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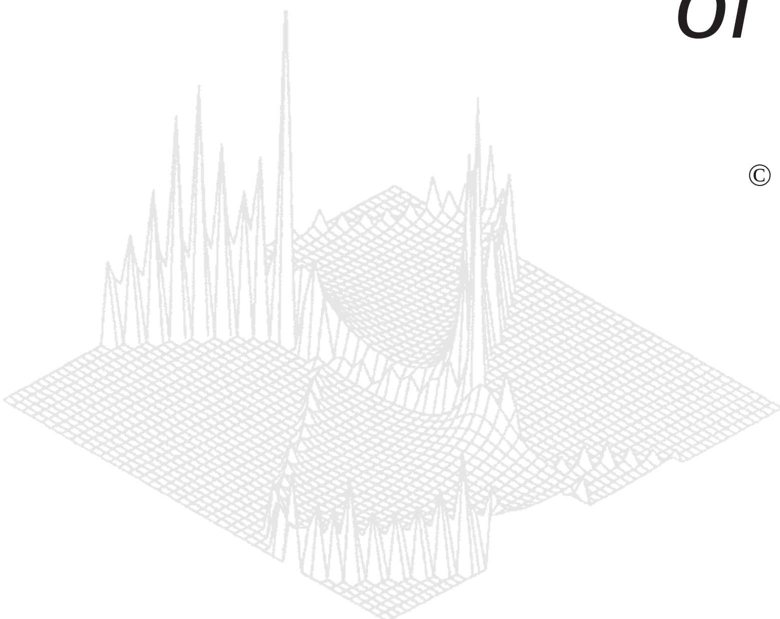

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Tunnelling in the Presence of an Environment: Insights from the Fusion of Heavy Nuclei*

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Abstract

A great many physical processes are mediated by the penetration or surmounting of a potential barrier. Some notable examples are the thermionic emission of electrons, chemical reactions, tunnelling of Cooper pairs through Josephson junctions, nuclear 'burning' in stars etc. Often the potential in question is not simply a function of the position of the intruding particle, but is a complicated landscape determined by the static structure of the physical objects concerned as well as by their dynamical response to their mutual interactions. For example, in a Josephson junction, the penetration of the barrier is strongly influenced by the excitation of lattice vibrations while catalysed chemical reactions proceed via complex routes which present a series of lower activation energies.

In a physical system with a well-defined temperature, the details of the potential landscape may be obscured by the Maxwell–Boltzmann distribution of energies. The fusion of heavy nuclei can, however, be achieved over a controlled range of well-defined beam energies to reveal fine details of some of these effects. To date the major new experimental work in this area has been performed at the ANU, Canberra and at the INFN, Legnaro. As well as yielding valuable information on nuclear structure (detailed information on nuclear shapes etc.) and some totally unexpected reaction dynamics (complexity of the induced surface oscillations, neutron flow), these experiments and their theoretical analysis give considerable insights into the general problem of 'tunnelling in the presence of an environment'.

1. Introduction

We have heard during the course of this conference of at least two problems (Kibble 1997, present issue p. 697; Phillips 1996) where tunnelling plays a rôle in vastly different domains, though through potentials of strikingly similar shapes (see Fig. 1). These are the tunnelling of the vacuum of a scalar field of the form $V(\phi) = (\phi^2 - \eta^2)^2$ from its minimum at $\phi = \eta$ to the minimum at $\phi = -\eta$ through the potential barrier at $\phi = 0$. On cooling down, different regions of the Universe will find themselves in one or other of these potential minima, with the different regions separated by domain walls. The tunnelling results, therefore, in a spatial displacement of these walls. A potential of essentially the same form is obtained for the total energy of a nucleus possessing an octupole or β_3 (pear-shaped) deformation. The resulting nuclear spectrum comprises 'parity doublets' whose energy spacing can be related to the time taken to tunnel from one potential

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minimum to the other. Other problems may differ in that the system may be in a scattering state on one or both sides of the barrier, e.g. in nuclear α-decay the particle is quasi-bound in the nuclear interior but may escape to infinity on the outside, whereas in the problem of tunnelling of Cooper pairs through a Josephson junction (Leggett 1993), the pair is free on each side of the junction.

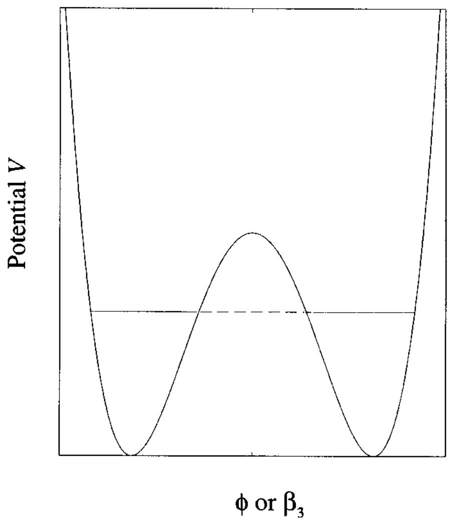

Fig. 1. Potential V corresponding to a scalar field ϕ or to the deformation parameter β_3 of an octupole-deformed nucleus.

The phenomenon of quantum tunnelling was observed long ago in the laboratory, though not understood for many years through the above-mentioned phenomenon of α-decay. In this problem the mass of the tunnelling particle is well known and so if the potential barrier is also understood one might expect that quantities such as tunnelling probabilities, lifetimes etc. could be readily calculated. However, the additional problem of the 'preformation factor' presents itself, i.e. what is the probability that the 'parent' nucleus wavefunction has a component which can be considered as an α-particle coupled to the 'daughter' or residual nucleus? Since α-emitters are also generally deformed, the relative motion may excite rotational states of the daughter nucleus (Stewart *et al.* 1996). This problem is, therefore, further complicated but also enriched by the extra possibility of decay to various final states. In the tunnelling of an octupole-deformed nucleus from one shape to its mirror reflection, even the 'mass parameter' of the system becomes difficult to define.

It is clear that there will always be such additional, frequently very deep, physical questions which must be posed before the basic quantum-mechanical problem of how an object of mass M penetrates a classically forbidden region of the simple potential $V(x)$ (which probably exists in such a form only in pedagogical examples) can even be asked. In real physical problems, one object may fuse with another by tunnelling through the field generated by their mutual interactions. Such objects will of course always possess internal structures and one of the important questions which arises is that of how the tunnelling is affected by coupling to these internal degrees of freedom, i.e. how does the 'environment' in which the tunnelling takes place affect the reaction/transmission probability. The environment may take many forms depending on the nature of the problem and the answer to that question may of course also depend on whether the system is initially in a unique quantum state, usually its ground state ($T = 0$), or at some finite temperature.

2. Nucleosynthesis

Tunnelling has a long history. Indeed the Universe itself is supposed to have come into existence by the tunnelling of an empty vacuum into its 'Big Bang' configuration. When the dust had settled, shortly afterwards, the Universe was populated by stable particles; p, ^{4}He, e$^-$, ν, $\bar{\nu}$, γ and small quantities of the lighter elements Li, Be and B, produced in a statistical process as the system cooled and before the relatively long-lived neutrons had decayed. This phase of the Universe's evolution is perhaps its least interesting; following the enormous energy densities which allowed all manner of exotic particles to roam free and before the gravitational contraction and reheating of the resulting gas (galaxy and star formation) which allowed nuclear reaction processes to switch on. This state probably represents a watershed between particle and nuclear physics, with much of the research in the former domain seeking to recreate the earlier conditions through high-energy collisions of these stable species exploiting large accelerators such as LEP, TEVATRON, HERA, LHC etc., and the latter being interested in the properties of the heavier nuclei built up from the remaining protons and neutrons (reborn through nuclear β-decays).

Of course much of our detailed knowledge of fundamental physical interactions also comes from the study of heavier nuclei, e.g. (i) weak interaction studies through β-decays such as the NEMO experiment which will look for the neutrino-less double β-decay of ^{100}Mo and (ii) the quest for the quark–gluon plasma through the collisions at relativistic energies of very heavy nuclei at RHIC and the ALICE experiment at the LHC.

The building of the nuclei of which the world as we know it is comprised, starts with the process of 'hydrogen burning' in stars:

$$p + p \rightarrow (pp) \rightarrow (pn) + W^+ \rightarrow d + e^+ + \nu \,.$$

The first stage of this process involves the tunnelling of two protons through their mutual Coulomb barrier to a distance comparable with the deuteron radius; a very unlikely event at normal stellar temperatures. Even when such a close approach is achieved, the majority of the time the two protons will separate without incident. Extremely rarely, however, the weak interaction intervenes, one proton turns into a neutron by emission of a W$^+$($\rightarrow$e$^+ + \nu$) and a stable deuteron is formed. This is, therefore, an example of an environment, i.e. the nucleon has internal structure through which the outcome of the tunnelling process is determined through coupling via the weak interaction. We can be grateful for the extreme slowness of this process (tunnelling + weak interaction) for giving the Sun a sufficiently long lifetime for life on Earth to have evolved.

Subsequently, the major route followed is then relatively fast, or at least slow only in first order (tunnelling + strong interaction):

$$d + p \rightarrow {}^3He + \gamma \,,$$

i.e. a deuteron is rapidly picked up by one of the enormous number of protons around it and then

$$^3He + ^3He \rightarrow ^4He + p + p\,.$$

The reactions $d + {}^3He \rightarrow {}^4He + p$ and $p + {}^3He \rightarrow {}^4He + e^+ + \nu$ are rare since in the former the deuterons are rapidly consumed by the much more abundant protons and since the latter requires a weak decay. A further rare event of interest is

$$^3He + ^4He \rightarrow ^7Be + \gamma\,,$$

since the subsequent electron capture (${}^7Be + e^- \rightarrow {}^7Li + \nu$) leads to the emission of the ν currently studied in the solar-neutrino problem. All of the above fusion reactions can of course occur only through the phenomenon of quantum tunnelling.

Although providing much light and heat, the above processes do not take us far down the path of nucleosynthesis (i.e. the production of heavier elements) since the major end-product ${}^4He$ already exists in abundance. To continue along this route requires the well-known triple-α process to bridge the missing stable mass-5 system. Although ${}^8Be$ is unstable, it possesses a 0^+ resonance with a width of $6\cdot 8$ eV enabling the reaction

$$\alpha + \alpha \rightleftharpoons {}^8Be$$

to give rise to a non-negligible concentration of ${}^8Be$ in a sufficiently hot star. The relatively long lifetime of ${}^8Be$ (at least on a nuclear timescale) is due to the fact that the two α-particles are trapped inside their mutual Coulomb barrier. Thus tunnelling plays a rôle both in the formation and decay of this ephemeral nucleus. Subsequently, the further *2-body* reaction

$$^8Be + \alpha \rightarrow {}^{12}C^* \rightarrow {}^{12}C + \gamma$$

successfully completes the bridging of the mass-5 gap. Again the tunnelling in the above reaction is strongly modified by other effects and owes its existence to a 0^+ resonance in ${}^{12}C$ close to the 3-α threshold. This state was unknown at the time of the development of the theory of nucleosynthesis, but its absolute requirement by the theory led Hoyle to speculate strongly on its existence through a paraphase of Decartes' *cogito ergo sum*—I think therefore I am—along the lines of I am therefore there must be a 0^+ resonance in ${}^{12}C$ at around $7\cdot 7$ MeV!

This state is thought to have a 3-α chain structure as opposed to the ground state which is supposed to resemble three α-particles at the corners of an equilateral triangle. The search for other exotic chain states of higher α-particle number is one of the main aims of the UK/Australian CHARISSA collaboration at the ANU.

Having built the more massive stable ${}^{12}C$ nucleus, another possibility for proton burning opens up through the CNO (carbon/nitrogen/oxygen)-cycle (see Fig. 2). This process comprises successive proton captures and β-decays

$$^{12}C + p \to {}^{13}N + \gamma\,,$$

$$^{13}N \to {}^{13}C + e^+ + \nu\,,$$

$$^{13}C + p \to {}^{14}N + \gamma\,,$$

$$^{14}N + p \to {}^{15}O + \gamma\,,$$

$$^{15}O \to {}^{15}N + e^+ + \nu\,,$$

$$^{15}N + p \to {}^{16}O^*\,,$$

$$^{16}O^* \to {}^{12}C + \alpha \quad \text{or rarely} \quad {}^{16}O^* \to {}^{16}O + \gamma\,.$$

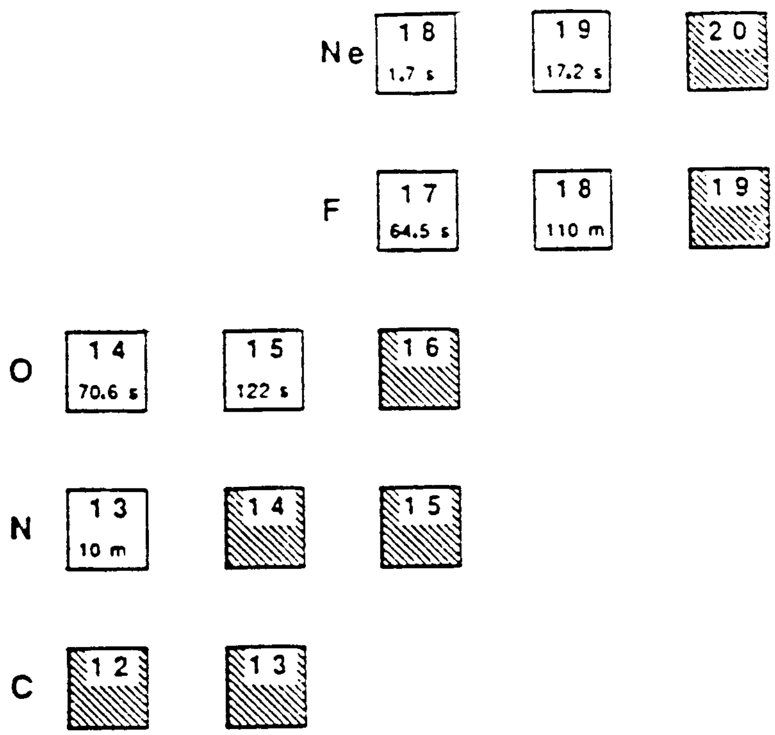

Fig. 2. Nuclei involved in the CNO cycle (see also Clayton 1983) and heavier ones which can be created by leaking out of the cycle through further proton capture.

The emission of an α-particle in the final stage gives back the original ^{12}C which has, therefore, played the rôle of a catalyst in this series and led effectively to the fusing of four protons into an α. This cycle becomes favoured over simple proton burning at high temperatures which permit the penetration of the higher Coulomb barrier between a proton and a heavier nucleus. This leads, in two of the above steps, to β-decaying nuclei. Here the decaying proton is trapped, leading to an inevitable decay as opposed to the very infrequent decay in the fleeting p+p scattering process.

At higher energies and/or proton densities, the slow decay (10 min) of ^{13}N may be bypassed by a further proton capture to produce ^{14}O which decays more rapidly and gives rise to the so-called hot CNO cycle. This is one of the many nuclear reactions of astrophysical interest whose study will become available at new radioactive beams facilities, e.g. at Louvain-la-Neuve (where ^{13}N beams have already been produced to study the above process), ISOLDE, Jyäskylä, Berkeley and GSI (Darmstadt) where other exotic beams have been produced, and at other facilities currently under construction in many laboratories, e.g. GANIL (SPIRAL project) in France, Oak Ridge (RIB project) in the US and at CERN (REX–ISOLDE project).

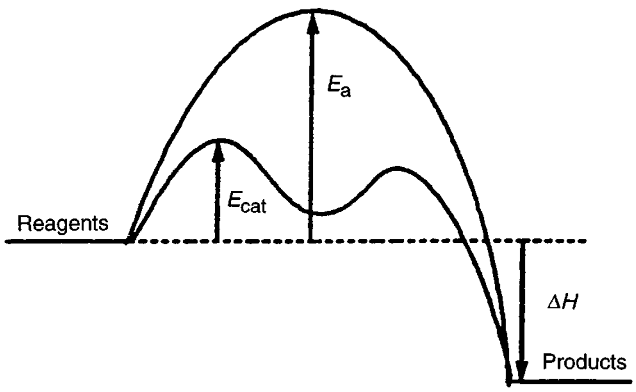

Fig. 3. In catalysis, the formation of an intermediate state replaces a single potential barrier (activation energy) by a series of lower ones.

3. Catalysis and Chemical Reactions

The above CNO cycle of reactions presents, in a rather perverse fashion, the facilitating of a reaction by the lowering of successive barriers and has strong analogies with catalysed chemical reactions. Here (see Fig. 3) the formation of intermediate states can give rise to a chain of barriers lower than the original one. A well-known example is the use of vanadium pentoxide in the 'contact process' exploited in the commercial production of sulphuric acid:

$$SO_2 + V_2O_5 + \tfrac{1}{2}O_2 \rightarrow SO_3 + V_2O_4 + \tfrac{1}{2}O_2 \rightarrow SO_3 + V_2O_5 \,.$$

In the chemical domain one can also find examples of some phenomena that we shall meet in the fusion of heavy nuclei. These are exemplified in Figs 4 and 5. In Fig. 4, the fusion of a polar hyrogen bromide molecule with ethene is shown. The excess negative charge of the carbon–carbon double bond leads to an attraction for the positively charged H, giving rise to an orientation-dependent reaction probability. In Fig. 5, we see the non-polar Br_2 molecule becoming dynamically polarised by the double bond and leading to a similar kind of reaction mechanism but where the orientation of the lighter partner is less important. These two cases should be compared with the static and dynamic (through phonon excitations) deformations we shall encounter later in heavy-ion fusion.

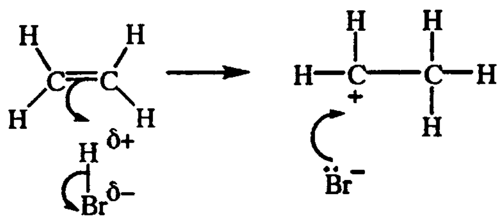

Fig. 4. Excess negative charge of the C–C double bond attracts the positively-charged H. The 'visibility' of the double bond leads to an orientation-dependent interaction.

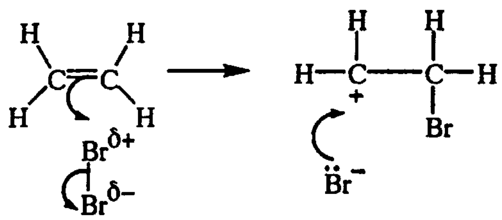

Fig. 5. Negatively charged C–C double bond polarises the Br_2 molecule and leads to a reaction mechanism similar to that in Fig. 4, but where the orientation of the Br_2 is less important than that of the HBr.

4. Heavy-ion Fusion and Barrier Distributions

Chemical reactions generally take place under conditions of finite temperature, where the detailed structures of the contributing potential barriers are obscured by the Maxwell–Boltzmann distribution of energies. Reactions between heavy nuclei, however, are performed with a beam of particles of a relatively well-defined energy, permitting such barrier structures to be studied in detail. The ideal accelerators for such studies are electrostatic machines since they are capable of producing intense beams of a well-defined energy. Indeed to date most of the recent detailed studies of fusion at energies close to the Coulomb barrier have been performed at the 14UD machine at the ANU in Canberra and at the tandem accelerator at the INFN laboratory in Legnaro. A similar programme is planned at the VIVITRON accelerator in Strasbourg.

The important question is how to exploit such experimental capabilities to study the reaction barriers present when two nuclei collide. Ray Satchler, Paul Stelson and I suggested a few years ago (Rowley *et al.* 1991) that the answer might lie in detailed measurements of the fusion cross section $\sigma(E)$ as a function of the incident energy E. We were able to show that the quantity $d^2(E\sigma)/dE^2$ should show the 'distribution of fusion barriers' present in the reaction, though we were not at that time very optimistic about the prospects of obtaining experimental data which were sufficiently precise for one to take their second derivative numerically. This challenge was, however, taken up by a group at the ANU led by Jack Leigh and very quickly data became available which exceeded all our expectations.

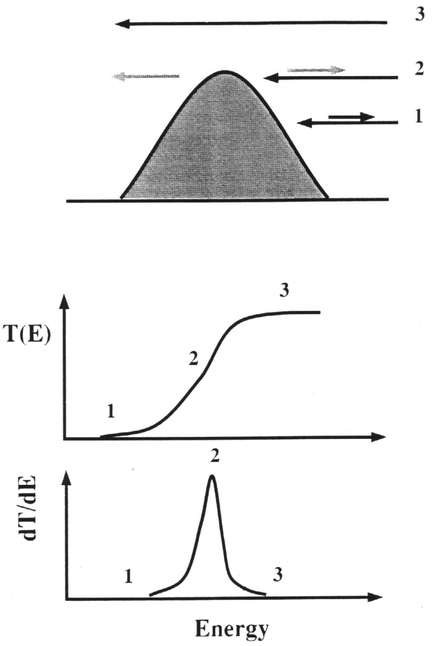

Fig. 6. Simple one-dimensional potential barrier and the corresponding transmission coefficient $T(E)$. The function dT/dE is peaked at the barrier height and has a width of about $0{\cdot}56\,\hbar\omega$.

The simplest way to understand this idea is to consider the barrier shown in Fig. 6. This shows schematically a one-dimensional potential and the associated transmission coefficient $T(E)$. Also shown is the derivative of T and we note that this function is peaked at the barrier height B. The wider the potential barrier, the narrower is the peak in dT/dE. More specifically, if the top of the barrier is approximately parabolic then

$$T(E) = \frac{1}{1 + \exp[2\pi(B - E)/\hbar\omega]}\,, \tag{1}$$

where ω is the oscillator frequency of the inverted barrier. From this equation it follows that

$$\frac{dT}{dE} = \frac{2\pi}{\hbar\omega}\frac{e^x}{(1 + e^x)^2}\,, \tag{2}$$

where $x = 2\pi(B - E)/\hbar\omega$. For most combinations of nuclei, the function dT/dE has a width (FWHM) of about 2 MeV ($= 0{\cdot}56\hbar\omega$).

Of course the nucleus is not a one-dimensional object, though the only difference in three dimensions is that one may approach the scattering centre with different impact parameters or angular momenta. The total cross section for penetration of the barrier is a sum over all angular momenta and explicitly one has

$$\sigma = \frac{\pi}{2\mu E}\sum_l \frac{2l+1}{1+\exp(2\pi[B-E+l(l+1)/2\mu R^2]/\hbar\omega)}$$
$$= \frac{\pi}{2\mu E}\sum_l (2l+1)T_l(E)\,, \tag{3}$$

where R is the barrier position, μ is the reduced mass of the system and the barrier height has simply been increased by the appropriate centrifugal term for each value of l. Since the transmission factor is a relatively smooth function of l, the above sum may be replaced by an integral which can be performed analytically to give

$$\sigma = \frac{\hbar\omega R^2}{2E}\ln[1+\exp(2\pi(E-B)/\hbar\omega)]\,. \tag{4}$$

Differentiating then readily gives the expression

$$\frac{d(E\sigma)}{dE} = \frac{\pi R^2}{1+e^x} = \pi R^2 T_0(E)\,. \tag{5}$$

In other words in the three-dimensional problem, $d(E\sigma)/dE$ has exactly the same form as the transmission factor for a one-dimensional barrier, except for a multiplicative factor which is just the geometrical area of the target. Then of course

$$\frac{1}{\pi R^2}\frac{d^2(E\sigma)}{dE^2} = \frac{2\pi}{\hbar\omega}\frac{e^x}{(1+e^x)^2} \tag{6}$$

is the same peaked function of (2) with a width of around 2 MeV and unit area with respect to integration over E.

The above analysis may be confirmed by looking at the second derivative obtained from the experimental fusion data (Aljuwair *et al.* 1984) for ^{40}Ca + ^{40}Ca. This is shown in Fig. 7. The function is strongly peaked and does indeed have a width of the expected value. The reason for this beautifully simple behaviour is that these closed-shell nuclei are difficult to excite and thus in this particular reaction, the environment is effectively switched off. The other curves in Fig. 7, however, show the 'barrier distributions' $D(E)$ for other combinations of non-closed-shell Ca isotopes and the simple one-barrier behaviour is clearly lost.

The simplest non-closed-shell problem is presented by the fusion of a spherical (closed-shell) projectile with a strongly deformed target and indeed the first detailed experiment of the Canberra group, ^{16}O + ^{154}Sm, had precisely this character (Wei *et al.* 1991; Leigh *et al.* 1993). The barrier distribution is shown in Fig. 8 and can be seen to be significantly wider than the tunnelling width of 2 MeV for a single barrier. As in the case of the HBr + C_2H_4 reaction, this is of course due to an orientation dependence of the barrier heights, which vary over 8 MeV depending on whether the ^{16}O is incident on the equator or the pole of the deformed ^{154}Sm. Given that this target nucleus has a spin 0^+, all of its possible orientations are equally likely and the barrier distribution is simply given by the solid angle which corresponds to each barrier height. This allows a rather simple analysis of $D(E)$ in terms of the deformation parameters of the target and one obtains a quadrupole contribution with $\beta_2 = 0 \cdot 30$ and a hexadecapole contribution with $\beta_4 = 0 \cdot 052$. Both of these values are in excellent agreement with those obtained from γ-ray spectroscopy experiments.

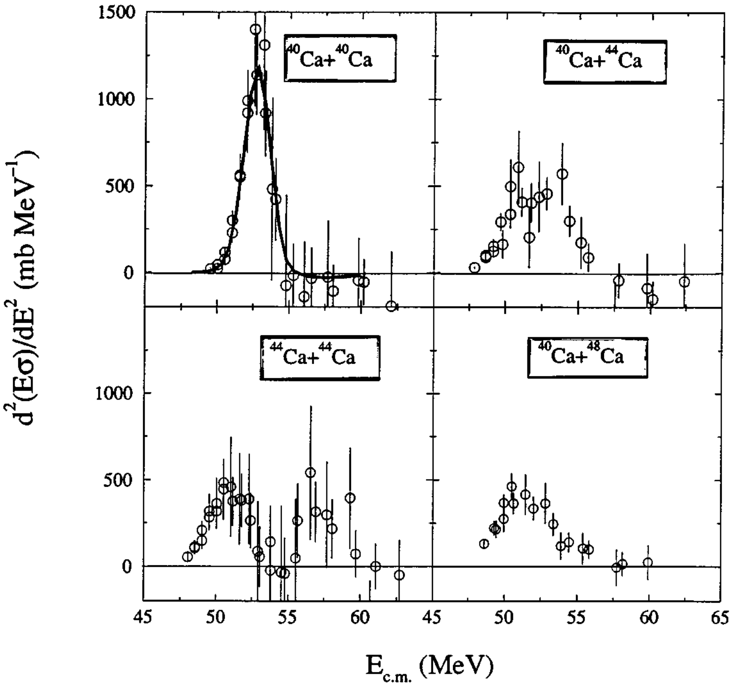

Fig. 7. In the fusion of various combinations of Ca isotopes, only $^{40}Ca + {}^{40}Ca$ manifests the distribution due to a single barrier. This is due to the closed-shell nature of this isotope which essentially switches off the environment.

It is worth noting that the above technique only gives the deformation of the nuclear ground state but in a totally independent manner from that in which these parameters are usually *inferred* in a rather model-dependent way. The fusion of heavy nuclei at energies above the Coulomb barrier yields compound nuclei at higher angular momenta, where the enormous Coriolis and centrifugal forces drive the nucleus into exotic shapes having very large deformations. These 'superdeformed' nuclei have been the object of intensive research over recent years, particularly using the EUROGAM detector array at the CRN Strasbourg and GAMMASPHERE at the LBNL Berkeley. It was only early this year that these two laboratories found the rather elusive 'linking' transitions which connect these superdeformed rotational bands to the normal-deformed bands based on the deformation of the ground state (Khoo *et al.* 1996; Lopez-Martens *et al.* 1996), allowing the energies and spins of the superdeformed states to be unambiguously pinned down. Since the information on deformations coming from such experiments is purely from γ-ray energies and lifetimes, it is reassuring to

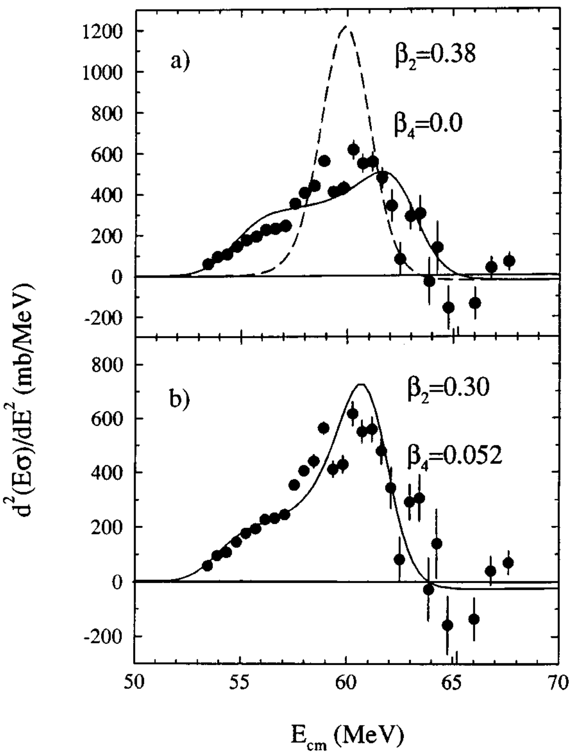

Fig. 8. The barrier distribution for ^{16}O + ^{154}Sm is typical of that for a spherical projectile on a deformed target. An analysis in terms of the solid angles leads relatively simply to the nuclear deformation parameters. The dashed curve in (a) is the single-barrier result, whereas the solid curve includes a quadrupole (β_2) deformation. In (b) an excellent fit is obtained by the inclusion of a hexadecapole (β_4) term.

have a totally independent confirmation from $D(E)$ of the model assumptions used in the γ-ray work, even though this can only be achieved for stable nuclei which have a 'normal' ground-state deformation.

The 'links' themselves appear to be a tunnelling phenomena related to the nucleus penetrating between two minima in its 'potential-energy surface'. Pairing effects may also play a rôle, switching back on as the nuclear rotation slows down.

5. Recent Developments

Since the first detailed experiments on deformed nuclei, other types of dynamics have been uncovered by appropriate choices of target and projectile nuclei. Indeed it is the great flexibility in this choice which makes the nucleus an ideal system for the study of tunnelling and indeed many other reaction phenomena. Fig. 9 summarises much of this work in a collection of barrier distributions for different systems. There emerges (see caption) much information on nuclear-phonon structures and how the coupling to these states can drastically modify the reaction dynamics. Phonon states in nuclei have many similarities with phonons in solids, though due to the enormous energy required to compress nuclear matter, they occur as vibrations of the surface. For many systems, the occurrence of several discrete barriers (phonon effects), or of a continuum of barriers (deformation effects), can completely change the angular momentum distribution of the compound nucleus created in these reactions, again with important consequences for γ-ray experiments. Studies of such effects, especially the dramatic structures (Stefanini *et al.* 1995) seen for $^{58}Ni + ^{60}Ni$, will be made with the EUROGAM array following its reincarnation as EUROBALL early next year.

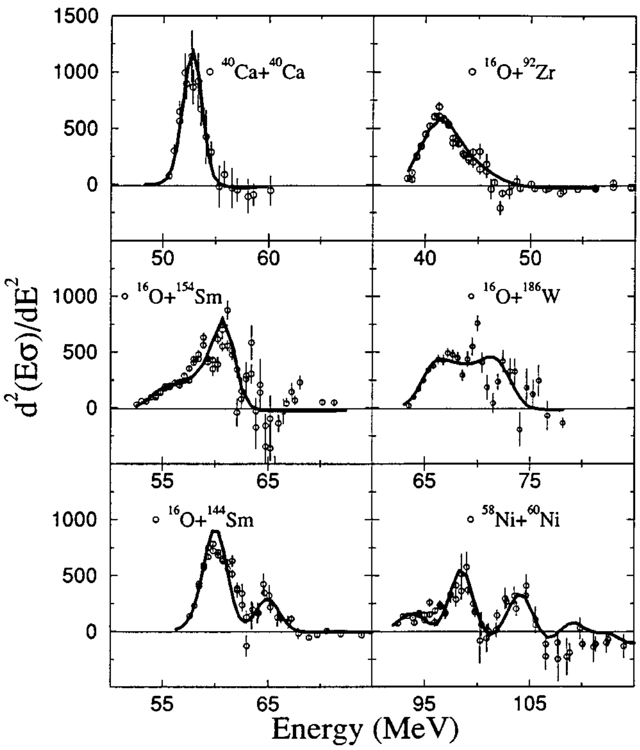

Fig. 9. The cases $^{40}Ca + ^{40}Ca$ and $^{16}O + ^{154}Sm$ have already been discussed in Figs 7 and 8. For $^{16}O + ^{92}Zr$ one sees a widened peak due to 'unresolved' phonon structures (Mein *et al.* 1996). The combination $^{16}O + ^{186}W$ again corresponds to a deformed target, but with a small negative β_4 (Lemmon *et al.* 1993) as opposed to the positive one for ^{154}Sm. Despite the smallness of β_4 a very different structure emerges. For $^{16}O + ^{144}Sm$ a second bump occurs due to the coupling to phonon states in the target (Morton *et al.* 1994). Finally, for $^{58}Ni + ^{60}Ni$, we see a spectacular three-barrier structure due to the complex surface vibrations induced in this reaction (Stefanini *et al.* 1995).

One type of nuclear reaction not mentioned in Fig. 9 is that of the transfer of nucleons between the target and projectile. All the couplings mentioned so far are inelastic and are also highly collective, i.e. the entire nuclear surface contributes either through its vibrations or its static deformation. The analogue of collectivity in a transfer reaction would be a flow of nuclear matter between the target and projectile. This is most likely to involve neutrons rather than protons due to the absence of a Coulomb barrier for these neutral particles. A small difference had earlier been observed (Morton *et al.* 1994) between the barrier distributions for the isotopes ^{16,17}O on ^{144}Sm. However, in a recent experiment performed in Legnaro, a massive difference has been observed for ^{40}Ca on the targets ^{90,96}Zr. The former target has a closed neutron shell, whereas the latter has six valence neutrons, giving rise to a $D(E)$ about twice as wide. The analysis of this system is, however, somewhat complicated due to the continuing presence of phonon effects and is still in progress (Timmers *et al.* 1996).

In the immediate future, the pinning down of the effects of neutron flow will remain an important topic. One of the other important aims that we have in this field is to relate the existence of distributions of barriers to what is happening in other reaction channels. As mentioned above, important differences from the accepted behaviour will arise for the population of different spin states in the compound nucleus. This will even have strong consequences on the way that particles are evaporated as the nucleus cools down and thus on the relative amounts of the various 'evaporation residues' produced.

Another fascinating phenomenon which appears to arise is the way that heavier systems fission according to the spatial configuration in which they were formed. This has already been studied in a little detail at the ANU for the system ^{16}O + ^{238}U, using the fission-fragment detector CUBE (Hinde *et al.* 1995, 1996). Strong dynamical differences appear corresponding to the ^{16}O arriving at the equator or pole of the deformed ^{238}U. This realisation was made possible only by a comparison of the energy dependence of fission anisotropies with the corresponding barrier distribution, which allows one to see where compound nucleus formation at the different orientations switches on.

In addition to the study of many other possible reaction mechanisms in laboratory nuclear physics, a variety of problems exist in other domains which will require considerable research to illuminate the details of the tunnelling process. Many of these examples are in the field of macroscopic quantum devices, e.g. Josephson junctions and SQUIDS. It has also been recently observed that in the reactions of light nuclei at very low energies, e.g. d + ^{3}He, the cross section depends on whether one uses an atomic deuteron beam or a molecular deuterium target (Broggini *et al.* 1994; Langanke *et al.* 1996). The reason for this is that at very low energies the screening effects of the electrons have a major effect on the tunnelling probability. This makes the extrapolation of the nuclear S factor down to the energies where such reactions occur in stars (the Wigner peak) rather dubious. In a stellar environment the electrons exist as a more-or-less uniform plasma with a concentration of charge around the Debye–Hückel radius. One must, therefore, understand the coupling of the reaction to the electron degrees of freedom. Purely static effects do not seem to give a good fit to the experimental data and dynamical effects of the type discussed above may play an important rôle. The understanding of this phenomenon may be important in the resolution of the problem of the flux of solar neutrinos produced following the ^{3}He + ^{4}He reaction.

Although the tunnelling problem has a long history, the large number of physical problems in which it plays a vital rôle will ensure that its study will also have a long future. Experiments on the fusion of heavy nuclei are of considerable interest in their own right, but will also continue to make a unique and valuable contribution to the phenomenon of tunnelling in the presence of an environment.

References

Aljuwair, H. A., Ledoux, R. J., Beckerman, M., Gazes, S. B., Wiggins, J., Cosman, E. R., Betts, R. R., Saini, S., and Hansen, O. (1984). *Phys. Rev.* C **30**, 1223.

Broggini, C., *et al.* (1994). *Z. Phys.* A **350**, 350.

Clayton, D. D. (1983). 'Principles of Stellar Evolution and Nucleosynthesis' (Univ. Chicago Press: Chicago).

Hinde, D. J., Dasgupta, M., Leigh, J. R., Lestone, J. P., Mein, J. C., Morton, C. R., Newton, J. O., and Timmers, H. (1995). *Phys. Rev. Lett.* **74**, 1295.

Hinde, D. J., *et al.* (1996). Twelfth AIP Congress, Hobart, July 1996, unpublished.

Khoo, T. L., *et al.* (1996). *Phys. Rev. Lett.* **76**, 1583.

Kibble, T. W. (1997). *Aust. J. Phys.* **50**, 697.

Langanke, K., Shoppa, T. D., Barnes, C. A., and Rolfs, C. (1996). *Phys. Lett.* B **369**, 211.

Leggett, A. J. (1993). Proc. 4th Int. Symp. on the Foundations of Quantum Mechanics, Tokyo, 1992, JJAP Series 9 (Eds M. Tsukada *et al.*), p. 10.

Leigh, J. R., Rowley, N., Lemmon, R. C., Hinde, D. J., Newton, J. O., Wei, J. X., Mein, J., Morton, C., Kuyucak, S., and Kruppa, A. T. (1993). *Phys. Rev.* C **47**, R437.

Lemmon, R. C., Leigh, J. R., Wei, J. X., Morton, C. R., Hinde, D. J., Newton, J. O., Mein, J. C., Dasgupta, M., and Rowley, N. (1993). *Phys. Lett.* B **316**, 32.

Lopez-Martens, A., *et al.* (1996). *Phys. Lett.* B **380**, 18.

Mein, J., *et al.* (1996). in progress.

Morton, C. R., Dasgupta, M., Hinde, D. J., Leigh, J. R., Lemmon, R. C., Lestone, J. P., Mein, J. C., Newton, J. O., Timmers, H., Rowley, N., and Kruppa, A. T. (1994). *Phys. Rev. Lett.* **72**, 4074.

Phillips, W. R. (1996). Twelfth AIP Congress, Hobart, July 1996, unpublished.

Rowley, N., Satchler, G. R., and Stelson, P. H. (1991). *Phys. Lett.* B **254**, 25.

Stefanini, A. M., Ackermann, D., Corradi, L., Napoli, D. R., Petrache, C., Spolaore, P., Bednarczyk, P., Zhang, H. Q., Beghini, S., Montagnoli, G., Mueller, L., Scarlassara, F., Segato, G. F., Soramel, F., and Rowley, N. (1995). *Phys. Rev. Lett.* **74**, 864.

Stewart, T. L., Kermode, M. W., Beachey, D. J., Rowley, N., Grant, I. S., and Kruppa, A. T. (1996). *Phys. Rev. Lett.* **77**, 36.

Timmers, H., Corradi, L., Stefanini, A. M., Ackermann, D., He, J. H., Beghini, S., Montagnoli, G., Scarlassara, F., Segato, G. F., and Rowley, N. (1996). submitted to *Phys. Lett*. B.

Wei, J. X., Leigh, J. R., Hinde, D. J., Newton, J. O., Lemmon, R. C., Elfstróm, S., Chen, J. X., and Rowley, N. (1991). *Phys. Rev. Lett.* **67,** 3368.

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