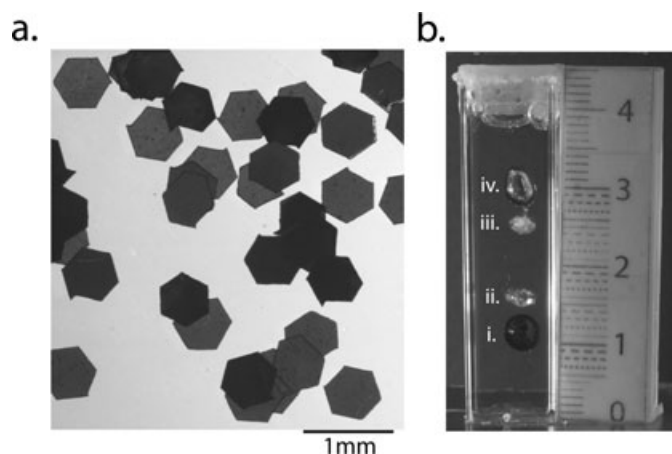

FIG. 5—(a) An optical microscope image of a mixture of Mirror Crystalina I and Chrome Silver 1P glitter samples. The two glitter samples are difficult to distinguish without the aid of a microscope, as they are the same size and shape. Their relative darkness is representative of their differences in thickness. (b) The mixture was placed in a cuvette containing 3.0 M $MnCl_2$, placed in the MagLev device, and a photograph was taken after 360 sec. The cuvette contains (i) a 1.450 g/cm³ density standard, (ii) the sample of Chrome Silver 1P glitter, (iii) the sample of Mirror Crystalina I glitter, and (iv) a 1.350 g/cm³ density standard. The mixture of glitter contained ~50 pieces of each glitter type.

The presence of air bubbles on a sample results in a density measurement that is less than the true density value, as air is much less dense than a typical sample. It is important to eliminate air bubbles from a sample before conducting a measurement. We measured the density of a glitter sample (Mirror Crystalina I) in cuvettes containing 3.0 M $MnCl_2$ solutions prepared under a variety of conditions: a $MnCl_2$ solution, a $MnCl_2$ solution containing 0.1% (vol/vol) detergent (Tween 20), and a $MnCl_2$ solution that was degassed. The glitter sample was added to each solution, inverted several times to thoroughly mix the glitter particles, inspected by eye for the presence of bubbles, and a density measurement taken. The average levitation height for each sample preparation was within the standard error of the other measurements (i.e., within 95% confidence, with $n = 7$ measurements of 20 pieces of glitter per measurement).

We then sonicated each cuvette for 20 sec to remove excess, and difficult to see, bubbles that had collected on the walls of the cuvette or the samples. In the absence of detergent, sonication of the samples resulted in a number of glitter particles adhering to the walls of the cuvette that were very difficult to remove. The spread of levitation heights of glitter within the cuvette was reduced when detergent was present and the sample was sonicated. Removing bubbles from samples is imperative to obtain an accurate density measurement. We found that adding a small amount of detergent (Tween 20, 0.1% (vol/vol)) and quickly sonicating the solution resulted in the most reproducible measurement of density for the glitter particles. The average density measurement obtained for each glitter sample was similar, independent of the solution conditions (e.g., the addition of detergent, sonication of the sample). The standard deviations for the glitter samples, however, were larger when detergent was not added and the sample was not sonicated.

The presence of tightly adhered particles (e.g., dust, grit, etc.) whose densities are different than the sample of interest will lead to an inaccurate density measurement. Careful preparation methods, in which the sample is cleaned but not altered, are needed to ensure that unwanted materials are removed from the sample. We have shown that the removal of nail polish from a glitter sample (via a simple extraction process with acetone and a filtration step) does not alter its density. Similar preparation processes can be implemented for other samples. The practice of carefully preparing and analyzing samples of interest is an integral part of forensic science and quantitative analytical chemical methods.

Conclusions

MagLev is a convenient and low-cost means for accurately determining the density (with a resolution of 0.001 g/cm³ readily achievable, and a resolution of 0.0002 g/cm³ with experimental care) of a diamagnetic object. The density of an object can be determined from its levitation height in the MagLev device. The density values obtained from a sample, when compared with known density standards, are not dependent on the MagLev device used. Thus, any forensic laboratory using MagLev could contribute to a generally available database and also access it for an estimate of how common or rare their sample might be.

An accurate density determination can aid in determining whether a questioned sample is, in fact, different from a known sample. We have demonstrated that the density of trace objects, glitter particles and smokeless gunpowder, can be determined with the MagLev system. We have shown that repeated density measurements and prolonged storage of trace objects in aqueous $MnCl_2$ do not affect their density. We show that trace objects

found in commercial cosmetic products can be extracted and their densities analyzed. We show that density measurements can differentiate glitter particles that are similar in appearance.

References

1. Grieve MC. Glitter particles: an unusual source of trace evidence. J Forensic Sci Soc 1987;27(6):405–12.
2. Kirk PL. Density and refractive index: their application in criminal identification. Springfield, IL: Thomas, 1951.
3. Mirica KA, Shevkoplyas SS, Phillips ST, Gupta M, Whitesides GM. Measuring densities of solids and liquids using magnetic levitation: fundamentals. J Am Chem Soc 2009;131(29):10049–58.
4. Mirica KA, Phillips ST, Mace CR, Whitesides GM. Magnetic levitation in the analysis of foods and water. J Agric Food Chem 2010;58(11):6565–9.
5. Mirica KA, Phillips ST, Shevkoplyas SS, Whitesides GM. Using magnetic levitation to distinguish atomic-level differences in chemical composition of polymers, and to monitor chemical reactions on solid supports. J Am Chem Soc 2008;130(52):17678–80.
6. Andres U. Magnetohydrodynamic & magnetohydrostatic methods of mineral separation. New York, NY: John Wiley & Sons, 1976.
7. Haynes WM, editor-in-chief. CRC handbook of chemistry and physics, 91st edn. Cleveland, OH: CRC Press, 2010.
8. Rasband WS. Image J. US National Institutes of Health, 1997–2011, http://imagej.nih.gov/ij/ (accessed June 26, 2012).
9. Blackledge RD, Jones EL Jr. All that glitters is gold! In: Blackledge RD, editor. Forensic analysis on the cutting edge: new methods for trace evidence analysis. Hoboken, NJ: Wiley Interscience, 2007;1–32.
10. Aardahl K, Kirkowski S, Blackledge RD. A target glitter study. Sci Justice 2005;45(1):7–12.
11. Meadowbrook Inventions Inc., Bernardsville, NJ, USA, 2011, http://www.meadowbrookinventions.com (accessed June 26, 2012).
12. Heramb RM, McCord BR. The manufacture of smokeless powders and their forensic analysis: a brief review. Forensic Sci Commun 2002;4(2).
13. Espinoza EO, Thornton JI. Characterization of smokeless gunpowder by means of diphenylamine stabilizer and its nitrate derivatives. Anal Chim Acta 1994;2:57–69.
14. Tilstone WJ, Savage KA, Clark LA. Encyclopedia of forensic science: an encyclopedia of history, methods, and techniques. Santa Barbara, CA: ABC-CLIO, Inc, 2006.
15. Moorehead W. Characterization of smokeless powders. In: Blackledge RD, editor. Forensic analysis on the cutting edge: new methods for trace evidence analysis. Hoboken, NJ: Wiley Interscience, 2007;241–68.
16. Skoog DA, Holler JF, Nieman TA. Principles of instrumental analysis, 5th edn. Fort Worth, TX: Saunders College Publishing, 1998.
17. Griggs S, Hahn J, Bonner HKS. Shimmer as forensic evidence. Global Forensic Sci Today 2011;1(10):19–23.

Additional information and reprint requests:
George M. Whitesides, Ph.D.
Department of Chemistry and Chemical Biology
Harvard University
12 Oxford Street
Cambridge, MA 02138
E-mail: gwhitesides@gmwgroup.harvard.edu