Geiger-Marsden experiments: 100 years on

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Abstract. The perceptive analysis of Rutherford, celebrated at this conference, turned the experiments of Geiger and Marsden into a measurement of the radius of the object that became known as the atomic “nucleus”. We now know that the nucleus can have a range of radii that depend on its static and dynamical deformations. These deformations give rise to the distributions of reaction barriers that have been extensively studied over recent years. While fusion reactions are most often used for such studies, there are cases where, for physical or practical reasons, the scattering channels must be exploited. Despite the major advantages gained from modern experimental techniques, the resulting experiments are in spirit essentially the same as those performed over 100 years ago by Rutherford and his colleagues.

1. Introduction

The fact that the 7.7 MeV $\alpha$-particles from the decay of $^{214}$Po are sometimes scattered through very large angles$^1$ by metal foil targets, was a surprise to Geiger and Marsden [1]. Indeed the accepted models of the atom led them to expect a deflection of less than one degree [2]. However, Rutherford quickly realised the significance of this result and developed a scattering theory based on a small, yet massive concentration of charge at the centre of the atom [3]. This birth of the concept of the atomic nucleus soon led to the Bohr model of the atom [4] and the subsequent, rapid paradigm shift from a classical description of the world to the wonders of its quantum mechanical interpretation.

While experiments with a gold foil [5] confirmed the details of Rutherford’s famous scattering formula [3], the limited $\alpha$-particle energy allowed only an upper limit of 34 fm to be established for the corresponding $^{197}$Au + $\alpha$ interaction radius, though later experiments with the lighter targets, nitrogen and oxygen, yielded excellent, actual values of the interaction radius, since the smaller target charge cannot prevent an $\alpha$-particle with small impact parameter from reaching the nuclear surface [6]. The fixed beam energy in these experiments obliges one to infer the interaction radius from an angular distribution by observing the angle at which the scattering cross section falls below its Rutherford value. Of course today, we are no longer limited to a fixed energy or to a single beam species, nor to a “count rate” that must be followed by the human eye; we may thus undertake deeper investigations that show us many other fascinating aspects of the nuclear radius, reflecting in particular the interplay between nuclear structure and nuclear reactions.

$^1$ Geiger and Marsden state: “A small fraction of the $\alpha$-particles falling upon a metal plate have their directions changed to such an extent that they emerge again at the side of incidence.” [1]
2. Fusion barrier distributions

Over recent years precision measurements of “experimental fusion barrier distributions” [7] have led to significant insights into how the collective modes (rotational and vibrational) of the target and projectile influence the dynamics of a nuclear reaction [8]. The simple idea behind these measurements is that since the classical fusion cross $\sigma_{\text{fus}}$ (zero below the Coulomb barrier) is given above the barrier by

$$E\sigma_{\text{fus}} = \pi R^2(E - B),$$

(1)

where $B$ and $R$ are the Coulomb barrier height and radius, and $E$ is the incident centre-of-mass energy. Then the second derivative $d^2(E\sigma_{\text{fus}})/dE^2$ is simply a delta function of area $\pi R^2$ located at the energy $E = B$. Quantum tunneling merely smooths out this function into a symmetric peak with a width of around 2-3 MeV, but if a range of barriers wider than that value is present in a given reaction then their “distribution” can be readily deduced from

$$D_{\text{fus}}(E) = \frac{d^2(E\sigma_{\text{fus}})}{dE^2}.$$  

(2)

Fig. 1 shows this quantity derived from experimental data on the reactions $^{16}\text{O} + 144,154\text{Sm}$ obtained in Canberra. The lower panel shows results for $^{144}\text{Sm}$ [9]. This isotope is essentially spherical due to its magic neutron number $N = 82$, and this is reflected in a barrier distribution that is concentrated largely in a single peak, corresponding to the unique spherical radius. However, the system possesses relatively high-lying phonon states (both quadrupole and octupole) and this gives rise to a weak secondary peak at a slightly higher energy, reflecting those surface vibrations.

The upper panel shows results for $^{154}\text{Sm}$ [10]. Here the neutron number is mid-shell and the system is known to be strongly deformed. The angle-dependent radius of this isotope leads to a barrier distribution that is more spread out in energy, and an detailed analysis of its shape
yields quadrupole and hexadecapole moments $\beta_2 = 0.30$ and $\beta_4 = 0.05$ in excellent agreement with those obtained from $\gamma$-ray spectroscopy. So we see that fusion measurements can give clear fingerprints of the properties of these intrinsic structures; is the nucleus rotational or vibrational, and what are its deformation parameters?

Note that to perform such fusion measurements, we require a variable-energy beam, so the mono-energetic $\alpha$-particles of the Geiger-Marsden experiment would be of no use here. Furthermore, what we measure is a distribution of fusion barriers arising from a distribution of target radii. The mapping from $R$ to $B$, given by $B = Z_1 Z_2 e^2/(4\pi\epsilon_o R)$, is proportional to the charge $Z_1$ of the projectile. Thus the oxygen projectile with $Z_1 = 8$ gives a barrier distribution four times wider than that for the $\alpha$-particle with $Z_1 = 2$. This produces a much better resolution of the structures in the barrier distribution that contain the information on the intrinsic structure of the target. So the projectile charge $Z_1$ acts as a magnifier of the barrier structures, again diminishing the usefulness of $\alpha$-particles for such experiments. For the same reason, much of the work in Legnaro has focused on experiments with a $^{40}\text{Ca}$ beam with $Z_1 = 20$; see for example Refs. [11, 12]. Note also that both $^{16}\text{O}$ ($N = Z = 8$) and $^{40}\text{Ca}$ ($N = Z = 20$) are double-closed shell nuclei, so that their own internal structures play a relatively minor role in the fusion, facilitating the interpretation of the experimental data.

3. Difficult systems

The Canberra and Legnaro fusion experiments used tandem accelerators to achieve the small energy steps required to give a good representation of the second derivative of the data expressed in Eq. (2). There are, however, circumstances where such fusion measurements are not feasible:

- With noble-gas projectiles such as $^{20}\text{Ne}$ or $^{86}\text{Kr}$. Here, it is not possible to create the negative ions necessary for a tandem accelerator and one must use a cyclotron. However, the many small energy changes required to obtain the barrier distribution are impractical with such an accelerator.

- For very heavy systems, there may be no fusion. That is, the composite system formed on impact does not evolve into an equilibrated compound nucleus that decays in flight by light-particle emission ($n$, $p$, $\alpha$) yielding a long-lived evaporation residue (ER). Instead, the system undergoes quasifission with fragments emerging at all angles rather than the more easily detected ER which emerge in a narrow cone around the beam direction. This limitation rules out fusion experiments on some of the most interesting systems that lead to superheavy elements (SHE).

Indeed the reaction $^{86}\text{Kr} + ^{208}\text{Pb}$ which leads to a composite system with $Z = 118$ suffers from both of the above constraints. In view of the failure to produce a long-lived isotope of element 118 via this “cold-fusion” reaction [13, 14], we decided to study the reaction dynamics at the Separated-Sector Cyclotron at iThemba LABS in South Africa by other means [15].

There are also special reasons for wishing to study reactions with $^{20}\text{Ne}$; this is the stable nuclide that is the most deformed in its ground state, and a campaign of experiments with this beam in Warsaw and Jyväskylä is proving extremely fruitful [16, 17].

4. Quasi-elastic barrier distributions

So how can we perform useful experiments on the reaction barriers for these systems? If we cannot measure the transmitted flux $T$ for a one-dimensional barrier, then we can infer it by measuring the reflected flux $R$, since by unitarity $T = 1 - R$. In a similar fashion, in the real three-dimensional problem of a nuclear reaction, instead of measuring the transmitted flux (fusion) we can measure the reflected flux (inelastic scattering). The three-dimensional problem is of course more complicated since the reflected flux can be scattered to all angles. Rather than being a problem, however, this provides an elegant solution to our problem of producing a small
energy step, since the quasi-elastic scattering cross section $\sigma_{QE}$ (that is, the sum over all direct-reaction channels: inelastic plus transfer) at different large angles $\theta$ is related to the scattering at $180^\circ$ by a small shift to an “effective” energy $E_{\text{eff}}$. This shift is equal to the centrifugal barrier for the angular momenta that contribute at the angle $\theta$, and using Rutherford/Coulomb trajectories we obtain [18]

$$E_{\text{eff}} = \frac{2E}{1 + \csc(\theta/2)}. \quad (3)$$

This means that for a given centre-of-mass beam energy, we can obtain a good approximation to $\sigma_{QE}$ at a range of effective energies simply by using detectors at several different angles.

Fig. 2 shows the results for the ratio of $\sigma_{QE}/\sigma_{Ruth}$ for the $^{86}\text{Kr} + ^{208}\text{Pb}$ system. The Rutherford cross section $\sigma_{Ruth}$ is simply what one would obtain for simple point charges. (Note that the different symbols of the legend correspond to the different beam energies employed but that the ensemble of data points essentially makes up a single continuous curve when mapped to $E_{\text{eff}}$.) Just as in the earlier experiments of Rutherford’s group, one can infer the interaction radius and barrier height from the energy at which this function falls off. Indeed, one can obtain a “quasi-elastic barrier distribution” that is very similar [19] to $D_{\text{fus}}$ from the first derivative of this function

$$D_{QE} = -\frac{d(\sigma_{QE}/\sigma_{Ruth})}{dE}, \quad (4)$$

and again seek to understand its structure in terms of the collective excitations of the target and projectile [15]. However, the major aim of this experiment was to demonstrate that the energy at which the reaction was performed [13, 14] to create the superheavy element $Z = 118$ was well above the entrance-channel barriers for the system, and that any failure to produce this element must, therefore, be due to the quasifission process. The optimum energy for creation via a cold fusion reaction (cooling by emission of a single neutron) is 317 MeV, corresponding to an energy where 1-$n$ emission drops just below the fission barrier for the system. Subsequent to our $D_{QE}$ measurement, other cold-fusion reactions ($^{48}\text{Ti}, ^{54}\text{Cr}, ^{56}\text{Fe}, ^{64}\text{Ni}$ and $^{70}\text{Zn}$ projectiles also on a $^{208}\text{Pb}$ target) that had been used successfully to produce SHE at GSI [13] were studied at the tandem-booster at JAEA [20] using the same quasi-elastic method (though as explained above our noble-gas beam was not available there). Of course since the earlier experiments [13, 14] the SHE $Z = 118$ has been created at the Flerov Laboratory in Dubna via the rather different “hot-fusion” reaction (3-$n$ emission) using the more asymmetric system $^{48}\text{Ca} + ^{249}\text{Cf}$ [21].
Figure 3. Upper panel: the quasi-elastic barrier distribution for $^{20}\text{Ne} + ^{90}\text{Zr}$ has a well defined structure whose shape is dominated by the large $^{20}\text{Ne}$ deformation. Different symbols are for different detector angles and show that the transformation (3) is good. The dashed line shows coupled-channels results.

Lower panel: the $D_{QE}$ for $^{20}\text{Ne} + ^{92}\text{Zr}$ should essentially be the same as above since the $^{20}\text{Ne}$ deformation is again dominant. However, the extra two neutrons outside the $N = 50$ closed shell give a significantly higher density of non-collective states whose weak couplings wash out the structure seen in the previous case. The solid line shows a mapping of the $^{90}\text{Zr}$ data discussed in the text.

5. The $^{20}\text{Ne}$ beam

Experiments with the $^{20}\text{Ne}$ beam have very different motivations from the heavy system discussed above. Here we wished to exploit the extreme deformation of $^{20}\text{Ne}$ ($\beta_2 = 0.46$ and $\beta_4 = 0.27$) to study particular questions relating to nuclear reaction dynamics. The first project [16] studied the effect on $D_{QE}$ of the many weakly-coupled channels that exist due to transfer reactions and non-collective nuclear excitations. This was achieved by exploiting two different zirconium isotopes as targets. The first, $^{90}\text{Zr}$, has a closed $N = 50$ neutron shell and the second, $^{92}\text{Zr}$, has two neutrons outside that shell. For this reason the latter has a significantly higher density of relatively low-lying non-collective states. Since the deformation of $^{20}\text{Ne}$ is so large, it completely dominates the collective dynamics, and coupled-channels calculations predict the same $D_{QE}$ for both reactions. It can be seen, however, from Fig. 3 that the structure present for $^{90}\text{Zr}$ is completely washed out for $^{92}\text{Zr}$. An analysis of this phenomenon in terms of a standard absorptive optical-model potential [16] confirms this interpretation by providing a mapping of data for $^{90}\text{Zr}$ to the solid line in the lower panel that beautifully fits the $^{92}\text{Zr}$ data.

The second project [17] sheds light on approximations to the nucleus-nucleus interaction for deformed systems. Some preliminary results are summarised in Figs. 4 and 5 for the $^{20}\text{Ne} + ^{208}\text{Pb}$ system. The fits to the quasi-elastic data in Fig. 4 use two different approaches to the interaction radius. Generally the nucleus-nucleus potential can be written as $V(r - [R_1 + R_2])$ where the nuclear radii $R_{1,2}$ may be angle dependent. The left panel of Fig. 4 is calculated with this assumption. However, we see from Fig. 5 that this approximation will be inadequate for large deformations since $r - [R_1 + R_2]$ is not the true distance between the nuclear surfaces. The right panel of Fig. 4 shows the considerably better results obtained with a first-order correction to this effect.
Figure 4. The experimental [17] quasi-elastic barrier distribution for $^{20}$Ne + $^{208}$Pb is compared with two calculations that treat the interaction radius differently. See text.

6. Conclusions
The century-old idea of looking for deviations from Rutherford scattering in order to evaluate the nuclear radius is alive and well. Indeed, the possibility of doing experiments with a wide range of intense beams of different projectiles (both stable and radioactive) at varying energies, using modern detectors and data acquisition systems, opens avenues to probe many fine details of the “distributions of nuclear radii” that arise in a wide variety of collisions.

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