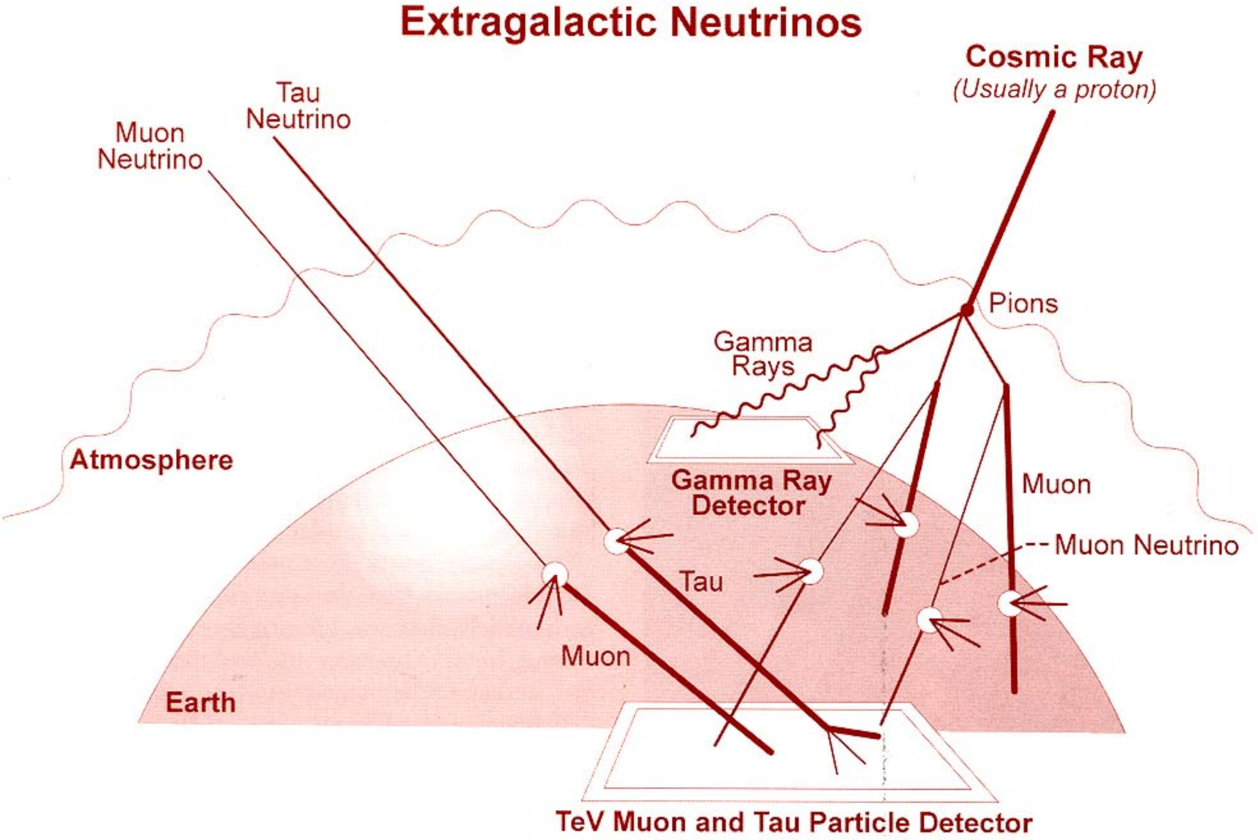
The Answer Isn't Elementary – It's Fundamental

What is matter made of? Most people answer that matter is made up of elements, or atoms. Ask a particle physicist that question, however, and you will enter the spectacular world of fundamental particles. Fundamental particles are the smallest particles in nature. During the past thirty years, physicists have discovered that fundamental particles are strongly bound to one another within the protons and neutrons that are inside atoms. Called quarks and gluons, these are the fundamental particles of which everything is made. Even though the particles cannot actually be seen, understanding the fundamental particles – quarks, gluons, and the elusive neutrinos – is crucial to understanding the history and fate of our universe.

Ina Sarcevic, CoS professor of physics, conducts theoretical research to understand the interactions of fundamental particles. She studies the strong interaction forces that keep quarks and gluons bound, not allowing them to escape from the protons and neutrons. She also studies the neutrino, which is a fundamental particle with no electric charge and probably very little mass if it has a mass at all. Unlike quarks and gluons, neutrinos are on the move, going large distances without interacting.

The rare interactions of the uncharged neutrino with matter are weak and, in fact, millions of neutrinos pass through our bodies every second! "They fly through everything," explains Sarcevic. "A typical neutrino can go through lead that is 1 light-year thick, which is about six million miles, without hindrance!"

Neutrinos can come from space, from the Earth, or even from activities of mankind. The big-bang model predicts that a cosmic background of neutrinos was produced at the birth of the universe. Additional sources of neutrinos from space include those produced by processes that occur inside stars like our sun, as well as those produced by cosmic rays penetrating Earth's atmosphere. Neutrinos also come from natural radioactivity that exists in the Earth, and from man-made nuclear reactors or particle accelerators that produce neutrinos for study.



High-energy neutrinos may interact with matter to create muon, tau, and electron particles. By detecting such particles scientists can learn more about neutrinos. (→○ represents interactions of neutrino with matter)

Illustration:
Dave Cantrell,
AHSC Biomedical
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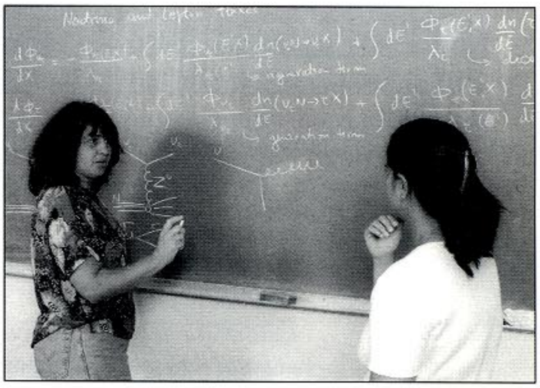
Sarcevic finds neutrinos intriguing because if they do have mass then neutrinos could explain the unobserved so-called dark matter of the universe. Astrophysicists do not know what dark matter is exactly, but they do know that the existence of all of the galaxies and other objects that can be seen in the universe cannot be sufficiently explained without the existence of some sort of extra matter. Scientists have inferred, from gravitational effects, the existence of dark matter – a type of matter that cannot be seen.

Theoreticians like Sarcevic believe that if neutrinos have mass, and because there are so many neutrinos, this fundamental particle could account for the dark matter of the universe. Therefore, understanding neutrino properties is crucial to explaining the evolution of the universe, which includes the formation of galaxies, and also crucial to theories of fundamental particle structure.

But how can the invisible neutrino be detected? The only way that physicists can gather experimental data on neutrinos is to detect them when they interact. Unfortunately, neutrinos rarely interact with matter. The challenge for Sarcevic lies in how to detect neutrinos. "The neutrino is beautiful," exclaims Sarcevic. "It can go 50 million or 50 billion light-years from a source somewhere else in the universe where it was created and come to you carrying all its information because it did not lose anything through interactions."

A detection mechanism is needed to look at the rare interactions of neutrinos with material. In a detector, for example, if a neutrino hits rock – which consists of atoms, protons, neutrons, quarks, and gluons – neutrino interaction depends on how many quarks exist in the rock and how the quarks are distributed. The higher the neutrino energy, the deeper it will probe inside, and the probability of interaction will get larger. Sarcevic is determining the probability of neutrinos interacting at a certain energy, and the probability of being able to detect them.



Sarcevic and Iyer discuss neutrino and lepton fluxes.

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There are different types, or flavors, of neutrinos – called muon, tau, or electron neutrinos. Theorists thought that neutrinos might change, or oscillate, from one type to another, but in order for them to change flavor they must have mass.

About a year ago, data from the Super-Kamiokande detector in Japan obtained preliminary evidence that neutrinos do have mass. Scientists noticed a deficit of muon neutrinos, which indicated that the particles had oscillated or changed to another flavor as they passed through Earth. This could only happen if the neutrino has mass.

"If neutrinos oscillate then that would change our Standard Model completely," explains Sarcevic. The Standard Model of particle physics is the most fundamental theory, and it does not predict a mass for the neutrino.

Active galactic nuclei (AGN) are galaxies with a massive black hole that has accreted gas at its center in a surrounding disk, and produce an enormous amount of energy across all wavelengths of the electromagnetic spectrum. Some AGN eject energetic particles in narrow beams in opposite directions from the disk.

Illustration: Dave Cantrell, AHSC Biomedical Communications

Since the recent data seems valid, the question then becomes where do the neutrinos go, or which particular flavor do the neutrinos oscillate to? Sarcevic, along with graduate student Sharada Iyer, is looking at how to detect the change if the oscillation is to a tau neutrino. Oscillation to a tau neutrino has never been observed, and Sarcevic believes that the Earth can be used as part of the detector. Their theoretical studies are looking at what the interactions might look like, what the final state might be, and where to put a detector to actually see these neutrinos and determine if they have mass.

Sarcevic's interest in neutrinos originated in the early 90s through discussions with a graduate student in one of her classes. The student studied active galactic nuclei (AGN), and came to her one day very excited about the discovery of Markarian 421. Sarcevic recalls asking, "What is Markarian 421?" It turns out that Markarian 421 was the first of a number of AGN that have now been detected on the basis of emitted radiation. Markarian 421 is an AGN that radiates at very high energy in the TeV range (10^{12} electron volts) of photons.

"AGN are the most powerful sources of energy detected in the universe," explains Sarcevic. "They are 10 to 15 billion light-years away and radiate at 10^{42} to 10^{48} ergs per second." Scientists do not know how this radiation is produced. Sarcevic began to think about the possibilities, which began her current focus on devising methods for detecting neutrinos. If neutrinos from AGN could be detected that would tell scientists how the radiation is produced.

"If you can detect these neutrinos that carry all of the information from the sources, which I predicted with models, then you know where the gamma rays are coming from," says Sarcevic. Working with collaborators, and an undergraduate student named Jeff Reifenberger who has since moved on to graduate school, Sarcevic looks at models and works on the particle production mechanisms that are responsible for the powerful AGN radiation. In particular, she would like to show that AGNs are sources of ultra high-energy neutrinos.

She has shown how one could search for extraterrestrial neutrinos, neutrinos produced in ejected beams from the black hole of AGN, neutrinos from gamma-ray bursters, and neutrinos that originate in topological defects formed in the early universe. Earth can be used as a sieve to filter atmospheric particles that could be mistaken as byproducts of neutrino-nucleon interactions. To detect ultra high-energy neutrinos, conditions need to optimize the probability of neutrinos interacting with the quarks in matter.

As extragalactic high-energy neutrinos pass through Earth, they interact with matter and produce detectable particles called muons. The muons can penetrate large distances and be observed in detectors. Sarcevic has predicted that extragalactic neutrinos can be observed with the kilometer-size neutrino detector that will be an extension of AMANDA. AMANDA is a neutrino detector at the South Pole located under the ice in order to shield against other types of neutrinos and by-products from their interactions.

Sarcevic, and her collaborators, have received enthusiastic support for their ultra high-energy neutrino proposal. In addition, Sarcevic has also received generous support for her theoretical studies on the so-called quark-gluon plasma. These studies are based on the belief that when quark-gluon interactions become weak, they form a new state of matter called quark-gluon plasma. The strong interactions between quarks and gluons may become weak under extreme conditions, such as very high temperatures or at a high density of matter. These conditions existed in the early times of the universe.

Sarcevic's theoretical studies are crucial for understanding how to experimentally detect quark-gluon plasma, and several of her predictions have become part of the experiments taking place at the world's largest Relativistic Heavy Ion Collider at Brookhaven National Laboratory. Quark-gluon plasma will be created to study its properties. Sarcevic's research on the strongly interacting quark and gluon particles and her research on neutrinos combine to address her overall goals of learning what matter is made of and what the interactions are within matter to see how it affects our universe and how our universe evolved.

"The field is really moving now," exclaims Sarcevic. "This is a very exciting time for me." Technology has improved tremendously, allowing for the design of experiments that were not previously possible. In addition, the greater degree of international collaboration and rapid exchange of ideas has led to greater progress for all scientists.

"There is a world out there and it is big," emphasizes Sarcevic. "Students need to be exposed to the research environment and new scientific ideas." She explains that teaching and working closely with students on research projects is particularly rewarding; however, she is concerned about a national trend toward lowering teaching standards. "I teach undergraduate and graduate courses and I get students who are not prepared, and that should not be," explains Sarcevic.

Her courses are some of the most challenging in physics, however, her door remains open to questions about physics or anything else. She believes in helping students in and out of the classroom. Since only a very small percentage of students in particle physics are women, Sarcevic pays special attention to encouraging women students. She is thankful for the tremendous support she received throughout her education and early career, although all her mentors were male.

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Teaching and research go hand in hand says Sarcevic, and one should not be emphasized at the expense of the other. She strives to provide a stimulating environment for students – encouraging them to explore the unknown, to discover, and to achieve their highest level of academic excellence. "I hope that with my strong support any special talent, creativity, and passion for knowledge will become an important part of their life," adds Sarcevic.