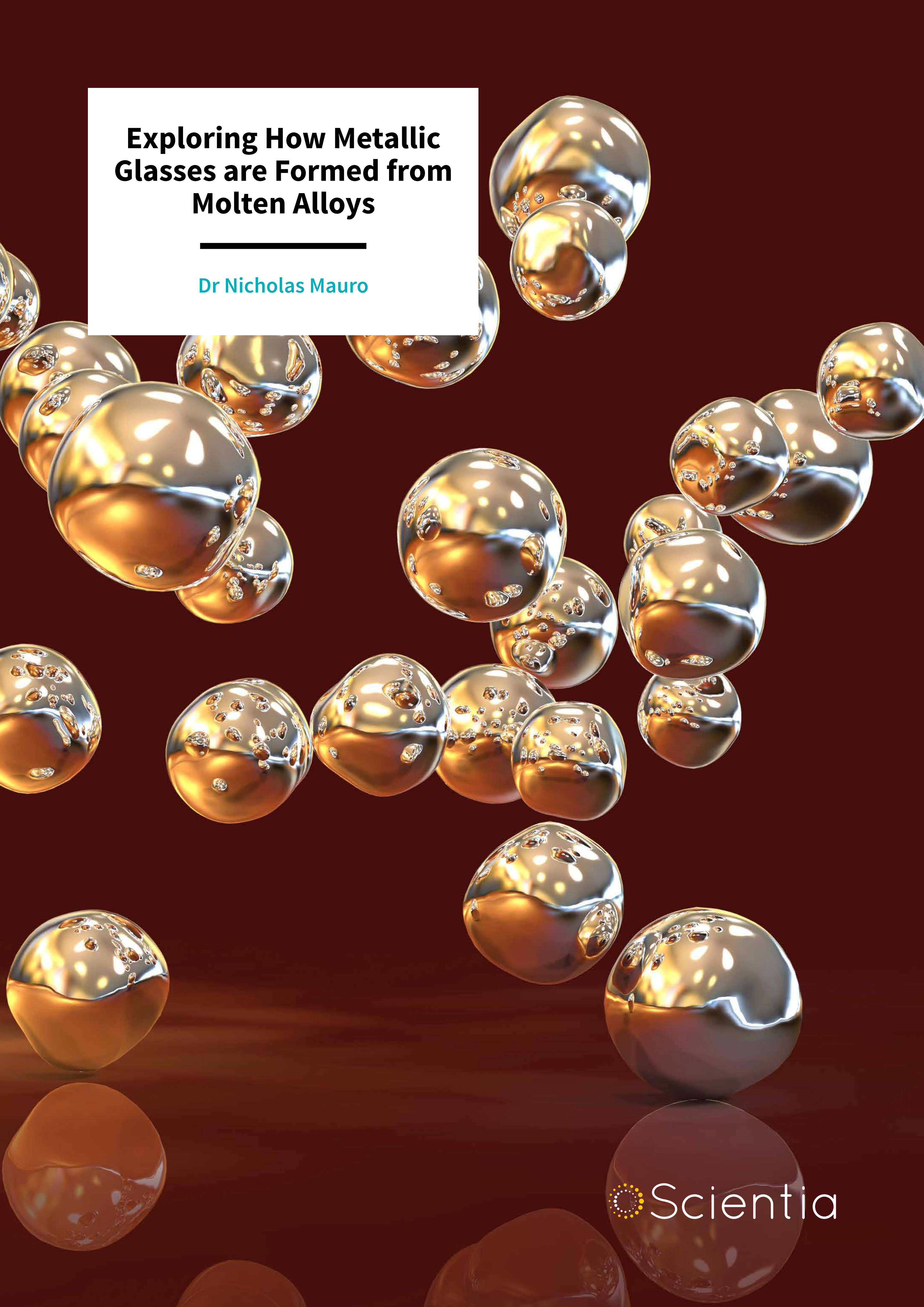
Exploring How Metallic Glasses are Formed from Molten Alloys

Dr Nicholas Mauro



Scientia

EXPLORING HOW METALLIC GLASSES ARE FORMED FROM MOLTEN ALLOYS

Metallic glasses are extraordinary materials that can be formed by rapidly cooling certain mixtures of molten metals. Their unique properties make them extremely desirable for various technological applications. However, scientists do not fully understand the processes that drive the formation of metallic glasses, and as such, they remain difficult to design and optimise for specific purposes. **Dr Nicholas Mauro** and his team at St. Norbert College in Wisconsin have been researching metallic glasses to understand exactly how these materials form from various molten alloys. By understanding the mechanisms that lead to the formation of metallic glasses, the team's work aids in the design of new metallic glasses and enables their optimisation for specific technological applications.

Metallic Glasses

When it comes to scientific research, there are few fields that hold as much importance as the development of novel materials. Almost all emerging technology comes into being because of new and exciting materials. For instance, the discovery of silicon-based semiconductors formed the bedrock for all modern computing, while implantable medical devices owe their biocompatibility to the development of polymer coatings.

One type of novel material that has been gaining interest is so-called 'metallic glass'. The growing interest in metallic glasses is mostly due to their unique and remarkable properties, which tend to be very different to those of typical metal-based materials. These materials are often more durable than conventional metals, with a higher resistance to wear and corrosion. Some metallic glasses even soften like plastic when heated, instead of immediately melting. Like typical metals, these materials also tend to be good conductors of electricity and heat, and show interesting magnetic properties.

Metallic glasses have been investigated for their potential as strong, durable aerospace materials. In fact, NASA is currently considering their use in shielding materials for spacecraft, and in gears for planetary rovers. Their unique combination of properties mean they could also be used in electrochemical water purification systems, and as coatings for biomedical devices.

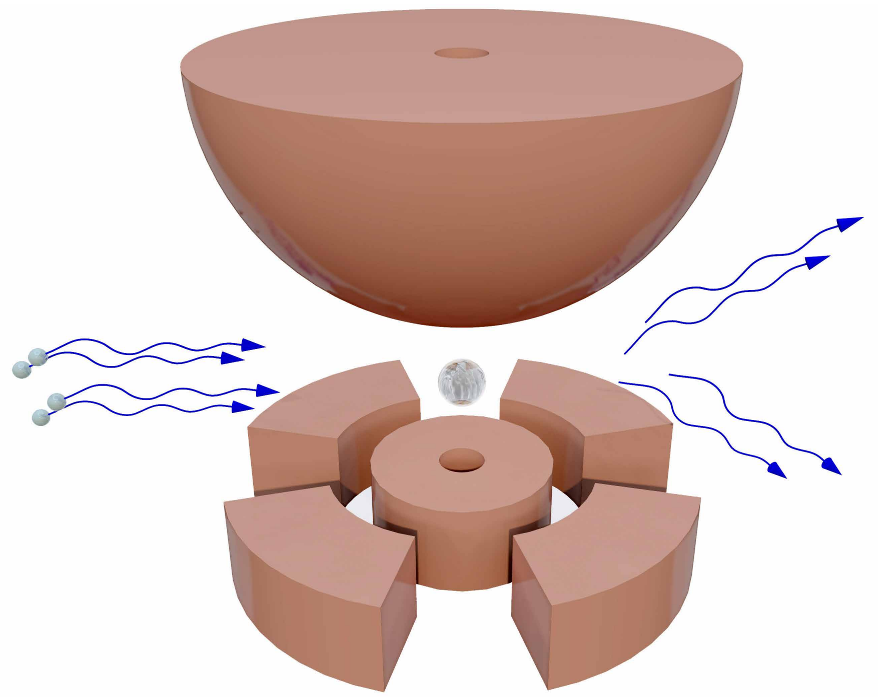
Although their useful properties have been recognised for decades, metallic glasses have not yet realised their full potential, as they still need to be optimised for their intended applications.

Amorphous vs Crystalline

The term 'glass' is often used to describe a material that has so-called 'amorphous' properties. Within a solid amorphous material, the constituent

atoms and molecules do not form a repeating pattern, and instead are arranged randomly to form a disordered structure. In the glass that makes up our windows and wine bottles, the constituent silicon dioxide molecules are arranged in this type of disordered structure. Many polymer-based materials, such as plastics, also fall into the 'amorphous' category.

On the opposite side of the coin are crystalline solids. These are defined by their well-ordered atoms and



molecules, which form a repeating three-dimensional pattern. Most metallic materials fall into this category, including iron, copper, silver, and alloys such as steel and bronze.

Although metallic glasses are made up of metal atoms, which typically form crystalline solids, they are created in an unusual way that leads to disordered, glassy structures. Because they do not have rigid internal structures, metallic glasses are often more flexible than their crystalline counterparts, meaning that they are often less likely to break under pressure.

Understanding the Solidification Process

When a molten metal cools, its constituent atoms lose their thermal energy and succumb to attractive forces with other atoms around them. As the liquid continues to cool, the metal atoms become locked into specific ordered arrangements due to these attractive forces. This solidification process balances the tendency of the atoms to form an ordered crystalline solid. Also, the increasing viscosity of the liquid tends to prevent the rearrangement of the atoms into that ordered state.

One of the key factors which can affect this process is the rate of cooling. If the molten metal is cooled rapidly enough, the atoms do not have sufficient time to arrange themselves into this ordered state, and instead become 'frozen' in place.

'Metals can form glassy, amorphous states when they are cooled rapidly enough,' explains Dr Nicholas Mauro of St. Norbert College. Through extensive research, Dr Mauro and his colleagues have been examining this process in detail.
In some of their previous research, the team analysed how the rate of cooling affected the formation of metallic glass in various alloy families. Their results highlighted the significant impact that the rate of cooling had on determining whether these materials would form amorphous or crystalline solids. Importantly, they also found that some of the alloys they studied were far more likely to form glassy solids than others.

'Very broadly, we are interested in connecting how changes in the atomic structure of liquids affects their ability to cool into different phases,' says Dr Mauro. 'In particular, we're looking for a signature in the liquid that differentiates good metallic-glass-forming liquids from poor ones.'

'Generally speaking, we don't yet understand why some metallic alloys form glasses more easily than others,' he continues. 'My work focuses on the nature of the link between the dynamics of a liquid, such as how rapidly the structure changes with temperature, and its glass-forming ability.' Achieving a deeper understanding of the glass-forming ability of different metal alloys would allow researchers to design new alloys that form metallic glasses, and then optimise them for specific technological applications.

Analysing Samples with Electrostatic Levitation

Understanding the mechanisms that drive the formation of an amorphous metal alloy can be extremely complicated. These processes are controlled by motions and interactions on atomic or sub-nanometre scales. A further complication is the fact that such processes occur on extremely rapid time scales, some of which need to be explored in one trillionth of a second. As such, Dr Mauro's team and their collaborators needed to develop sophisticated methods that would allow them to explore processes at such small length scales and rapid time scales

Towards this aim, the researchers decided to explore two powerful techniques: 'inelastic neutron scattering' and 'high-energy x-ray scattering'. During a neutron scattering experiment, a beam of subatomic particles called neutrons is fired at a sample of a given material. Most of these neutrons pass through the empty spaces between the atomic nuclei, but some interact with the material in various ways, are scattered and detected in a chamber around the sample.

By analysing where and when the scattered neutrons hit the detector, the technique can build a picture of the positions of atoms within the material, providing detailed information about its structure. High-energy x-ray scattering operates using the same principle, but a beam of x-rays is used instead of neutrons.

In order to conduct these kinds of experiments, great care has to be taken to make sure the metallic liquid doesn't touch the walls of the container. Additionally, the experiments need to be performed in a near-perfect vacuum. These experiments are incredibly challenging, requiring careful design and execution by knowledgeable researchers and students. Facilities for conducting such experiments exist in only a few places around the world and require large-scale government support.

Dr Mauro and his team propose a solution to these issues, using the phenomenon of levitation. In this context, levitation involves suspending small amounts of metallic liquids using an electric field. Using a sophisticated computer algorithm and measuring the sample position, a charged metallic liquid can be successfully suspended in a vacuum. By levitating samples of molten alloys, Dr Mauro and his colleagues can perform scattering experiments on them, and obtain detailed information on the atomic-scale properties of the alloys as they transition from a molten state to a solid state.

This technique enables the team to gather better data than when using a conventional neutron or x-ray scattering setup, and even allows the experiments to be run by a single person, making the process far more efficient.

Dynamics of Metallic Glass Formation

Recently, Dr Mauro and his team have been exploring alloys that contain various ratios of copper, zirconium and aluminium, and how they form metallic glasses. 'These compositions were chosen because they are reported to have dramatically different glass forming-ability,' explains Dr Mauro.

After melting these three pure metals together, the team uses electrostatic levitation to suspend tiny spheres of the mixture. The team then probes the liquids with x-rays while

simultaneously cooling the samples, allowing them to explore how the atomic structure changes with temperature.

The scattering data provided the team with valuable insights into the atomic behaviours of each alloy and the mechanisms that allows each material to form a glass upon rapid cooling. The team then ran computer simulations to gain an even clearer understanding of the atomic-scale processed involved.

'This work, combined with our previous investigations linking structural evolution and viscosity across different glass-forming families suggests a deep and foundational link between the onset of structural ordering and the associated development of dynamical slow down of atomic motion and cluster formation,' explains Dr Mauro.

In essence, this means that the formation of these fascinating materials is controlled by the motions that occur on an atomic level. By understanding and controlling these motions, the team is now better equipped to create metallic glasses using a wider range of metal alloys.

Dr Mauro and his colleagues have not only demonstrated what makes metallic glasses so special, but they have also delved deep into the physical processes that enable their formation. By doing so, the team has paved the way for the design of novel metallic glasses that are optimised for their intended application. From space exploration to implantable medical devices, numerous fields stand to benefit from these remarkable materials.

Meet the researcher

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Dr Nicholas Mauro achieved his MA and PhD in Physics at Washington University. Upon completing two years of postdoctoral research at Washington University, Dr Mauro then worked as an Assistant Professor at Lawrence University, North Central College and St. Norbert College in De Pere, Wisconsin. In 2022, he was promoted to his current position as Associate Professor in the Department of Physics at St. Norbert College. Here, his research investigates the properties of various novel materials, with a particular focus on understanding the transitions between liquid and solid phases. At the same time, Dr Mauro teaches various physics classes and mentors a group of undergraduate research students. Over the years, his research has been awarded with several prestigious grants from the US National Science Foundation and NASA.

KEY COLLABORATORS

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FURTHER READING

F Chen, N Mauro, S Bertrand, P McGrath, L Zimmer, and K Kelton, Breakdown of the Stokes–Einstein relationship and rapid structural ordering in CuZrAl metallic glass-forming liquids, The Journal of Chemical Physics, 2021, 155, 104501.

N Mauro, M Blodgett, M Johnson, A Vogt, K Kelton, A structural signature of liquid fragility, Nature Communications, 2014, 5, 4616.