physics in action

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Neutron skins on nuclei revealed

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ARE neutrons more likely to be found in one part of the nucleus and protons in another? Ever since this question was first asked in the 1950s, the radii of their density distributions have seemed to be the same to within 0.2 fm. A typical nucleus has a radius of 4 fm.

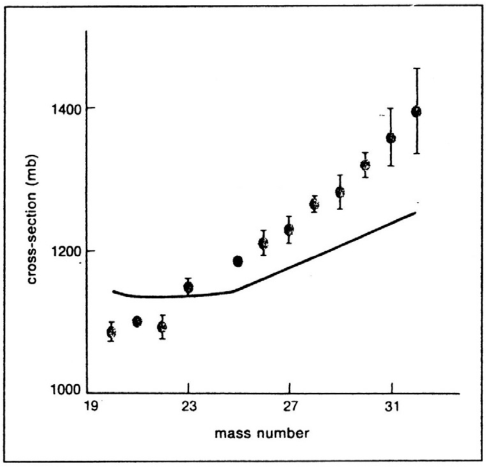
In recent years, however, nuclear physicists have been able to perform experiments with nuclei that are only just stable. As a result, our knowledge of the neutron and proton distributions is improving. The discovery of neutron "haloes" 10 years ago was one such improvement. Now an experiment by Takenori Suzuki and colleagues at the GSI laboratory in Darmstadt, Germany, has shown that as more and more neutrons are added to a nucleus, they tend to form a "neutron skin" (T Suzuki *et al.* 1995 *Phys. Rev. Lett.* 75 3241).

Adding neutrons or protons to a nucleus will increase its radius. Indeed, there is a well known rule that the radius cubed is proportional to the mass number. In stable nuclei, the ratio of neutrons to protons varies from 1, for light nuclei, up to more than 1.5 for the heaviest nuclei. Therefore one might expect this difference to be reflected in the radii of the proton and neutron distributions. However, the configuration of lowest energy turns out to be the one where the radii are about equal.

The first large deviation from this general rule was the discovery of neutron haloes, where the outermost neutrons form an extended tail in the density distribution. These systems have a larger neutron radius than proton radius. However, neutron haloes were only observed in nuclei at the limit of their stability. The GSI team, together with colleagues from RIKEN in Japan and the Kurchatov Institute in Moscow, have now found other deviations – neutron skins – in less extreme nuclear systems.

Early indications for a neutron skin came from heavy helium isotopes, but the interpretation of results depended on which theoretical model was used. Much heavier elements cannot yet be reliably produced at the limit of their stability. However, it is possible to produce sodium nuclei that are only just stable. The charge (i.e. proton) radii for sodium are also known from laser spectroscopy measurements performed on low-energy ionic beams during the last 15 years at CERN. The GSI–RIKEN–Kurchatov team, led by Suzuki, Hans Geissel and Isao Tanihata (who also co-discovered the neutron halo), realized that sodium isotopes were a perfect testing ground for neutron skins.

It is very hard to measure the neutron radii directly, so they concentrated on measuring the total matter radius of the sodium nuclei. This is straightforward at high beam energies because the total reaction probability – the interaction cross-section – is directly related to the size of a nucleus. The high-energy beams of radioactive nuclei needed for such an experiment are only available from the fragment separator at GSI. The experiments used a fixed carbon target.



Interaction cross-section for sodium isotopes with a carbon target measured at 950 MeV per nucleon. The solid line is the result expected for equal proton and neutron radii; data points lying above this line indicate the existence of a neutron skin.

The measured cross-sections for ^{20}Na, which has 9 neutrons and 11 protons, to ^{32}Na, which has 21 neutrons, are shown in the figure. At both extremes, the results deviate from the solid line – which corresponds to the proton and neutron radii being equal – indicating that the neutrons extend beyond the protons. Although a clear signal was obtained, the extraction of detailed separate neutron and proton distributions will still depend to some degree on the model used.

Neutron skins have been studied theoretically for some time – indeed they were studied in the nuclear droplet model more than 25 years ago. More recently, microscopic calculations have been performed for nuclei far from stability and several groups have published results in the last few years. Generally speaking, these calculations reproduce the trend in the latest sodium experiment. It has been suggested that the difference in nucleon separation energies – or Fermi energies – of the neutrons and protons determine the extent of the neutron skin, rather than the absolute number of neutrons and protons.

For a nuclear physicist the most fascinating aspect of this discovery is probably the many questions it raises. Since the basic nucleon–nucleon cross-section is energy dependent, Suzuki and colleagues suggest performing experiments at a different beam energy. These should provide a more model-independent and a detailed determination of the density distributions. The result should also be tested for other elements.

If neutron skins – and perhaps also proton skins – turn out to be a general phenomenon encountered as nuclei become less stable, we need to pin down what the "driving force" is for this separation of neutrons and protons. The dynamics of a nucleus might also change when neutrons and protons become spatially separated. Dramatic changes have already been seen in halo systems; it seems reasonable to expect similar surprises from nuclei with a neutron skin. □

A white light speed trap

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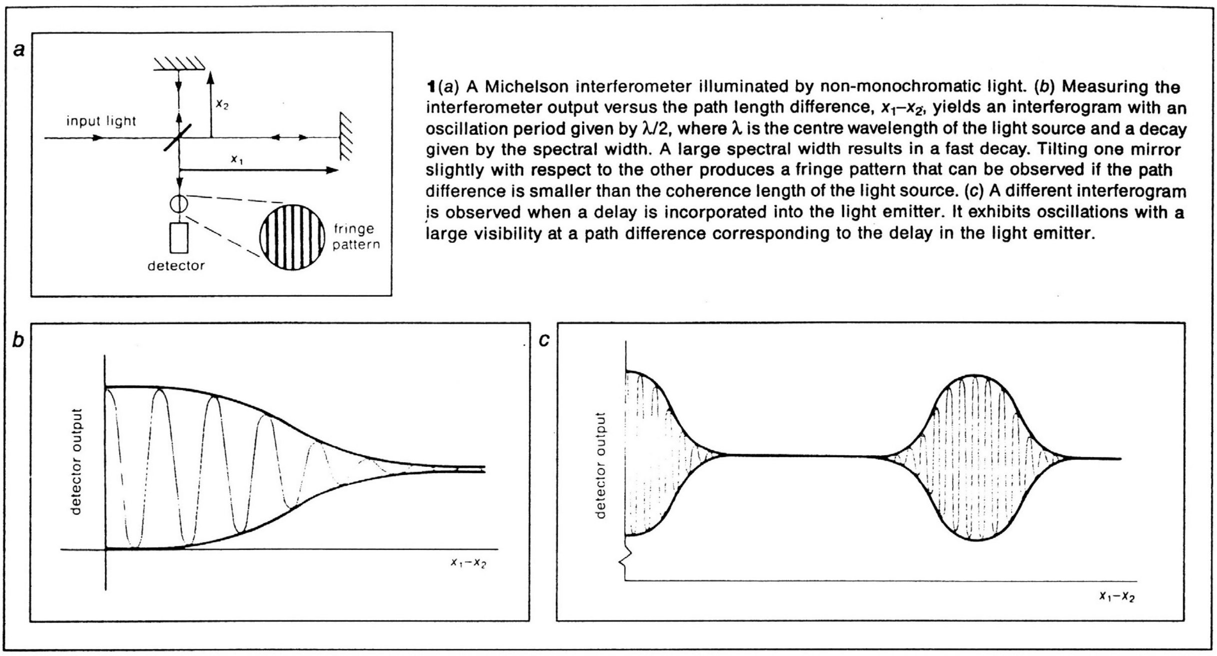
THE Doppler effect is familiar in everyday life – for example, as the change in pitch of an ambulance siren as it speeds past. The effect is widely used for velocity measurements. A source, such as a police radar, emits radiation that is reflected by a moving target, like a speeding car. The reflected light is then collected and the difference between the transmitted and received frequencies – and hence the difference in velocity between the radar and the car – can be determined.

Until recently, it was commonly accepted that the spectral width of the radiation source had to be smaller than the Doppler shift for the frequency shift to be measured by direct optical analysis. It was thus essential to use a monochromatic source such as a laser, and broadband incoherent light sources were not considered suitable. However, this is not necessarily true. David Erskine and Neil Holmes of the Lawrence Livermore National Laboratory in California have now devised a technique that



1(*a*) A Michelson interferometer illuminated by non-monochromatic light. (*b*) Measuring the interferometer output versus the path length difference, x_1-x_2, yields an interferogram with an oscillation period given by λ/2, where λ is the centre wavelength of the light source and a decay given by the spectral width. A large spectral width results in a fast decay. Tilting one mirror slightly with respect to the other produces a fringe pattern that can be observed if the path difference is smaller than the coherence length of the light source. (*c*) A different interferogram is observed when a delay is incorporated into the light emitter. It exhibits oscillations with a large visibility at a path difference corresponding to the delay in the light emitter.

works with an inexpensive broadband incoherent light source instead of a monochromatic laser (*Nature* **1995 377** 317).

Erskine and Holmes used an interferometer to analyse the reflected light. For good resolution, the path difference in the interferometer must exceed the coherence length of the emitter, which is inversely proportional to the spectral width. To obtain interference – despite the large path difference – Erskine and Holmes have had to tailor the coherence properties of the light by incorporating an optical delay in the transmitter, which is external to the light source. The delay closely matches the path difference of the analysing interferometer.

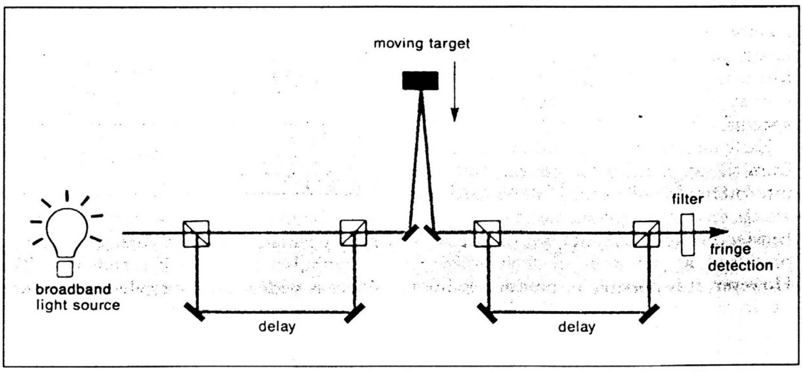
To illustrate the concept, consider a Michelson interferometer (figure 1*a*). A light source with a small spectral width illuminates the interferometer and the output power of the interferometer is measured as a function of path length difference (x_1-x_2). The interferogram is an oscillating function within an envelope that decays as (x_1-x_2) increases (figure 1*b*). The period of oscillation, Δx, is given by λ/2, where λ is the wavelength. The width of the envelope is inversely proportional to the spectral width. Measuring the period of the oscillation and determining the envelope is the basis for Fourier transform spectroscopy. (Fourier transforming the temporal envelope gives the spectral shape, and the period gives the centre frequency of the light source).

A velocity measurement is made by determining a frequency or wavelength change – a Doppler shift. This changes the period of oscillation of the interferometer, which can be seen as a phase shift in the output of the second interferometer (when the path length difference is fixed). To detect this phase shift, one mirror of the interferometer is tilted with respect to the other, producing a fringe pattern. A change in frequency produces a change in the phase of the fringe pattern, which can be measured. A velocity meter based on this concept is called a VISAR (velocity interferometer system for any reflector).

To measure a small frequency shift, a large path difference is needed. For a non-monochromatic light source, this path difference may be so large that the oscillatory part of the interferogram vanishes. To prevent this from happening, Erskine and Holmes tailored the coherence properties of the non-monochromatic light source. They did this by superpositioning light from the source with light from the same source but delayed by an amount that closely matches the delay of the analysing interferometer (figure 2).

This results in a displaced peak in the coherence function, as can be seen from the interferogram (figure 1*c*). Erskine and Holmes checked their technique by measuring the velocity of a rotating target at around 16 m s^{-1}, although the technique will be used to measure much higher velocities.

The method uses a light source that is much cheaper and probably more robust than a laser. However, using an incoherent source can also be preferable for physical reasons. One advantage is that a discontinuous jump in velocity, such as that produced by a shock wave, can be readily detected. Using laser techniques, a large change in frequency could shift the phases of the fringe pattern by an integer multiple, giving an ambiguous result. Using a grating to separate the different spectral components and applying a multichannel detection scheme can overcome the problem. Monochromatic light cannot be used for this method, proving that broadband sources have their own strengths. □



2 Two-interferometer concept for a white-light velocimeter. The delay in the transmitter part displaces the coherence function. Incorporating almost the same delay in the receiver creates interference with a delay that is much larger than the coherence length of the light source.