

QUANTUM GRAVITY

Beyond the screen of time

Can we ever know what happened before the Big Bang? It may have been only a stage in the existence of our Universe rather than its beginning, but analysis suggests the Big Bang is a barrier beyond which we may never see with clarity.

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Science has frontiers; sometimes these frontiers move. One of the most impressive of science's frontiers is the Big Bang, and now a quantum theory of gravity — loop quantum gravity — is providing equations with which to explore it. Although these equations are still tentative, and rely on drastic approximations, they introduce a definite method of exploration, and are capable of describing the Universe not only close to the Big Bang but also beyond it. It is in this context that Martin Bojowald reports, in this issue, on the possibility of a peculiar limitation to our ability to observe fully the 'other side' of the Big Bang — whatever that expression might mean (*Nature Phys.* **3**, 523–525; 2007).

The deduction that there has been a cosmological Big Bang is one of the most spectacular consequences of Einstein's jewel theory, general relativity. Combined with the observation of the expansion of the Universe, first made by the American astronomer Edwin Powell Hubble in 1929, Einstein's equations imply that the Universe has evolved from a primordial state in which it was extremely compressed and hot. This astonishing inference has been confirmed by an impressive variety of astronomical observations, which have given rise to the booming field of modern cosmology.

But how did that primordial hot, dense state arise? If we apply Einstein's equations to trace the evolution of the Universe back further, we run into trouble: at a point conventionally called 'the Big Bang', temperature becomes infinite, spacetime curvature becomes infinite, and all well-established equations of physics become meaningless. The Universe seems to have been incomprehensibly born out of nothing, in a flash. However, we also know that it is incorrect to apply

Einstein's equations all the way back to this hypothetical initial point, because quantum effects become dominant at high temperature and Einstein's equations fail to take these effects into account. Disregarding quantum effects can generate spurious infinities. For instance, if we neglect these effects we predict that an electron orbiting a nucleus falls rapidly into the nucleus, radiating potentially infinite energy. But this is not the case in reality: quantum effects prevent the fall of the electron, and hence atoms are stable. The prediction of the existence of a Big Bang where physical quantities blow up, therefore, is not reliable at all: to study the early Universe we need to develop Einstein's general relativity into a quantum theory of gravity.

There is as yet no consensus on a quantum theory of gravity. What we know with confidence about the fundamental laws of nature is encapsulated in quantum theory, the standard model of particle physics and classical general relativity. Beyond that, the landscape of theoretical physics is full of speculative ideas, such as higher dimensions, supersymmetry, strings, branes, and so on. One of the more conservative directions of research is loop quantum gravity (LQG), which focuses only on the quantum properties of the gravitational field, using physical assumptions that are limited to general relativity and quantum mechanics, both of which are firmly established empirically. In LQG, there is no ambition of unification, or a 'theory of everything', but its theoretical consequences are nevertheless far-reaching. Its most characteristic feature is that, at short scales, space and time dissolve into a granular and probabilistic, or quantized, structure. The application of LQG to cosmology — 'loop cosmology' — has been developed by Abhay Ashtekar, Bojowald and their collaborators.

In loop cosmology, it is possible to investigate models that describe the quantum evolution of the Universe. The key result is that the evolution equations do not become ill-defined near the

Big Bang. This is in drastic contrast not only with classical general relativity but also with several previous attempts to create quantum-cosmological models. It is a consequence of the discrete structure of space predicted by LQG: because space is formed by indivisible quanta, when the Universe approaches the Big Bang it cannot fall continuously towards arbitrary small volumes; rather, it makes probabilistic quantum leaps between different, finite, quantized volumes. In other words, the Big Bang infinities are controlled by the very same quantum mechanism that stabilizes the electron orbits in the atom.

If the evolution equations are traced through the highly quantum phase of the near-Big Bang region, it seems that the Universe 'bounces' back to large scales. This 'other side' of the Big Bang is often referred to as "before the Big Bang", but the reader should treat these expressions with caution: temporal concepts become ill-defined in the quantum-gravitational regime, and notions such as 'before' and 'after' might be misleading. For example, imagine walking due north — what happens when you reach the North Pole? You may still keep walking, but this does not mean you are heading to a place 'more north' than the North Pole. What the 'bounce' analogy provides is only a first, simple, intuitive picture of what might have happened at the Big Bang.

In his paper in this issue, Bojowald presents an investigation, using an LQG model, of the possibility that we might be able to deduce features of the other side of the bounce by means of measurements performed on 'our' side. He finds, unexpectedly, that there might be intrinsic limitations to doing so. It seems that the dynamics of the Big Bang act as a kind of mixer, churning macroscopic features of one side into super-microscopic features of the other. This is similar to — but should not be confused with — other well-known sources of a lack of predictability in physics, such as quantum measurement and the chaotic behaviour of many dynamical systems. If this effect is real, the hypothetical other side of the Big Bang

would always be partially obscure: to see what happens (or has happened) there, we would need to make impossibly precise measurements on our side.

Clearly these investigations are still speculative. The hope is that models like this could be developed to yield quantitative predictions that could be compared with cosmological observations — such as imprints in the

spectrum of the cosmic background radiation, and gravitational radiation, whose remnants we hope to see using the planned space gravitational antenna LISA. This connection to the rapidly growing field of observational cosmology could provide the long-sought window of empirical verification for quantum gravity. The fact that questions about the physics of the Big Bang, and about

the observability of the other side of the bounce, can be cleanly formulated and tentatively answered in loop cosmology represents definite progress. But it must be remembered that no quantum theory of gravity has received any direct empirical support so far. Until one does, the application of any such theory to the Big Bang is certainly to be considered conjectural.

SPINTRONICS

Silicon takes a spin

An efficient way to transport electron spins from a ferromagnet into silicon essentially makes silicon magnetic, and provides an exciting step towards integration of magnetism and mainstream semiconductor electronics.

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Semiconductor electronics — the cornerstone of information technology for many decades — is based on the manipulation and storage of electrical charge. But as it becomes increasingly difficult to improve the performance of successive generations of conventional integrated circuits, the need to find alternatives becomes ever greater. Spintronics is one such alternative, which seeks to use the magnetic moment, or spin, that electrons possess, to achieve similar purposes for which their charge is used in electronics. Significant progress has been made in the transport and manipulation of spin in semiconductors such as GaAs (refs 1–3). But for spintronics to hit the big time commercially, these advances will need to be reproduced in silicon, the material on which most electronics is based. On page 542 of this issue⁴, Jonker and colleagues make the first important steps towards doing just this, by demonstrating an efficient and versatile way to inject electron spins from a ferromagnetic contact into silicon.

At first glance, it may seem that it should be straightforward to inject spin-polarized currents into a semiconductor. A ferromagnetic metal will contain an excess of carriers whose spin points in a preferred direction, depending on the direction of the metal's magnetization. This spin imbalance

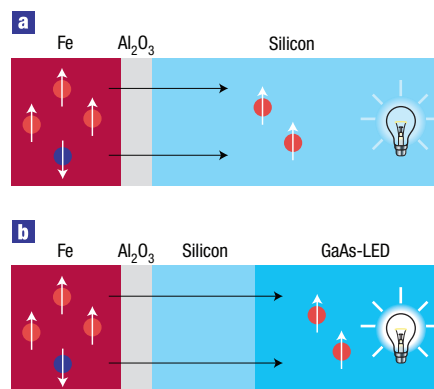


Figure 1 Demonstration of the injection of spin into silicon. **a**, By measuring the polarization of the light emitted by the recombination of carriers injected from a magnetized Fe contact across an Al_2O_3 tunnel barrier, Jonker *et al.*⁴ prove that polarized spin injection into silicon does indeed take place. **b**, By allowing spins injected in the silicon to pass through and into a GaAs light emitting diode (LED) structure, they were able to obtain a lower bound for the spin polarization of 10%. In future, this approach could be used to determine how far spins can travel in silicon, and to explore how different materials and structures affect the spin-polarization efficiency of the contacts. This will provide better understanding of the possibilities of silicon spintronic devices.

should then, in principle, be transferred to a semiconductor when charge carriers are injected into it from a ferromagnetic electrode. In reality, however, the situation is not so simple.

The electrical resistance of a ferromagnetic metal is much smaller than that of a semiconductor. And so any voltage applied to a contact between them will drop completely within the semiconductor, the non-magnetic properties of which dominate the behaviour of the contact. As a result, the current across such a contact will consist of carriers with no preferred spin direction, regardless of the relative population of spins within the ferromagnetic metal. This is known as the conductivity-mismatch problem⁵, and can be overcome by introducing an additional, spin-dependent, barrier at the boundary between a ferromagnetic contact and a semiconductor, for example a thin oxide. This provides a spin-dependent tunnel resistance that can be made comparable to, or larger than, the resistance of the semiconductor. The success of this approach for injecting spins into GaAs is demonstrated by the circular polarization of the light that is emitted when these spin-polarized electrons subsequently recombine with holes^{1,2}.

It was generally expected that using the same optical approach to that used to verify the injection of spins into GaAs would be difficult to apply in the case of silicon. Owing to its indirect bandgap, silicon is a much poorer light emitter than GaAs; moreover, although there is a direct relation between the circular polarization of the emitted light and the electron spin polarization for GaAs, the same cannot be said for silicon, whose electronic structure is qualitatively different⁶. This precludes a direct quantitative analysis of the spin