bats using lower-frequency calls (longer wavelengths). Kingston and Rossiter suggest that the range of echolocation calls in one species would generate 'disruptive selection' because larger bats do not have the same access to small prey as do smaller ones. Theirs is the first demonstration of how adaptive evolution in bats, and so speciation, might have been driven through divergences in echolocation signals.

For their part, Siemers and Schnitzler (page 657)[5] examined the behavioural consequences of differences in echolocation signals used by similar species of bats to detect prey. In a portable flight-room, they challenged flying individuals of five European species of mouse-eared bats (*Myotis* species) to detect and attack prey sitting on or close to vegetation. This is presumed to be difficult for the bats because echoes from prey could be masked by echoes — 'clutter' — from the background. Siemers and Schnitzler standardized the degree of clutter in which the bats operated, and documented their behaviour and foraging performance. The five species they used have similar hunting behaviour and are placed in the same 'foraging guild' of bats (the 'edge space aerial/trawling foragers'). The five species might have been expected to perform at the same level, but they did not.

In the tradition of Griffin and Spallanzani, Siemers and Schnitzler controlled for other cues (vision, olfaction) and demonstrated a significant relationship between the design of echolocation calls and foraging performance. Specifically, they showed that foraging performance in clutter was predictable from echolocation call design, particularly from differences in calls that had been considered minor. Their study is the first to provide empirical evidence that seemingly minor differences in call design can have real behavioural consequences. In contrast to Kingston and Rossiter, Siemers and Schnitzler show that signal designs of similar species can converge, reflecting foraging behaviour that is independent of presumed evolutionary relationships.

Individually and jointly, these two papers advance our understanding of the diversity of echolocation in bats. They have opened doors to a better appreciation of the variety of echolocation call designs, including the identification of cryptic species[7] — that is, the discovery that what had been considered a single species really consists of two or more. Coupled with data on the enhanced echoes that some flowers return to the bats that pollinate them[8], the new findings also allow better interpretation of insights into other pressures acting on the evolution of bats. For example, another component of the echolocation story is the listeners — other bats, or other animals that, like Griffin, eavesdrop on the calls[9,10]. Kingston and Rossiter's work shows clearly that changes in echolocation calls can affect not only bats' views of the world, but also the ability of one individual to communicate with another. Siemers and Schnitzler's results set the stage for examining the influence of call design on the ability of potential insect prey to detect and evade hunting bats[9,10].

The two studies[4,5] used species from both sides of the bat echolocation fence. On one side, mouse-eared bats, like most bats, separate call and echo in time (low-duty cycle); on the other, horseshoe bats separate them in frequency (high-duty cycle) (Fig. 1). Both approaches to echolocation are ancient, with fossil evidence indicating that they were present in bats some 50 million years ago[11]. The new data speak to the divergence of call design after the evolution of echolocation, but the early history of bats and echolocation remains unclear. There is plenty of opportunity in this line of research: stay tuned for the next chapter. ■

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1. Griffin, D. R. *Listening in the Dark* (Yale Univ. Press, New Haven, 1959).
2. Galambos, R. & Griffin, D. R. *Anat. Rec.* **78,** 95 (1940).
3. Thomas, J., Moss, C. & Vater, M. (eds) *Echolocation in Bats and Dolphins* (Univ. Chicago Press, 2004).
4. Kingston, T. & Rossiter, S. J. *Nature* **429,** 654–657 (2004).
5. Siemers, B. M. & Schnitzler, H.-U. *Nature* **429,** 657–661 (2004).
6. Simmons, J. A. & Stein, R. A. *J. Comp. Physiol. A* **135,** 61–84 (1980).
7. Barratt, E. M. *et al. Nature* **387,** 138–139 (1997).
8. von Helversen, D. & von Helversen, O. *Nature* **398,** 759–760 (1999).
9. Pye, J. D. *Nature* **218,** 797 (1968).
10. Fullard, J. H. in *Comparative Hearing: Insects* (eds Hoy, R. R., Popper, A. N. & Fay, R. R.) 279–326 (Springer, New York, 1998).
11. Simmons, N. B. & Geilser, J. H. *Bull. Am. Mus. Nat. Hist.* **235,** 1–182 (1998).

Particle physics

From the top…

Georg Weiglein

The top quark is by far the heaviest elementary particle known. A measurement of its mass with higher precision has bearing on our understanding of the fundamental interactions of nature.

The basic building-blocks of matter, as far as we know, are quarks and leptons, together with the force-carrying particles that mediate their interactions. Quarks and leptons (the latter group including the electron) are grouped in three generations; the particles in the second and third generations seem a perfect copy of those of the first generation, except that their masses are much larger. The top quark is the heaviest of all quarks and leptons, and is central to some of the most pressing questions in particle physics. For instance, why is the third-generation top quark more than 300,000 times heavier than the first-generation electron? Why are there two other quarks with precisely the same properties as the top quark but with very different masses? And what is the origin of mass itself?

Precise knowledge of the mass of the top quark and its interactions is a key ingredient in testing theory against experimental data. On page 638 of this issue[1], the DØ Collaboration report an improved measurement of the top-quark mass, using data taken at the Tevatron proton–antiproton collider at Fermilab, near Chicago. Combining this with previous measurements from DØ and its sister experiment CDF, the new world average[2] for the mass of the top quark is 178.0 ± 4.3 GeV/c^2, where c is the speed of light (the mass of the proton expressed in these units is about 1 GeV/c^2). Compared with the previous world average[3], the central value of the mass has shifted upwards by about 4 GeV/c^2. The experimental error has been reduced by about 15%, sharpening our view of the underlying physics.

The role of the top quark in disentangling the fundamental principles of nature is twofold. On the one hand, its large mass makes the top quark a prime target in the search for new physics that might so far be unaccounted for. For instance, the long-hypothesized Higgs boson, which is the last missing ingredient of the standard model of particle physics, is predicted to interact with other particles with a strength that is proportional to their masses. So the physics of the heavy top quark would be significantly influenced by its interaction with the Higgs boson. On the other hand, the mass of the top quark is a key parameter in the predictions for many observable quantities. Small deviations between measurement and prediction could be a signal of new physics, so the uncertainty in the predictions that arises from the experimental error on the top-quark mass limits the sensitivity of experiment to new physics.

The values of several precisely measured quantities, as predicted by the standard model, depend on the square of the top-quark mass, M_t; their dependence is much weaker on the as yet unknown mass of the Higgs boson (so far, experiment has excluded[4] any mass value below 114.4 GeV/c^2). Therefore, in using a so-called global fit of the model predictions to all available data, an improved knowledge of M_t better constrains

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100 YEARS AGO

An interesting mathematical study of the conditions which probably obtained in the primitive solar nebula has been communicated to the Academy of Science of St. Louis by Mr. Francis E. Nipher… According to the equations developed by the author, it seems impossible that at the time when the planets were separating from the parent mass the nebula was wholly gaseous. The idea that the planets were formed from condensing swarms of meteorites is the only reasonable one which conforms with the numerical results obtained. It also appears that at the times when the moon separated from the earth, and Mercury from the sun, the respective parent masses must have been in the solid state, the sun having fused and become vaporised since the separation of Mercury. Further, it seems unnecessary, and even improbable, that the earth should ever have been in a state of fusion. By substituting the proper conditions in one of his general equations, Mr. Nipher finds that the isothermal 7000° C. is probably the one existing at the sun's surface at the present time.

From *Nature* 9 June 1904.

50 YEARS AGO

A variety of cells and tissues of mammals survive for long periods at the temperature of 'dry ice', − 79° C., when frozen in media containing glycerol. At the other extreme, Andjus's work on the whole animal shows that, by special methods of cooling and rewarming, rats can be revived from deep body temperatures of about + 0.5° C.… Hamsters, chosen because of their known adaptability to body temperatures between 2.5 and 38° C., were cooled by the method recently described by Andjus and Smith for rats… The animals stiffened progressively during this process until they were wood-like to the touch, and presumably consisted of a hard frozen shell surrounding an unfrozen or only slightly frozen interior… The extremities intimately exposed to the bath fluid at − 4° C. to − 7° C. were severely frozen — the ears, for example, attained the consistency of cardboard, and may well have undergone crystallization of 80 per cent of their water content. It is remarkable, however, that damage obviously due to this cause has been seen in only two of the twenty-one animals revived completely, some of which have been kept for many weeks afterwards in apparently normal health. **A. U. Smith, J. E. Lovelock, A. S. Parkes**

From *Nature* 12 June 1954.

the likely value of the Higgs-boson mass. In fact, the 4 GeV/c^2 shift in the central value of M_t has shifted the upper limit on the Higgs-boson mass by more than 30 GeV/c^2, to 251 GeV/c^2 (at 95% confidence level)[1]. This upper limit has an important impact on the experimental strategies used to search for the Higgs boson at present and future colliders.

Finding the Higgs boson in the predicted range would be another triumph for the standard model — as, of course, was the discovery of the top quark itself. Historically, the mass of the top quark had been predicted from a global fit to a wealth of precise measurements made at the LEP and SLC electron–positron colliders (at CERN in Geneva and at SLAC in Stanford, respectively). The top quark was discovered at the Tevatron in 1995, with a mass value in perfect agreement with the predicted range.

Although the standard model has passed many experimental tests with great success, it cannot be the ultimate theory of the fundamental interactions. This is evident from the fact that it describes only three of the four known interactions — namely, the electromagnetic, weak and strong interactions, but not gravity. It also has several theoretical shortcomings and leaves many questions unanswered. Perhaps the most attractive framework for extending the standard model is supersymmetry. A supersymmetric extension of the standard model could be the low-energy limit of a more fundamental high-energy theory that would consistently include gravity and would describe all the fundamental forces in a unified way. Supersymmetric theories predict that there are partners for all the known particles. The minimal supersymmetric extension of the standard model — the 'MSSM' — comprises one pair of superpartners for each quark and lepton, superpartners for the force carriers, and five Higgs bosons.

In supersymmetric models, as a consequence of the higher degree of symmetry, the mass of the lightest Higgs boson can be predicted directly (in contrast to the standard model, in which the Higgs mass is a free parameter, allowing only an indirect determination via a global fit). The predicted mass is very sensitive to the mass of the top quark, scaling as M_t^4 — an even more pronounced dependence than in the standard-model case. Figure 1 shows the prediction[5,6] for the lightest Higgs-boson mass in the MSSM: the effect of the change in the top-quark mass, to 178.0 ± 4.3 GeV/c^2, is clearly seen. The direct experimental detection of the Higgs boson would enable its mass to be measured with an accuracy below the 1% level. Thus, a precise knowledge of M_t with an accuracy even better than presently available will be crucial for Higgs physics in supersymmetric extensions of the standard model[7].

Besides having an important impact on Higgs physics, the top-quark mass influences

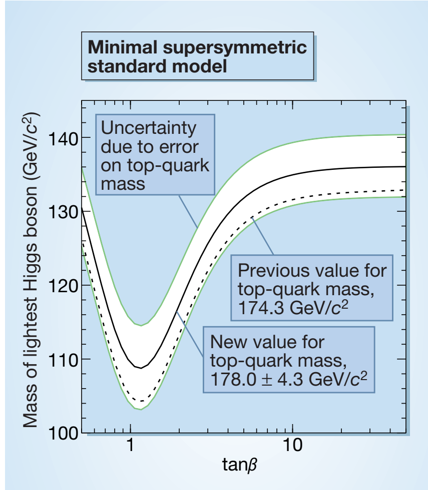

Figure 1 **The mass of the lightest Higgs boson in the minimal supersymmetric standard model (MSSM). The predicted value[5,6] is shown as a function of the parameter tanβ, which relates the properties of the different Higgs bosons of the MSSM to each other (the other MSSM parameters are chosen such that they maximize the resulting value of the Higgs mass). The predicted Higgs mass is sensitive to the value of the top-quark mass used in the calculation. The solid line indicates the prediction using the new measurement of the top-quark mass from the DØ Collaboration[1]; the white band indicates the uncertainty of the prediction that results from the error on the top-quark mass. The dashed line shows the situation before the new measurement (the previous experimental error of ± 5.1 GeV/c^2 is not shown). Based on the new value of the top-quark mass, an upper bound on the mass of the lightest MSSM Higgs boson of about 140 GeV/c^2 is established.**

many other predictions of the MSSM — for instance, the masses of the superpartners of the top quark and the strengths of their interactions. The ultimate goal is to connect the predictions of the MSSM, or other extensions of the standard model, with a more fundamental theory at a higher energy scale. This may provide evidence for the unification of all of the forces of nature into a single fundamental interaction. Measurements made at the energy scales directly accessible to us in collider experiments can be extrapolated to very high energy scales, but for this to be reliable a precise knowledge of M_t is crucial[7]. If the extrapolation is sufficiently precise, it may even give us clues about the structure of the unified force itself.

Further progress will require new experimental data — both the discovery of new particles, such as the Higgs boson or supersymmetric partners, and more precise measurements of observable quantities that allow a sensitive test of the underlying theory. Among these, improving the accuracy of the measurement of the top-quark mass will continue to be of the utmost importance. From data taken during the present phase

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of operation at the Tevatron (known as 'Run II'), the experimental error on M_t will be reduced to 2–3 GeV/c^2; at the Large Hadron Collider[8], currently under construction at CERN, this accuracy will be improved further to 1–2 GeV/c^2.

The ultimate precision on M_t, however, will be achieved at a linear electron–positron collider. Such a machine is currently in the planning phase and could go into operation around the middle of the next decade. Data from the linear collider could improve the accuracy on the top-quark mass by about a factor of ten[9–11]. Only then will the uncertainty due to the experimental error of the top-quark mass be well enough under control for the information gleaned from the LHC in the next decade — on the Higgs boson (or bosons), supersymmetric partners or other new physics — to be fully exploited. ■

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1. The DØ Collaboration *Nature* **429**, 638–642 (2004).
2. The CDF Collaboration, the DØ Collaboration and the Tevatron Electroweak Working Group. Preprint at http://arxiv.org/abs/hep-ex/0404010 (2004).
3. Hagiwara, K. *et al. Phys. Rev. D* **66,** 010001, 271–433 (2002).
4. The ALEPH, DELPHI, L3 and OPAL Collaborations and the LEP Working Group for Higgs Boson Searches *Phys. Lett. B* **565,** 61–75 (2003).
5. Heinemeyer, S., Hollik, W. & Weiglein, G. *Comput. Phys. Commun.* **124,** 76–89 (2000).
6. www.feynhiggs.de
7. Heinemeyer, S., Kraml, S., Porod, W. & Weiglein, G. *J. High Energy Phys.* JHEP09(2003)075 (2003).
8. Beneke, M. *et al.* in *Standard Model Physics (and More) at the LHC* (eds Altarelli, G. & Mangano, M.) 419–529 (CERN, Geneva, 1999).
9. Heuer, R.-D. *et al.* Preprint at http://arxiv.org/abs/hep-ph/0106315 (2001).
10. Abe, T. *et al.* Preprint at http://arxiv.org/abs/hep-ex/0106056 (2001).
11. ACFA Linear Collider Working Group. Preprint at http://arxiv.org/abs/hep-ph/0109166 (2001).

Interstellar chemistry

Molecular nitrogen in space

Theodore P. Snow

Astronomers have found evidence of molecular nitrogen in the clouds of gas between the Earth and a distant star. The chemistry involved in the formation of these diffuse clouds might need to be rethought.

On page 636 of this issue, David C. Knauth and colleagues[1] claim the first detection of molecular nitrogen (N_2) in interstellar space. This simple diatomic molecule, made of one of the most abundant elements in the Universe, is the most common constituent of Earth's modern atmosphere. It is also a major component of the atmosphere of Saturn's moon Titan, and has been detected in trace amounts in the atmospheres of Venus and Mars. But it has proved surprisingly difficult to find N_2 in any environment beyond the Solar System.

Chemical models of dark interstellar clouds (whose densities are usually in the range of 10^3 to 10^5 particles per cm^3) suggest that N_2 should be the most abundant form of nitrogen in these regions. This leads to the prediction[2–4] that the ratio of N_2 to hydrogen should be about 10^{-5}. In contrast, models for diffuse interstellar clouds, which are transparent and have densities of about 10^2 particles per cm^3, predict a much lower N_2 abundance, in the range between 10^{-9} and 10^{-8} that of hydrogen[2,5].

Both predictions suggest that N_2 might be observable, but searches for this molecule in interstellar space had been fruitless until now. One of the difficulties in detecting interstellar N_2 arises from the fact that the symmetric diatomic molecule has no allowed rotational or vibrational (dipole) transitions. Thus, N_2 — unlike most of the 120 or more species now detected in dark interstellar clouds — cannot be detected either through millimetre-wavelength observations of rotational emission lines or through infrared spectroscopic detection of vibrational bands (absorption or emission).

The only viable approach to finding interstellar N_2 is to search for the spectral lines created by electronic transitions in the molecule. These lines are found exclusively at far-ultraviolet wavelengths (shorter than 100 nm), for which space-based telescopes are required because the Earth's atmosphere blocks such radiation. For technical reasons, however, most ultraviolet telescopes have not covered the far-ultraviolet spectral region where the N_2 bands lie. For example, the Hubble Space Telescope cuts off at about 115 nm, well above the wavelength needed for an N_2 search. The Copernicus satellite — a small mission that was developed and led by the late Lyman Spitzer and operated from 1972 until 1980 — was the first orbiting spectroscopic observatory capable of far-ultraviolet searches for N_2 in interstellar space, but no detection was achieved[6].

The best chance for astronomers to search for interstellar N_2 has been afforded by the Far Ultraviolet Spectroscopic Explorer (FUSE) mission, now in its fifth year of operation. FUSE was designed specifically to extend ultraviolet spectroscopy to the shorter wavelengths that are not accessible to the Hubble Space Telescope, including the spectral region where the electronic bands of N_2 lie. Knauth *et al.*[1] have taken advantage of FUSE's far-ultraviolet sensitivity to search for N_2 — and apparently they have found it.

In a classic example of spectroscopic sleuth work, Knauth *et al.* have detected absorption by N_2 in the line of sight towards the star HD 124314 by sorting through and eliminating other features that are blended into the spectrum. These other features arise through the absorption of radiation by the star's own atmosphere, by foreground interstellar gas (mostly molecular hydrogen) and by N_2 in the outer vestiges of Earth's atmosphere. The detection of interstellar N_2 was aided by the fact that several individual N_2 lines are accessible to FUSE and also because FUSE covers the N_2 wavelength region with two separate detectors, which means that instrumental artefacts in the data can be eliminated.

The line of sight towards HD 124314 does not intersect a dark molecular cloud; rather, this is a long pathlength, probing one or more diffuse clouds. So, according to model calculations, the ratio of N_2 to hydrogen should be closer to the 10^{-9} to 10^{-8} level that is predicted for diffuse clouds than to the 10^{-5} level predicted for dense clouds. Knauth *et al.* have found an intermediate value, with N_2 representing about 10^{-7} of the total hydrogen abundance in their observed line of sight. This abundance of N_2 does not fit either the dense-cloud or diffuse-cloud models.

Among the possible explanations is that the line of sight towards this star contains one or more 'translucent' clouds, which are reckoned by astronomers to be intermediate (or possibly transitional) between dense and diffuse clouds[7]. Alternatively, the models for diffuse clouds might be incorrect, or the detection claimed by Knauth *et al.* is wrong. The first and third of these options can probably be eliminated, as the line-of-sight dust extinction to this particular star is too small to include a translucent cloud, and the claimed detection of N_2 seems secure. So we must surmise that the chemical models for N_2 in diffuse clouds are inadequate.

Normally it is assumed that, with the exception of hydrogen, molecules in diffuse clouds form through gas-phase chemical reactions[2,5]. But in dense clouds an additional process, that of molecule formation on grain surfaces, is probably important[8,9]. The detection of N_2 by Knauth *et al.*[1] suggests that grain-surface reactions might contribute more to diffuse-cloud chemistry than previously thought. This conclusion is consistent with earlier searches in diffuse clouds for NH, another simple diatomic molecule found to be more abundant than expected from gas-phase chemistry alone[10,11]. If grain-surface reactions are required to explain the measured abundances of N_2 and NH, it is possible that other surface reactions

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