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91524



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Mana Tohu Mātauranga o Aotearoa  
New Zealand Qualifications Authority

## Level 3 Physics 2025

### 91524 Demonstrate understanding of mechanical systems

Credits: Six

Achievement	Achievement with Merit	Achievement with Excellence
Demonstrate understanding of mechanical systems.	Demonstrate in-depth understanding of mechanical systems.	Demonstrate comprehensive understanding of mechanical systems.

Check that the National Student Number (NSN) on your admission slip is the same as the number at the top of this page.

**You should attempt ALL the questions in this booklet.**

Make sure that you have Resource Booklet L3-PHYSR.

In your answers use clear numerical working, words, and/or diagrams as required.

Numerical answers should be given with an appropriate SI unit.

If you need more room for any answer, use the extra space provided at the back of this booklet.

Check that this booklet has pages 2–12 in the correct order and that none of these pages is blank.

Do not write in the margins (✂/✂/✂). This area will be cut off when the booklet is marked.

**YOU MUST HAND THIS BOOKLET TO THE SUPERVISOR AT THE END OF THE EXAMINATION.**

Excellence

TOTAL 23

**QUESTION ONE: MOMENTUM AND CIRCULAR MOTION**

Titan is the largest of Saturn's moons. For the sake of this question, you can ignore the gravitational effects of the other moons of Saturn and the rest of the objects in the solar system, and assume that Titan is in a perfectly circular orbit.

Mass of Saturn:  $5.68 \times 10^{26}$  kg

Radius of Saturn:  $5.82 \times 10^7$  m

Mass of Titan:  $1.35 \times 10^{23}$  kg

Distance between the centres of mass of Saturn and Titan:  $1.22 \times 10^9$  m

[https://science.nasa.gov/wp-content/uploads/2023/07/titan\\_carousel2.jpg](https://science.nasa.gov/wp-content/uploads/2023/07/titan_carousel2.jpg)

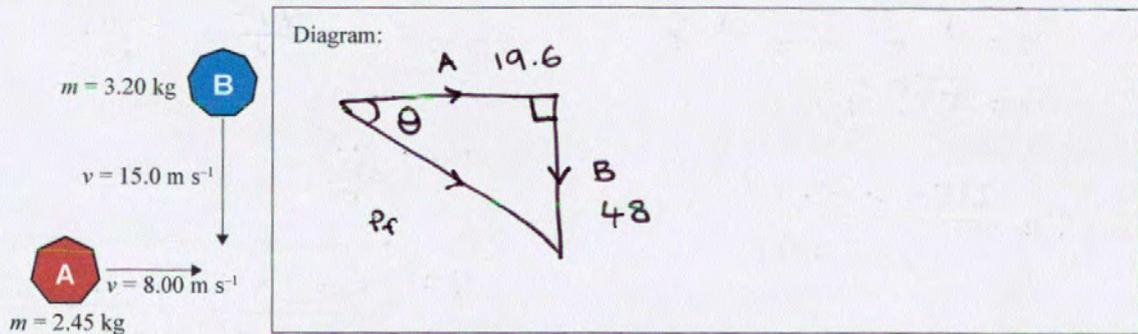
- (a) Show that the centre of mass of Saturn and Titan is  $2.90 \times 10^5$  m from the centre of Saturn.

$$x_{\text{com}} = \frac{(0 \times 5.68 \times 10^{26}) + (1.22 \times 10^9 \times 1.35 \times 10^{23})}{(1.35 \times 10^{23} + 5.68 \times 10^{26})}$$

$$= 289895.8874 \text{ m}$$

$$\text{or } = 2.90 \times 10^5 \text{ m from centre of saturn (3sf)}$$

- (b) Two ice particles around Saturn move toward each other, as shown below. Particle A has a mass of 2.45 kg and a velocity of  $8.00 \text{ m s}^{-1}$ ; particle B has a mass of 3.20 kg and a velocity of  $15.0 \text{ m s}^{-1}$ . The particles collide and stick together without losing any mass.



If you need to redraw your response, use the diagram on page 9.

Calculate the size and direction of the momentum of the two particles when they are stuck together.

Determine the direction relative to the initial velocity of particle A.

A diagram may assist your answer.

$$P = mv$$

$$P_{iB} = 3.20 \times 15 \\ = 48 \text{ kg m s}^{-1}$$

$$\tan \theta = \frac{P_B}{P_A}$$

$$\tan^{-1} \left( \frac{48}{19.6} \right) = \theta$$

$$\theta = 67.8^\circ \text{ (3sf)}$$

$$P_{iA} = 2.45 \times 8 \\ = 19.6$$

↑ ↑ (relative to A)  
initial velocity  
direction of momentum

$$\sqrt{19.6^2 + 48^2} = P_f \quad (P_f = 51.8 \text{ kg m s}^{-1})$$

← size of momentum when both stick together

- (c) Calculate the time it takes for Titan to complete one orbit of Saturn.  
You could begin by calculating the velocity of Titan in its orbit.

$$v = d/t \quad t = d/v$$

$$t = 2\pi r / v$$

$$T = \frac{2\pi \times 1.22 \times 10^9}{5572.6 \dots}$$

$$T = 1375569 \text{ seconds or } 1.37 \times 10^6 \text{ seconds}$$

$$F_c = F_g \quad \frac{mv^2}{r} = \frac{GMm}{r^2}$$

$$v^2 = \frac{GM}{r}$$

$$v = \sqrt{\frac{GM}{r}}$$

$$v = \sqrt{\frac{6.67 \times 10^{-11} \times 5.68 \times 10^{26}}{1.22 \times 10^9}}$$

$$v = 5572.6 \text{ ms}^{-1}$$

- (d) Future manned missions to the solar system are most likely to be launched from space stations in low earth orbit, similar to the International Space Station. Astronauts on the International Space Station appear to be weightless, even though Earth's gravity is still acting on them.

Explain why astronauts appear to be weightless yet can remain in orbit.

Whether or not they feel weightless depends on the reaction force faced. In orbits centripetal force to keep the astronauts in orbit is fully provided by gravitational force, meaning there is no/negligible reaction force. Therefore, even though Earth's gravity is still acting on them, they appear to be weightless while in orbit, due to lack of the reaction force.

### QUESTION TWO: ROTATIONAL MOTION

Rihari and Jane are playing on a roundabout (sometimes known as a merry-go-round) in the local playground. The roundabout has a radius of 1.30 m. Rihari stands on the roundabout whilst Jane pushes on it to make it spin as shown in the diagram. Starting from rest Jane steadily accelerates the roundabout so that it takes 12.0 s to make 4.00 rotations.

<https://www.findtheneedle.co.uk/companies/yates-playgrounds/products/playground-roundabout-design-and-manufacture1>

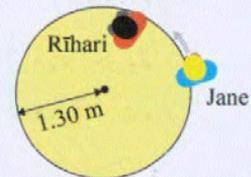
- (a) Show that the angular velocity of the roundabout after the 12.0 s is  $4.19 \text{ rad s}^{-1}$ .

$$r = 1.30 \text{ m} \quad t = 12 \text{ s} \quad 4 \text{ rotations}$$

$$w_i = 0 \quad w_f = 4.19 \text{ rad s}^{-1}$$

$$\theta = 8\pi \text{ (4 rotations)} \quad \theta = \frac{w_f + w_i}{2} t \quad 8\pi = \frac{w_f + 0}{2} \times 12$$

$$\frac{8\pi}{12} \times 2 = w_f \quad w_f = 4.19 \text{ rad s}^{-1}$$



- (b) Rihari then drags his foot along the ground to bring the roundabout to a stop over 19.2 s.

Calculate the average torque exerted to slow the roundabout, if the roundabout and Rihari have a rotational inertia of  $430 \text{ kg m}^2$ .

$$\tau = I\alpha \quad \tau = Fr$$

$$w_i = 4.19 \text{ rad s}^{-1} \quad w_f = 0$$

$$t = 19.2$$

$$w_f = w_i + \alpha t$$

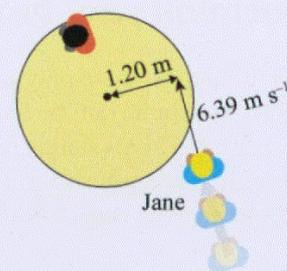
$$0 = 4.19 + 19.2\alpha$$

$$\alpha = -0.218 \text{ rad s}^{-2}$$

$$\tau = 430 \times 0.218 = 93.8 \text{ Nm}$$

↑ average torque

- (c) Jane has a mass of 52.0 kg. She runs at  $6.39 \text{ m s}^{-1}$  and jumps onto the stationary roundabout, close to the edge, landing 1.20 m from the axis of rotation, as indicated in the diagram. This causes the roundabout to rotate slowly.



The roundabout and Rīhari have a rotational inertia of  $430 \text{ kg m}^2$ .

The rotational inertia of a point mass is  $I = mr^2$ .

Calculate the angular velocity of the roundabout after Jane has jumped on.

$$m = 52 \text{ kg} \quad v = 6.39 \text{ m s}^{-1} \quad r = 1.20 \text{ m}$$

$$L = mvr \quad L = I\omega \quad \text{- momentum is conserved}$$

$$52 \times 6.39 \times 1.20 = L \quad I_J = mr^2$$

$$L = 398.74 \quad = 52 \times 1.2^2$$

$$L = I\omega \quad = 74.88 \text{ kg m}^2$$

$$\frac{398.74}{504.8} \quad I_T = 430 + 74.88$$

$$= 504.88 \text{ kg m}^2$$

$$\omega = 0.7897 \text{ rads}^{-1} \quad \text{angular velocity of roundabout after Jane jumped on is } 0.790 \text{ rads}^{-1} \text{ (3sf)}$$

- (d) Later, Rīhari and Jane are both standing on the edge of the roundabout while it is rotating at a constant angular velocity.

Rīhari moves inwards, towards the centre of the roundabout.

Explain the effect this has on the rotational energy of the system.

When Rīhari moves inwards, his mass becomes distributed closer to the rotational axis of the roundabout. This causes his inertia, and therefore the systems inertia to decrease. As  $L = I\omega$ , ~~assuming~~ (momentum is conserved, assuming no external unbalanced forces are acting) and momentum is conserved, the angular velocity of the roundabout will increase. As  $E_{\text{rot}} = \frac{1}{2}I\omega^2$ , the increase in angular velocity which is squared, outweighs the decrease in inertia, causing the rotational energy of the system to ~~increase~~ ultimately increase.

### QUESTION THREE: SIMPLE HARMONIC MOTION

Rihari is playing with a ball on a string and lets it swing as a pendulum. It is 1.20 m from the fixed point of the string to the centre of mass of the ball. The top of the string is held, and the ball is released from the starting position at an angle of  $5.60^\circ$  from the vertical. The mass of the string is insignificant compared to the mass of the ball.

- (a) Show that the maximum displacement of the ball is 0.117 m.

$$\begin{array}{c} \text{1.20} \\ \text{5.60}^\circ \\ \text{Displacement} \end{array} \quad \sin \theta = \frac{O}{H} \quad 1.20 \sin 5.60 = \text{displacement}$$

$$= 0.117 \text{ m is max displacement}$$

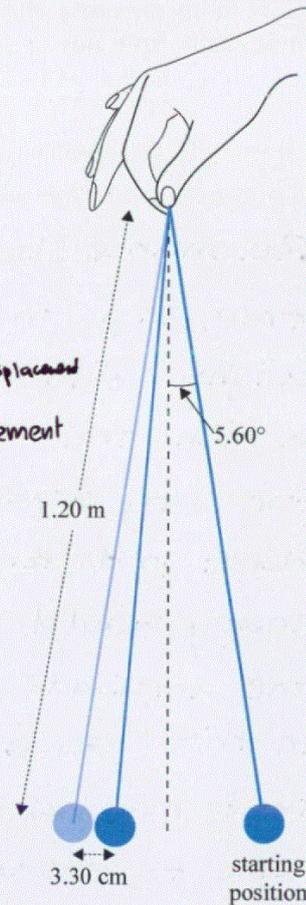
- (b) Show that the angular frequency of the ball's motion is  $2.86 \text{ rad s}^{-1}$ .

$$\omega = \frac{2\pi}{T} \quad T = 2\pi \sqrt{\frac{l}{g}}$$

$$T = 2\pi \sqrt{\frac{1.20}{9.81}} \quad T = 2.198 \text{ s}$$

$$\omega = \frac{2\pi}{2.198}$$

$$\omega = 2.86 \text{ rad s}^{-1}$$



- (c) After the ball is released from the starting position, calculate the time it will take for the ball to reach a point 3.30 cm before its next stationary position, as shown on the diagram.

A reference circle may be used to calculate your answer. <sup>max displacement</sup>

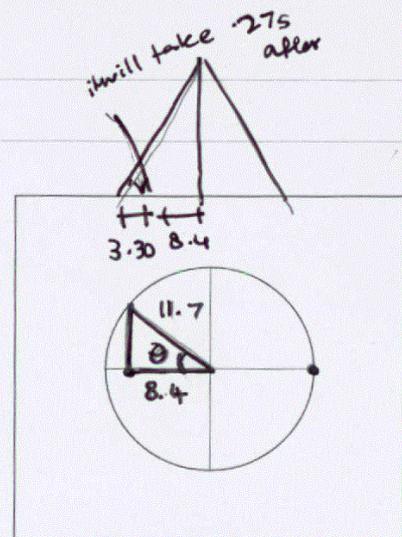
total displacement ~~to~~ 11.7 cm

$$\cos^{-1}\left(\frac{8.4}{11.7}\right) = 0.7699$$

$$\pi - 0.7699 = 2.37$$

$$\frac{2.37}{2\pi} \times 2.198 = 0.8296 \dots$$

$$= 0.830 \text{ s (3sf)}$$



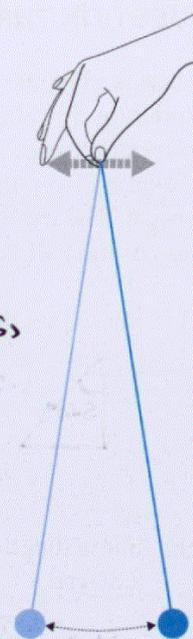
If you need to redraw your response, use the diagram on page 9.

- (d) Rihari holds the end of the string between his fingers, and moves his hand horizontally from side to side. He notices that at a certain frequency of movement, the ball will oscillate with a very large amplitude.

Explain why this occurs.

Your answer should include both force and energy considerations.

Resonance is occurring. At this certain frequency, the driving force Rihari provides, aligns with the natural frequency at which the ball oscillates, allowing for very large amplitude. Essentially, if he weren't to do this, due to damping, kinetic energy would be lost as heat. As  $E_k = E_{\text{input}}$ , the amplitude would subsequently decrease. However, in this case, by providing a sufficient driving force that matches the ball's natural frequency, Rihari is able to ensure that input energy = kinetic energy lost, allowing for very large oscillation amplitudes at this particular frequency.



## Excellence

**Subject:** L3 Physics

**Standard:** 91524

**Total score:** 23

Q	Grade score	Marker commentary
One	7	<p>(a) Correct solution.</p> <p>(b) Correct use of vector addition in 2D to solve for both momentum after collision and recognised how to determine the angle with reference to A.</p> <p>(c) Correct use of <math>F_c = F_g</math> to solve for <math>v</math> and correct use of <math>v = \frac{2\pi}{T}</math> to solve for time period.</p> <p>(d) The candidate has recognised that reaction force is required for a sensation of weight and the effect of <math>F_g</math> in providing the <math>F_c</math> for the orbit. For excellence, they needed to link in free fall or that the station and astronaut are both accelerating towards the Earth at same rate.</p>
Two	8	<p>(a) Correct use of kinematics, recognising an acceleration has occurred.</p> <p>(b) Correct solving for torque using calculated angular acceleration.</p> <p>(c) The candidate has recognised that the roundabout is not moving and so has no momentum, so is able to determine the linear momentum of Jane, and that the final angular velocity depends on the final momentum and the combined inertia of Jane and the roundabout, assuming momentum is conserved.</p> <p>(d) The candidate has produced a clear summary, including the use of axis of rotation to explain inertia drop, no net forces to explain conservation of momentum, and the impact of the squaring of angular velocity to outweigh decrease in <math>l</math>.</p>
Three	8	<p>(a) Correct solution.</p> <p>(b) The candidate has a clear understanding of determining angular frequency by first determining the time period.</p> <p>(c) The candidate has demonstrated effective use of the reference circle to determine <math>t</math> from the correct position.</p> <p>(d) The candidate has recognised the impact of a driving force that matches the natural frequency of the system and the exact type of energy transformations that occur. Includes reference to both resonance for increasing amplitude and damping as to why the driving force must be applied at the natural frequency of the system.</p>