Demonstrations of the action and reaction law and the energy conservation law using fine spherical plastic beads

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A Khumaeni[1], S Tanaka[1], A Kobayashi[1], Y I Lee[2], K H Kurniawan[3], K Ishii[1] and K Kagawa[1]

[1] Department of Physics, Faculty of Education and Regional Studies, University of Fukui, Fukui 910-8507, Japan
[2] Department of Physics, Research Institute of Physics and Chemistry, Chonbuk National University, Chonju 561-756, Republic of Korea
[3] Research Centre of Maju Makmur Mandiri Foundation, 40 Srengseng Raya, Kembangan, Jakarta Barat 11630, Indonesia

E-mail: Kagawa@edu00.f-edu.fukui-u.ac.jp

Abstract
Equipment for demonstrating Newton's third law and the energy conservation law in mechanics have successfully been constructed utilizing fine spherical plastic beads in place of metal ball bearings. To demonstrate Newton's third law, special magnetized Petri dishes were employed as objects, while to examine the energy conservation law, a large-angle frictionless slope ($\theta = 50°$) consisting of a thin plastic sheet on which the fine plastic beads were attached by the electrostatic force was employed. Using this method, a quantitative measurement of the energy conservation law was successfully carried out with a small error of less than 3%. A great advantage of this frictionless method is that we can use the same object (a Petri dish) to demonstrate many kinds of mechanics laws, such as the first, second and third laws of motion, the momentum conservation law, and the energy conservation law.

Introduction

Mechanics is the most fundamental subject in all branches of physics. It is difficult to study other fields of physics without mastering the general laws in mechanics. Thus, it is necessary for students to comprehensively grasp the concepts of mechanics. However, in most senior high-school classes, physics is taught theoretically, and teachers ask the students to practise solving physics problems related to the theory studied. In this case, the students still do not have clear concepts, and finally they come to dislike physics. This is a serious problem for countries in which science and technology are crucial for future development. In order to overcome this problem, demonstration experiments, namely visualizing and observing actual phenomena that are being studied theoretically, should be carried

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out to convey the complete concept. However, experiments related to fundamental mechanics laws, such as the first, second and third laws of motion, the momentum conservation law, and the energy conservation law (between the potential energy and the kinetic energy) are generally difficult to carry out because of the effect of friction between the object and the plate surface.

Recently, experimental equipment and tools which can be employed to demonstrate the energy conservation law, such as the rail slope, pendulum assembly and cars with low friction wheels, have become commercially available [1, 2]. Unfortunately, such equipment is hard to obtain in developing countries; it is expensive and the materials are unfamiliar to students. In addition, each of them can only be used for limited purposes and cannot be applied for many kinds of demonstration in mechanics.

On the other hand, many years ago, a new method was developed by utilizing small metal ball bearings (diameters of 1–2 mm on average) to significantly reduce the friction on a plate surface, as reported in the Nuffield O-level course [3, 4]. This technique can applied for some demonstrations in mechanics such as Newton's laws of motion and the momentum conservation law. However, in this equipment, the object should have a large mass (about 1 kg), and the frictionless plate cannot be inclined because the ball bearings fall down due to their weight. Therefore, the frictionless plate also has limitations in mechanics demonstrations.

In our previous paper [5], we presented frictionless movements using fine plastic beads (spheres, about 0.3 mm in diameter) in place of the metal ball bearings which were used in Nuffield physics. By this technique, the fundamental mechanics laws, such as the first law of motion and the momentum conservation law using a collision between two objects (aluminium discs, 50 mm in diameter and 5 mm in thickness) have successfully been demonstrated. Also, uniformly accelerated motion was demonstrated using a tilted frictionless plate. All of the demonstrations were carried out using familiar objects with light mass, such as Petri dishes, flat cosmetic lids, and aluminium discs. Furthermore, this experimental method is not only limited to making qualitative observation but also allows making quantitative measurements by using a stroboscopic technique. We have confirmed in actual classes that this method is very effective and that students can learn physics with much enjoyment. This innovative method can solve the present problem in physics education. In order to extend the experiment using our frictionless plate, this article deals with the third law of motion and the energy conservation law.

Experimental procedure

In this study, we have devised two kinds of frictionless plate. One is a big frictionless plate mainly used for demonstrating many kinds of experiment in a big class, and the other was constructed for small group experiments, as displayed in figures 1(a) and (b), respectively. The big frictionless plate was made of a good quality flat glass plate (with dimensions of 850 mm × 1700 mm and a thickness of 3 mm). The glass plate was placed on a black acrylic plate (with a thickness of 3 mm) of the same size as the glass plate, and they were put on a wooden plate of good quality flatness and hardness (with dimensions of 920 mm × 1840 mm and a thickness of 20 mm). This equipment was then fixed on a commercial, movable desk (with a length of 1800 mm, a width of 60 mm and a height of 70 mm). In order to demonstrate the movement of the object on the slope, one side of the frictionless plate was equipped with a slope made of a plastic sheet (Kasai Sangyo Co. LTD, K72116, with a thickness of 0.5 mm) attached to an acrylic plate (dimensions of 130 mm × 700 mm, with a thickness of 10 mm); the plastic sheet was smoothly attached to the horizontal glass plate and fixed using vinyl tape. It should be mentioned that the plastic surface should have enough tension to sustain the object(s) moving on the plastic sheet. Rubber bands (of size 320 mm × 17 mm × 1.1 mm) were employed as sidewalls of the frictionless glass plate by expanding them about twice their length, and each of the two ends of the rubber bands was fixed by a nail. In this method, the Petri dish continued to move back and forth with repeated collisions on the horizontal frictionless plate, on which the two parallel rubber bands were placed at a distance of 850 mm. This qualitatively proved that the friction between the object and the glass plate is very low and that the lost energy due to the collision between the object and the rubber bands is very low. This equipment is a little different from that we reported in our previous paper: namely, the

(a) (b)

Figure 1. (a) Large frictionless glass plate equipped with a large-angle frictionless slope. (b) Small frictionless glass plate.

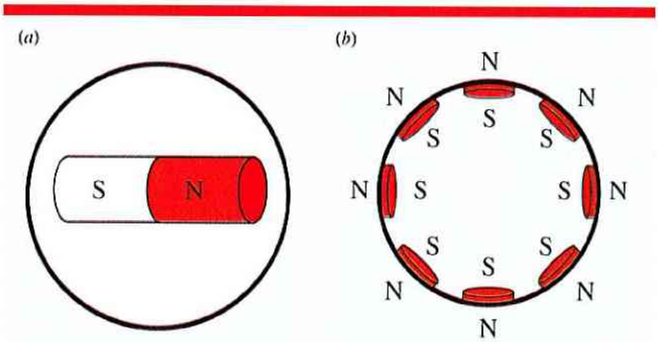

Figure 2. Illustration of (*a*) a petri dish with a rod magnet. (*b*) A petri dish with an assembly of small neodymium magnets.

previous frictionless plate was constructed using an all-glass plate, including the sidewalls. In such a case, energy was lost in the collisions taking place between the object and the glass wall, which were accompanied by a loud noise.

Another frictionless plate (dimensions of 890 mm × 580 mm) was also constructed in almost the same manner as in the case of the large frictionless plate; a blue acrylic plate was used instead of a black acrylic plate. In this case, the frictionless plate does not have any slope. Rubber bands were also attached to the four sides of the frictionless plate.

The plastic beads used in this experiment are commercially available (Nakamura Rika Kogyo D-20-1406-01); they have been used in demonstrating artificial rainbows in schools in Japan for many years. There are no serious health and safety issues related to the use of styrocell beads in this experiment. The density of the scattered beads is around 10–30 cm^{-2}; it should be mentioned that the density should not be too high because the friction coefficient will increase otherwise. In this experiment, the objects used for the third law demonstration were Petri dishes (65 mm in diameter and 31 g in mass) in which a rod magnet (with a length of 50 mm, diameter of 5 mm and mass of 14 g) was fixed at the centre, as illustrated in figure 2(a). For convenience, in this article we will call such a Petri dish a magnetized Petri dish. Figure 2(b) shows an illustration of another magnetized Petri dish, specially designed for the third law demonstration by utilizing eight small neodymium magnets (10 mm in diameter

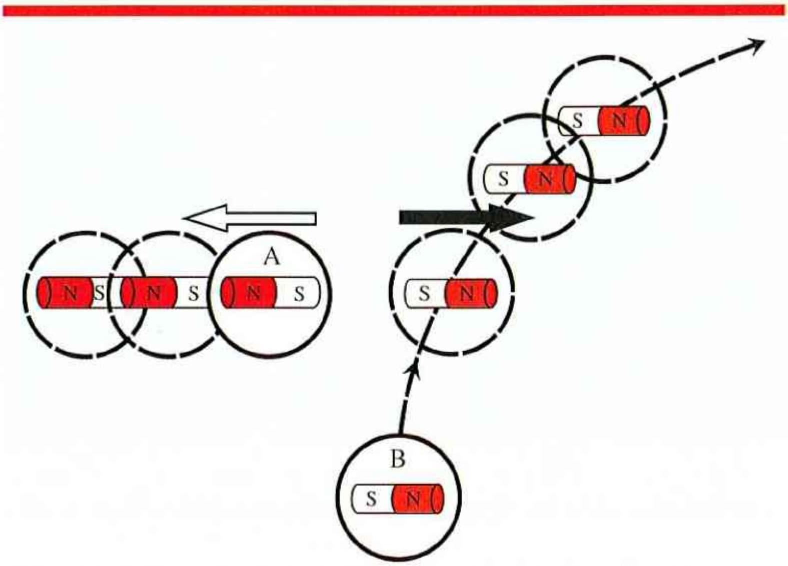

Figure 3. An illustration of Newton's third law demonstration using rod magnetized petri dishes which move on a glass frictionless plate.

and 5 mm in thickness) uniformly distributed in the inner wall of the Petri dish. The small magnets were then fixed using a Styrofoam. The mass of the magnetized Petri dish is 60 g. A stroboscopic method using an electronic flash lamp (with a flash repetition of 3 Hz) was employed to record the Petri dish movement. The tops of the Petri dishes were designed differently to distinguish them. The Petri dish movement was recorded by a digital camera. In order to demonstrate the energy conservation law (between the potential energy and the kinetic energy), a small Petri dish (45 mm in diameter and 18.2 g in mass) was used as an object. The object was released at a certain height up the slope and then the speed of the object was measured by a digital speed meter (Nakamura Rika Kogyo, S77-1320) just after the moving Petri dish arrived at the frictionless horizontal plate.

Results and discussion

Generally, it is very difficult to understand the action–reaction law (Newton's third law of motion) because we cannot directly see the existence of the force. In ordinary high-school textbooks, the action–reaction law is explained using two springs connected to each other. When one spring expands, the other spring is also extended due to the action–reaction force. However, with this demonstration, students cannot satisfactorily understand the concept of the third law.

In order to overcome this problem, we have developed an interesting and much more understandable method using a frictionless plate. In this method, two magnetized Petri dishes, in which a rod magnet was fixed at the centre of each Petri dish, were employed as objects. Figure 3 is an illustration demonstrating the action–reaction law using the two magnetized Petri dishes on the frictionless plate. One Petri dish, marked 'A', was fixed, while the other magnetized Petri dish, marked 'B', moved with a constant speed close to magnetized Petri dish 'A'. The orbit of magnetized Petri dish 'B' was suddenly bent at the closest region due to the action force from magnetized Petri dish 'A'. Simultaneously, magnetized Petri dish 'A' started moving due to the reaction force from magnetized Petri dish 'B'. It should be noted that the speed of magnetized Petri dish 'B' decreased after bending because part of the kinetic energy was used as that of magnetized Petri dish 'A'. This demonstration is easily understandable by students. However, it does not always succeed, because the movements of the magnetized Petri dishes are unstable and they attract each other.

In order to resolve this instability problem, the rod magnet was replaced by an assembly of small magnets, as shown in figure 2(b); namely, eight small neodymium magnets, which have strong

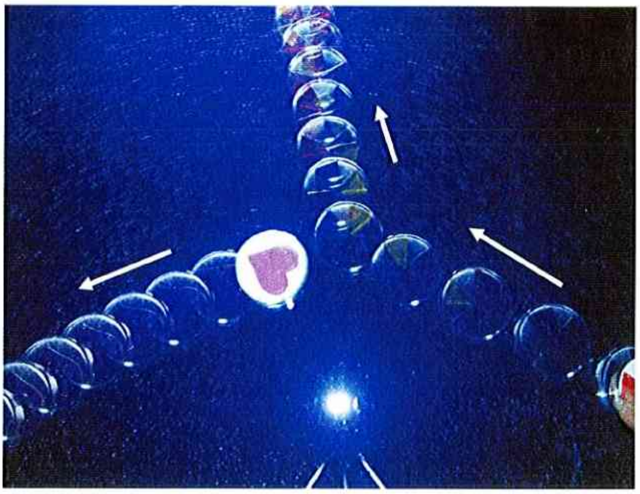

Figure 4. Stroboscopic photograph demonstrating Newton's third law using Petri dishes with an assembly of small neodymium magnets. The repetition of the stroboscopic flash is 3 Hz.

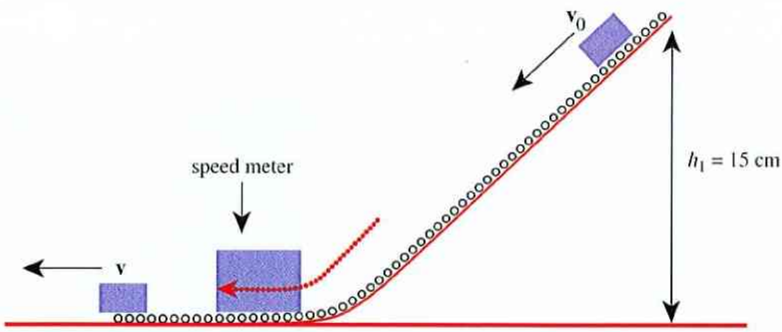

Figure 5. An illustration of the energy conservation law experiment using a plastic sheet with fine plastic beads attached to it.

magnetic forces, were uniformly arranged in the inner wall of the Petri dish. When we use these special magnetized Petri dishes, a repulsion force always exists between them without rotation. Figure 4 shows a stroboscopic photograph for demonstrating the third law of motion using these special magnetized Petri dishes. The magnetized Petri dishes have different marks to distinguish them. We confirmed using a questionnaire that the students were really satisfied and accepted Newton's third law. It should be mentioned that when we sent the magnetized Petri dish along the straight line which connects the centre of the two magnetized Petri dishes too close to another magnetized Petri dish, the speed of the magnetized Petri dish decreased with time and finally stopped, while the other magnetized Petri dish started moving along the line, at the same speed as the former Petri dish. This is a phenomenon due to the action–reaction law. However, it is difficult for students to distinguish it from the ordinary demonstration of the momentum conservation law.

The energy conservation law is also a very important concept in mechanics. In demonstrations of the energy conservation law, teachers usually use a spherical ball as an object. The object is released to fall down a large-angle slope. By using this equipment, the measured speed does not coincide with the theoretical value because some of the potential energy is used in rotating the object. As reported in previous work [5], we have successfully demonstrated

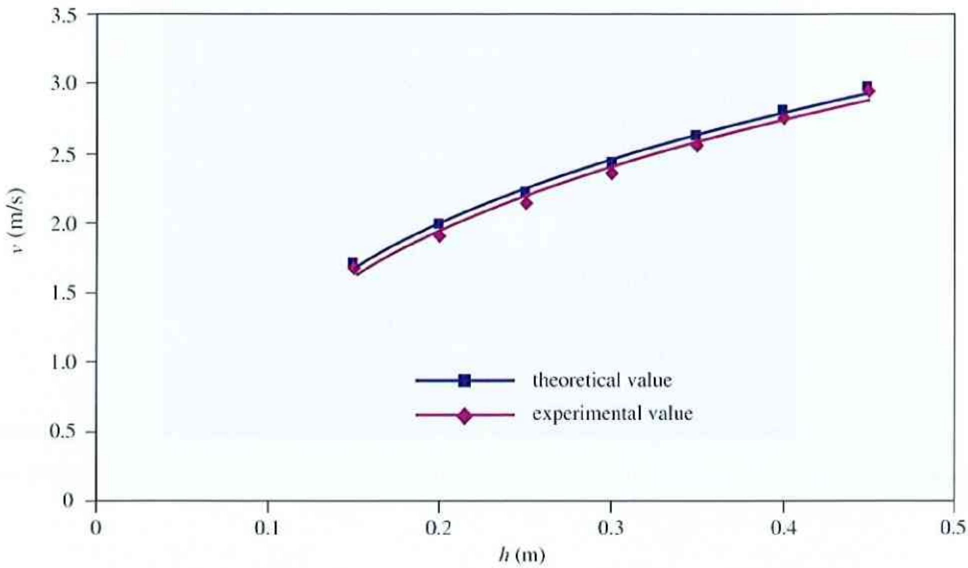

Figure 6. The relationship between the measured speed (v) and the position (h).

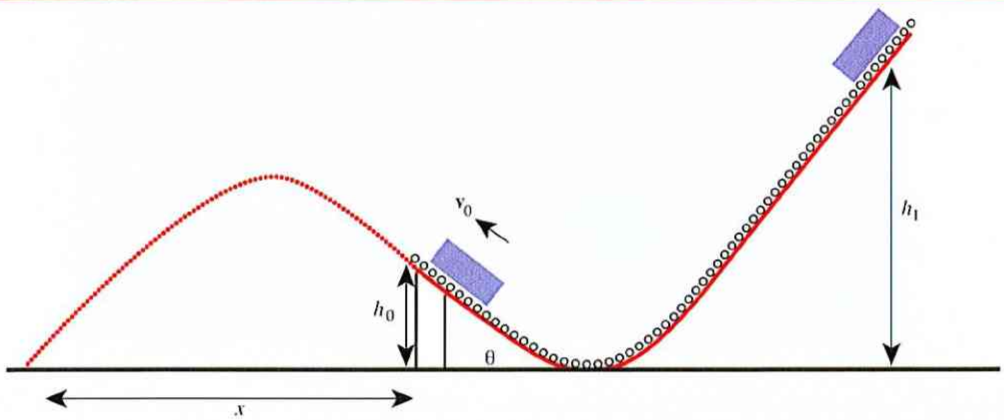

Figure 7. An illustration of the ski-jumping experiment.

the uniformly accelerated motion using a tilted frictionless glass plate. However, the frictionless glass plate cannot be inclined more than 5° because the beads fall down from the slope. Therefore, we devised new equipment using a plastic sheet, as shown in figure 5; namely, the beads were attached to the plastic sheet by electrostatic force and they behaved as ball bearings to reduce the friction between the object and the slope. In this experiment, a small Petri dish (45 mm in diameter and 18.2 g in mass, as an object) was released with initial speed of zero from height h. The speed of the object increased as it came down the slope and it finally moved with a constant speed, **v**, on the horizontal frictionless plate. We measured the constant **v** with varying h using a speed meter, as shown in figure 5. The experimental result is shown in figure 6. As is well known, the relationship between h and **v** is theoretically derived as follows:

$$\mathbf{v} = \sqrt{2gh} \qquad (1)$$

where g is the acceleration due to gravity. The curve in figure 6 shows the specific shape of the root function. Also, it is seen that the experimental and theoretical values almost coincide. It should be noted that the error of the experiment is less than 3%. Therefore this method really can be employed for quantitatively demonstrating the energy conservation law. Using this slope technique, we have also confirmed that a more complicated experiment, such as ski-jumping, can also be demonstrated, as illustrated in figure 7. The error of the distance of the object, x, on the horizontal frictionless plate is about 5%.

Conclusion

In order to counter the influence of friction, a new demonstration method has been developed with the aid of fine spherical plastic beads. Using a frictionless plate, we have successfully demonstrated the action–reaction law, using a special magnetized Petri dish as an object. By employing a special slope consisting of a plastic sheet on which the beads were attached by electrostatic force, a quantitative demonstration of the energy conservation law was also carried out, with only a small error. The major advantage of this method is that we can always use Petri dishes as the objects for demonstrating many kinds of mechanics law, such as the first, second and third laws of motion, the momentum conservation law, and the energy conservation law. This surely has a beneficial effect for students, who can then understand mechanics laws systematically with a unified concept and no confusion.

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Ali Khumaeni graduated from the Department of Physics, Diponegoro University, Indonesia, in 2006, majoring in laser applications. He directs research into laser plasma spectroscopy. He is also studying physics education at the Kagawa Laboratory, University of Fukui, Japan.

Satoru Tanaka is a 4th grade student in the Department of Physics, University of Fukui, Japan. He is now studying physics education at the Kagawa Laboratory.

Akane Kobayashi is a 4th grade student in the Department of Physics, University of Fukui, Japan. She is now studying physics education at the Kagawa Laboratory.

Yong Inn Lee is a professor in the Department of Physics, Chonbuk National University, Korea. His major field is the theoretical study of solid-state physics, and also physics education.

Koo Hendrik Kurniawan obtained his PhD in 1992 in the field of plasma spectroscopy and its application to spectrochemical analysis. Under the direction of Kiichiro Kagawa, he is trying to develop simple physics experiments for high-school physics teachers. Currently he is the head of the Makmur Maju Mandiri Research Center. In 2007, he was appointed as a Fellow of the Royal Society of Chemistry.

Kyoko Ishii is an associate professor in the Faculty of Education and Regional Studies, University of Fukui, Japan. Her major field of research is science education.

Kiichiro Kagawa is a professor in the Faculty of Education and Regional Studies, University of Fukui, Japan. His major field of research is laser-induced plasma spectroscopy. Recently, he became interested in physics education, developing unique experiments using simple and readily available equipment and materials.

SIPEX—exploring the Antarctic sea ice zone

Sandra Zicus[1,2], **Jane Dobson**[3] **and Anthony Worby**[1,4]

[1] Antarctic Climate and Ecosystems Cooperative Research Centre, Hobart, Tasmania, Australia
[2] Institute of Antarctic and Southern Ocean Studies, University of Tasmania, Hobart, Tasmania, Australia
[3] Claremont College, Claremont, Tasmania, Australia
[4] Australian Antarctic Division, Kingston, Tasmania, Australia

Abstract

Sea ice in the polar regions plays a key role in both regulating global climate and maintaining marine ecosystems. The international Sea Ice Physics and Ecosystem eXperiment (SIPEX) explored the sea ice zone around Antarctica in September and October 2007, investigating relationships between the physical sea ice environment and the structure of Southern Ocean ecosystems. One of the main goals of SIPEX was to conduct large-scale sea ice and snow thickness surveys for the validation of satellite-based measurements. SIPEX scientists used a variety of techniques including helicopter-based radar and laser altimetry, as well as a remotely operated underwater vehicle, to gather baseline data on Antarctic sea ice thickness and the under-ice environment. These data will be invaluable for monitoring possible future changes in the sea ice around Antarctica.

On 4 September 2007, 45 scientists and 48 support personnel from ten different countries left Hobart, Tasmania, aboard Australia's icebreaking research vessel *Aurora Australis* and headed south towards Antarctica. We were participating in the international Sea Ice Physics and Ecosystem eXperiment (SIPEX), a six-week research journey to one of the least visited realms on Earth—the Antarctic sea ice zone at the height of its seasonal extent.

After six days and nights of rocking, rolling and bouncing our way through the waves of the Southern Ocean, there was an abrupt change and we were treated to a gentle rocking motion and the sound of ice scraping on the ship's hull. We had reached the edge of the frozen sea ice zone that surrounds the Antarctic continent.

First light revealed that we were going through bands of ice separated by open water, some of which had an oily sheen to it. When the sea-surface temperature drops to −1.9 °C, small plate-like ice crystals called *frazil* begin to form. A thick slurry of frazil crystals damps the smallest waves and alters the visual appearance of the surface to resemble an oil slick—this is called *grease ice* (figure 1(a)). As the cold winds passed over the open water, more frazil was forming before our eyes. We were seeing the birth of sea ice.

In calm water, the slurry solidifies into *nilas*—a sheet of randomly oriented crystals a few centimetres thick containing a high concentration of bubbles and brine inclusions that are effective at scattering light (figure 1(b)). Nilas grows downward into the water column as *congelation ice*, which is clearer than the surface frazil layer.

In the presence of significant wind and waves, the frazil crystals cannot form nilas; they instead

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