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Nuclear physics with simple and multi-element detectors and with stable and radioactive beams

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Abstract. The phenomenon of fusion barrier distributions is discussed in the context of a problem already investigated in some detail with simple detection systems, but possessing avenues to studies with multi-detector arrays. The complementarity of research with simple and complex detectors, as well as with stable and radioactive beams, will be highlighted.

Keywords. Fusion; scattering and transfer reactions; radioactive beams; superheavy nuclei.

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1. Introduction

The field of nuclear physics covers a vast range of phenomena spanning both nuclear reaction mechanisms and structure. The latter involves both single-particle modes and various types of collective motion, as well as their possible couplings. It is, therefore, more difficult to find the defining questions in this discipline (and design the ideal detector systems to answer them) than, for example, in particle physics where questions on the existence and properties of the Higgs boson and the quark-gluon plasma are more obvious.

We are of course interested in the underlying behaviour of the only strongly-interacting many-body system with which Nature provides us – a problem enriched by the simultaneous presence of two different types of nucleon. The variables defining our system become the neutron and proton numbers N, Z and the fundamental question arises as to how far we can go from β-stability and how high in atomic number and still have a nucleus of sufficiently long lifetime to possess meaningful structures which we can study.

The intrinsic nature of such structures will of course change with N and Z, some regions giving rise to vibrational modes and others to statically deformed systems with well defined rotational bands. Such bands also exist in many other nuclei whose ground states are relatively spherical, so long as we can pump enough angular momentum into them. Yet other systems may behave as two or more clusters of their constituent nucleons, particularly low-mass nuclei, where new exotic examples are currently being explored.

No single detector system can answer all the pertinent questions relating to such phenomena – nor indeed can any single accelerator provide the good quality beams (stable or radioactive), with the right energies to give us all the insights necessary to trace these threads in the fabric of science.

I would like to talk about my own main research project over the last few years in order to demonstrate this point. This concerns the fusion of heavy nuclei at energies close to the Coulomb barrier, a phenomenon which was long thought to display little sensitivity to the structure of the participating target and projectile. Or at least if such effects were present, they were thought to lead to rather structureless excitation functions and be almost impossible to interpret.

2. Barrier distributions

Paul Stelon [1] had worked for some years on the notion of fusion barrier distributions and in 1991, along with Ray Satchler, we came up with the idea of obtaining them directly from experimental data via the formula [2]:

$$D(E) = \frac{\mathrm{d}^2(E\sigma_f)}{\mathrm{d}E^2}. \tag{1}$$

When applied to the classical fusion cross section for a Coulomb barrier of height B and radius R,

$$\sigma_f = \pi\, R^2 \left(1 - \frac{B}{E}\right), \tag{2}$$

this leads to the simple but striking expression

$$D(E) = \pi\, R^2\, \delta(E - B). \tag{3}$$

When applied to the Wong [3] fusion cross section (which accounts for quantum mechanical barrier penetration by exploiting the analytic result for transmission through an inverted oscillator potential of frequency ω) it gives

$$D(E) = \pi R^2\, G(E - B), \tag{4}$$

where $G(E - B)$ is a normalized, peaked, symmetric function centred at $E = B$ with a width (FWHM) of $0.56\,\hbar\,\omega$ (around 2–3 MeV for most heavy-ion systems). Thus, when applied to real data, a distribution of peaks should be observed, reflecting the heights and weights of the different fusion barriers arising from coupling to excitations of the target and projectile.

Of course the application of eq. (1) requires high-precision data, and initially we did not expect this challenge to be met experimentally. However, quite soon after our suggestion, the first new data (for ^{16}O + ^{154}Sm) emerged from the group of Jack Leigh at the Australian National University in Canberra [4]. These demonstrated beautifully the barrier distribution expected for a target with a large static quadrupole deformation (see figure 1c). In fact good enough data already existed for the sytem ^{40}Ca + ^{40}Ca [5], in which both the target and projectile are double-closed-shell nuclei and thus relatively inert. Figure 1a shows that this case correponds very well to the simple quantum mechanical result for a single barrier.

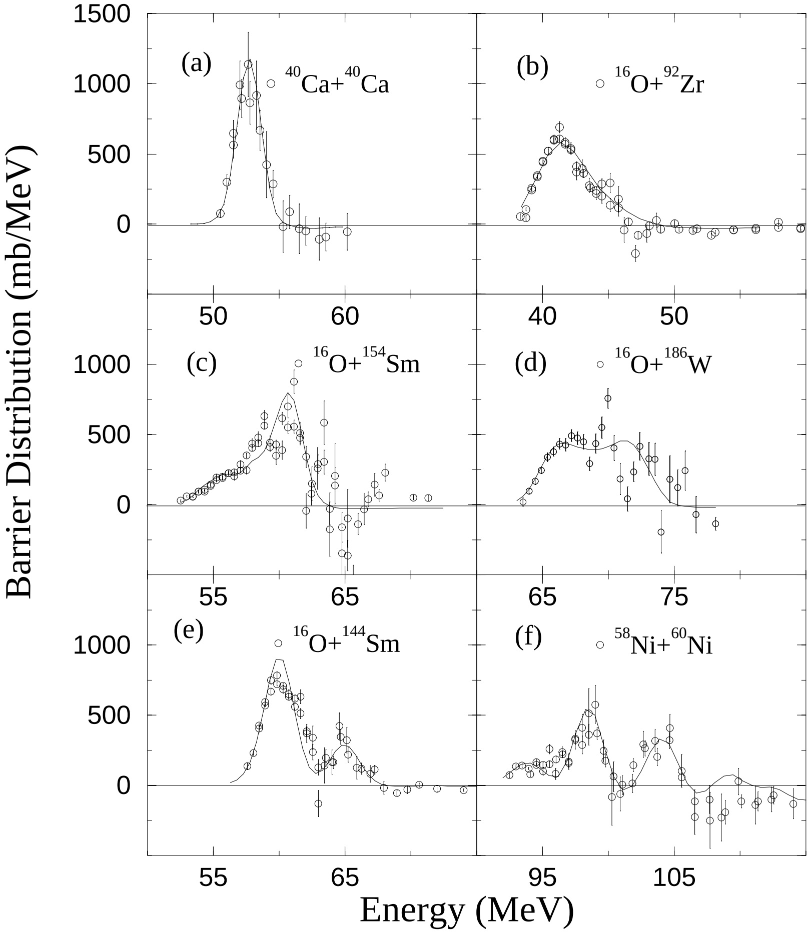

Figure 1. The great variety of experimental barrier distributions is demonstrated even when coupling is confined to inelastic excitations. Solid lines are theoretical results.

Far from finding that the details of the nuclear structure were not apparent in the fusion data, later results on a second deformed system (^{16}O + ^{186}W [6]) showed that the shape of the distribution was actually rather sensitive even to the small hexadecapole components in the nuclear deformation (compare figure 1c and 1d, the former target having a small positive β_4 and the latter a small negative one).

Shortly after, the effects of phonon excitations were investigated by going to the most neutron-deficient stable isotope of Sm via the reaction ^{16}O + ^{144}Sm. The observed structure [7] (figure 1e) is well fitted by coupling to the strong octupole and quadrupole vibrational states of ^{144}Sm (2^+ at 1.660 MeV and 3^- at 1.810 MeV). This strong and distinct isotopic dependence, reflecting faithfully the known experimental structure of these two Sm isotopes, appears to rule out more macroscopic explanations of the spread of barriers.

Perhaps the most spectacular effect of phonons seen so far arises in the case of ^{58}Ni + ^{60}Ni, a reaction studied at the INFN laboratory in Legnaro [8]. Here the rather discrete three-barrier structure (figure 1f) results from the complex surface vibrations arising from couplings to the 1-phonon and 2-phonon states present in both the target and projectile. We shall meet this case again later since it presented some interesting possibilities for further investigation.

The remaining panel figure 1b for $^{16}\mathrm{O} + {}^{92}\mathrm{Zr}$ [9] is interesting in the following respect: the total width of the distribution of barriers is related to the difference of Coulomb barrier heights for the extreme orientations in the deformed nucleus case, or from the extreme phases of the surface vibrations in the phonon case. For both systems the width varies as $Z_1\,Z_2\,\beta$, where β is the corresponding static or rms deformation. In this particular case, interesting structures are in principle present but $Z_1\,Z_2$ is simply not large enough for the different barriers to be 'resolved'. This is not an experimental problem, but rather due to the finite 'tunnelling' width of the single barrier which causes them to overlap. We shall see later some interesting results for other Zr isotopes when the projectile charge is increased by using a ^{40}Ca beam.

The above experiments and many others have led to a deeper understanding of nuclear reaction mechanisms and shown quite unambiguously that the fusion cross section carries an enormous amount of information if only one looks carefully enough. Other results have been recently reviewed in ref. [10].

3. Spin distributions and γ-ray arrays

The above results already give many insights into the interplay of nuclear structure and reaction dynamics. It is interesting, however, to ask if we can now exploit what we have learned. One important consequence of a distribution of barriers is spin populations very different from those generally assumed in the study of high-spin physics. Sandrine Courtin [11] at the IReS undertook the study of this effect in the case of ^{58}Ni + ^{60}Ni, where the compound nucleus spin distribution was already well-known from the detailed theoretical fit to high-quality fusion data.

Figure 2 summarizes the results of this work. In fact there are three different distributions to consider:

(i) P_{CN}, that of the compound nucleus on formation
(ii) P_{ER}, that of the evaporation residues following particle emission and
(iii) P_{Yr}, that observed in transitions along rotational bands close to the yrast line. These follow a percolation of the γ-ray intensity through 'statistical' decays and complex interband transitions.

This third distribution P_{Yr} was measured at the IReS using the 15-element γ-ray array Garel. The experiment was performed at three different incident energies, corresponding to E_{cm} values just above each of the three barriers of figure 1f. It was found that despite the much higher spins entering the sytem at the two higher energies, very little extra spin was observed in P_{Yr}. This quantity is shown in the lowest inset in figure 2 for the highest energy $E_{\mathrm{cm}} = 105$ MeV.

This experiment was followed by a second one using the Gasp array (plus its inner ball multiplicity filter) at the INFN laboratory in Legnaro. The resulting curves for P_{ER} are shown in figure 2 for all three energies, and P_{CN} is compared with its theoretical value for the highest energy. Obtaining these curves requires various assumptions about the amount

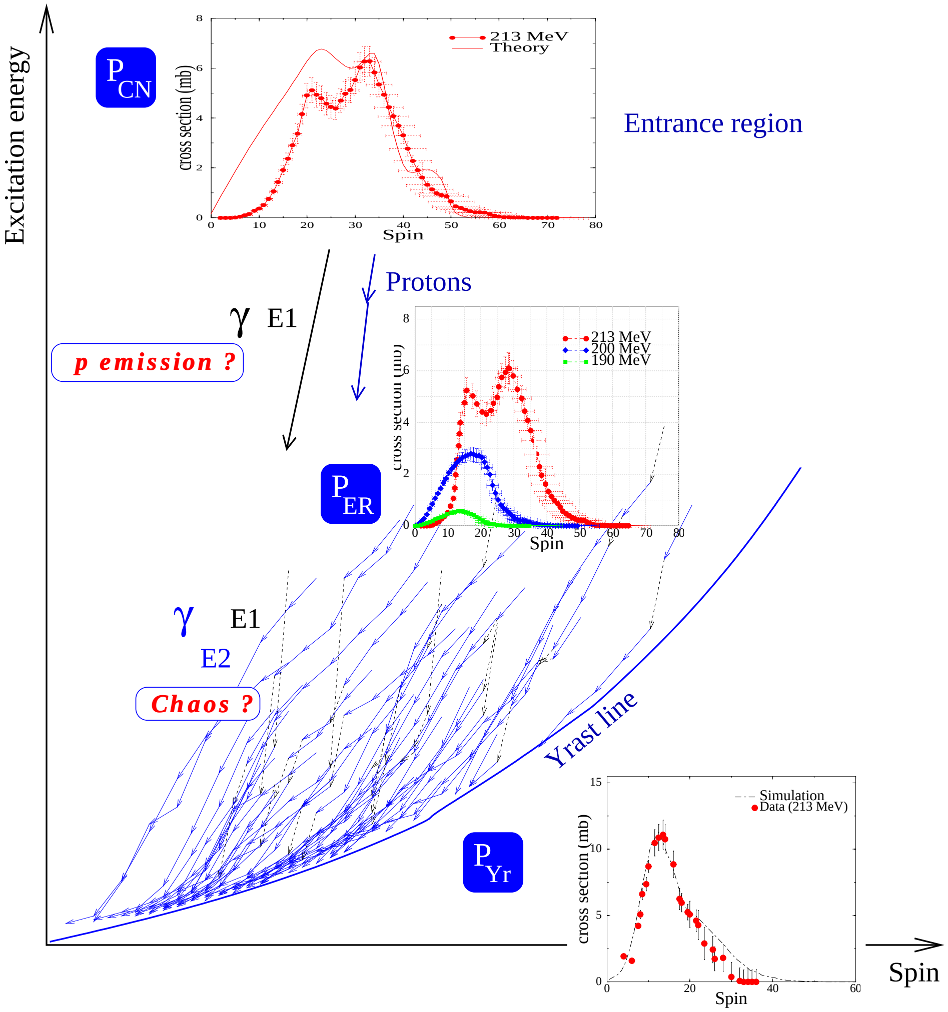

Figure 2. The $E^* - I$ plane is shown along with insets of the three different spin distributions discussed in the text. Indicated energies are E_{lab}.

of angular momentum carried away by particle evaporation and about the relationship between γ-ray multiplicity and spin. It can be seen, from the discrepancies between the P_{CN} given by the fusion data and that obtained from the γ-ray experiment, that the theoretical aspects of these phenomena are far from well understood. Nonetheless it is clear that the barrier structures are well reflected in the derived compound-nucleus spin distribution. Much can be learned about the dynamics of the $E^* - I$ plane from such experiments. Of special interest is the comparison of P_{CN} and P_{Yr} which may indicate a rapid change of the spreading width of the rotational bands around spin 20 $\hbar$, with possible implications for the chaocity of the system. The important point for this talk, however, is that experiments with simple detection systems led the way to other interesting work using multi-detector arrays.

Some further consequences of the barrier distribution for ^{58}Ni $+$ ^{60}Ni are the following:

(i) The lowered barrier allows one to produce compound nuclei with less excitation energy, where fewer neutrons will be evaporated. Thus we might expect to produce nuclei further from β-stability by this method, while still exploiting stable beams. In the present experiments, γ-decays from ^{116}Cs were observed but unfortunately we were able to recognize them only after their energies were identified at the Argonne Laboratory using gammasphere [12] (good channel selection being provided through the detection of evaporated particles).

(ii) The strong coupling to the phonon states means that they are greatly excited during the collision, though since their energies are high, these excitations have, to a large extent, time to 'relax' away in the inelastic exit channels. However, the disruption of the wavefunction caused by absorption into fusion at near-barrier energies, should reduce this effect and lead to a greater survival probability of the phonon excitations. In order to study this it would be necessary to detect the scattered nickel nuclei and correct the corresponding γ-ray energies for their Doppler shifts. Such experiments might prove useful in searching for unknown phonon states in other targets.

A further example of the importance of spin distributions can be found in the ^{16}O $+$ ^{186}W system which has been studied at Legnaro [13] as a means of enhancing the production of particular high-spin states by populating them through the incomplete fusion reaction. Since this is a peripheral process, a knowledge of the high-angular-momentum edge of the spin distribution is essential in the analysis of the experimental results. Calculations show that this is significantly smoothed out by entrance-channel effects.

4. Transfer channels

The fusion reactions ^{40}Ca $+$ $^{90,\,96}$Zr show remarkably different behaviour. Figure 3 shows the experimental results for these two systems which were measured in Legnaro [14]. The solid curve shows the results of a coupled-channels (phonon) calculation for the ^{90}Zr system while the dashed curve shows the corresponding no-coupling result. Whereas this calculation explains the data very well for ^{90}Zr, a similar calculation fails completely to fit the excitation function for ^{96}Zr. The major difference between these two targets is the presence of 6 neutrons outside the $N = 50$ closed shell in the heavier isotope. This gives rise to positive-Q transfer channels which appear to be the only explanation for the greatly enhanced σ_f in this case. However, in order to confirm this result and obtain some insight into how to calculate such effects theoretically, it was necessary to measure the transfer cross sections themselves. This again invokes the use of yet another detection system. The results [15] showed that multi-particle transfer is strong for ^{40}Ca $+$ ^{96}Zr, especially for the 6 nucleons outside the $N = 50$ closed shell which give rise to positive Q-value channels (see figure 4).

This observation along with the results for the Q-value spectrum itself allowed a simple model [16] to be applied to fit these data, as shown in figure 5. Again we learn something from one detection system and find how to understand it from another.

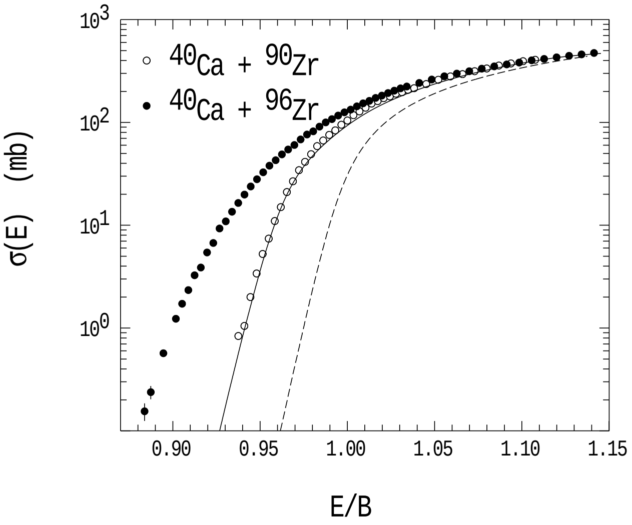

Figure 3. Fusion excitation functions for ^{40}Ca + ^{90,96}Zr around the average barrier B. The solid curve represents a coupled-channels (phonon) calculation for the lighter Zr isotope, and the dashed curve the corresponding no-coupling result. A similar calculation fails completely for the heavier system.

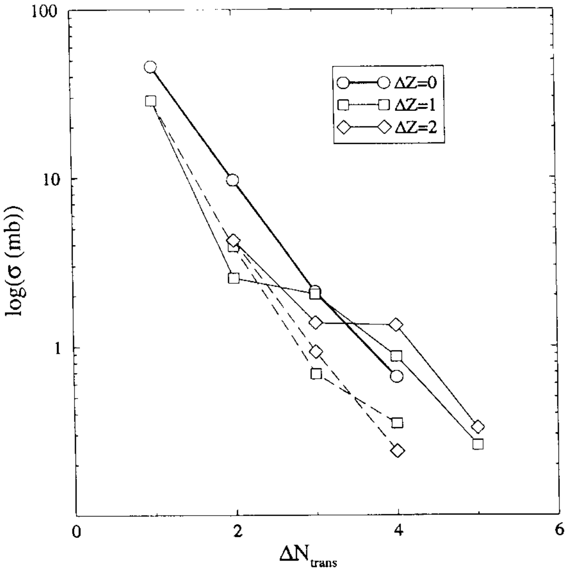

Figure 4. Transfer cross sections for the ^{40}Ca + ^{96}Zr reaction at an energy close to the average Coulomb barrier B. The quantity $\Delta N_{\rm trans}$ is the total number of transferred particles. Note the dominance of the neutron channels for low ΔN. Solid and dashed lines indicate neutron transfers to and from the calcium projectile respectively. All protons transfers are away from the projectile.

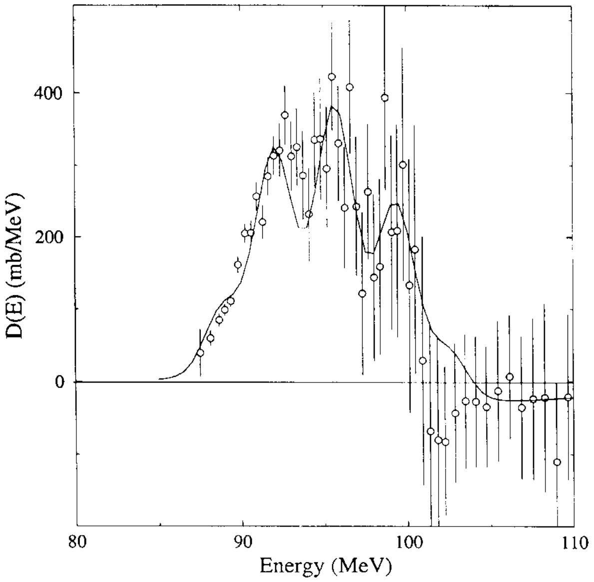

Figure 5. Experimental barrier distributions for ^{40}Ca + ^{90,96}Zr along with the results of the theoretical calculation mentioned in the text.

5. Superheavy elements and fission

Isotopes of the new superheavy elements $Z = 114$ [17] and 116 [18] have recently been discovered at the Flerov Laboratory (JINR) in Dubna. Again this work requires the exploitation of a very specialized detector system, the DGFRS (Dubna gas-filled recoil separator), though one should also mention the important contribution of the ECR source in generating the very high-intensity ^{48}Ca beams (μA) necessary to make such work feasible.

It is well-known that to form such heavy compound systems, one is severely limited by the phenomenon of fission. The cross section for the formation of these high-Z systems is the product of the fusion (passage to a compound nucleus) and the probability that they will survive fission. The latter probability increases rapidly with decreasing excitation energy, so taking advantage of entrance-channel effects may be of paramount importance here. The understanding of coupling effects in such systems would prove extremely useful. Their fission dynamics are also under investigation at Dubna (see for example ref. [19]), recently exploiting the Demon neutron multidetector array.

For the systems discussed earlier, σ_f was simply the total evaporation residue cross section. For heavier ones this is no longer the case. The relatively simple example of ^{16}O + U, for which a compound nucleus is actually formed but practically always decays by fission, was studied at Canberra, using a high-efficiency fission-fragment detector [20]. It still proved possible to define $\sigma_f \equiv \sigma_{\text{fission}}$ and hence obtain a fusion barrier distribution. This showed the typical shape expected for the deformed target. More importantly it demonstrated a strong correlation between the structure of this barrier distribution and the energy dependence of the fission-fragment anisotropy. The correlation apparently corresponding to the compound system possessing a memory of the compactness of its configuration on formation, a result which disagrees with the predictions of the statistical saddle-point method. Again our underlying theme exploits different detectors to discover new physics.

6. Effects in other channels

The phenomenon of barrier distributions also applies to reaction channels other than fusion. For example, the presence of mutiple barriers is manifest in the elastic [21] and quasielastic channels [22], though the structures in the derived distributions tend to be smeared out due to phase-shift effects which are absent in the fusion channel itself.

Another recent experiment performed at the ANU [23] also suggests an important effect arising from the break-up channel. The system studied was ^{9}Be + ^{208}Pb, which is of particular interest due to the *borromean* nature of the projectile. The results (this time obtained through a measurement of the subsequent activity of the target) show what is effectively an overall renormalization of the excitation function (hence the barrier distribution) due to the strong break-up channel.

The break-up channel itself was subsequently investigated at the Vivitron accelerator at the IReS [24] by coupling detectors of the Charissa set-up to the neutron multidetector Demon. This final example of where barrier distributions may play a role has clear implications for work with radioactive beams, where other weakly-bound borromean systems can be found.

7. Conclusions

Our excursion through some of the nuclear physics related to reaction barriers has shown the need for complementary work in different laboratories, exploiting different accelerators, different beams and different techniques with a wide variety of detectors. We have also seen the complementarity of work with stable and radioactive beams. Indeed many fusion experiments have now been successfully performed with radioactive beams despite the low intensities available (see for example ref. [25] and references therein). Some further examples are:

(i) The exploitation of stable-beam accelerators to give detailed data on the naturally occuring isotopes of lithium in order to assist our understanding of fusion with ^{11}Li. Of course the same comment applies to all other elements whose full isotopic dependence has not been explored with stable beams.
(ii) Detailed investigations of the effect of the two valence neutrons in, for example, ^{18}O reactions in order to understand their effects in ^{6}He etc. With lightly bound exotic nuclei do the major effects come from the larger spatial extent of these additional neutrons or from Q-value effects resulting from the difference of their Fermi energies in the target and projectile?

The plurality of our discipline is important to all of the above problems and we look forward to valuable contributions from the new facilities under construction in Calcutta.

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