Elastic scattering a hundred years on; what can it tell us?

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Abstract. Elastic scattering is often dismissed as trivial to measure and uninteresting to analyse. In fact, it is neither, as this contribution hopes to show. Provided care is taken to make precise measurements and the target carefully selected the nuclear structure of the projectile can — and does in a profound way in many cases — influence the near-barrier elastic scattering through strong channel-coupling effects.

A century ago Rutherford inferred the existence of the atomic nucleus from an analysis of sub-barrier elastic scattering of alpha particles from thin gold foils [1]. While sub-barrier elastic scattering usually follows the Rutherford law — at least for stable projectiles; the scattering of exotic nuclei can deviate significantly from pure Rutherford scattering even at quite deep sub-barrier energies — for incident energies up to about 10-20 MeV above the nominal Coulomb barrier strong coupling can provide a means for the specific nuclear structure properties of the projectile or target to influence profoundly the elastic scattering. While such effects have been observed for stable nuclei, due both to the specific properties of the target [2] and the projectile [3], radioactive beams provide the most striking examples.

As a first example we take $^6$He, which has a low threshold against $\alpha+2n$ breakup, $S_{2n} = 0.973$ MeV, and very large Coulomb dipole coupling to the low-lying continuum. The stable weakly-bound nucleus $^6$Li makes an excellent comparison, with a threshold against $\alpha+d$ breakup of 1.47 MeV and, in a strict $\alpha+d$ cluster model picture, no dipole coupling whatsoever. If we compare the elastic scattering angular distributions for $^6$He + $^{208}$Pb at 22 MeV incident $^6$He energy [4] and $^6$Li + $^{208}$Pb at 33 MeV incident $^6$Li energy [3] (i.e. at the same centre of mass energies with respect to the nominal Coulomb barriers) we immediately observe a striking difference in the angular region around the Coulomb rainbow: $^6$Li exhibits a classic Fresnel scattering pattern with a small but distinct rainbow peak, while for $^6$He the rainbow peak is completely absent, the elastic scattering cross section being considerably depleted in this region, see Figure 1.

As these are both systems where Coulomb excitation should be important it is natural to conjecture that the large difference in behaviour between $^6$Li and $^6$He is due to the strong Coulomb dipole coupling to the low-lying continuum in $^6$He, this being the main nuclear structure difference between the two nuclides. Detailed Coupled Discretised Continuum Channels (CDCC) calculations bear this out, cf. the curves on Figure 1. The calculations were performed using global potentials and were not tuned to fit the data, but it will be noted that they describe rather well the two angular distributions, see Ref. [5] for details. It is found that switching off the dipole excitation in the $^6$He calculation destroys the agreement with the data and yields an
Figure 1. Adapted from Ref. [5]. Filled and open circles denote 33 MeV $^6$Li + $^{208}$Pb [3] and 22 MeV $^6$He + $^{208}$Pb [4] elastic scattering data respectively and the solid and dashed curves the results of CDCC calculations for $^6$Li and $^6$He respectively.

angular distribution similar to that for $^6$Li + $^{208}$Pb, confirming the vital rôle of this coupling in producing the unusual form of the $^6$He data.

However, as shown by calculations presented in Ref. [5] and borne out by the data for the $^6$He + $^{64}$Zn system of Ref. [6], the choice of the target is crucial if this nuclear-structure-dependent effect is to be observed in the elastic scattering data. If the charge of the target nucleus is too small the dipole coupling effect in $^6$He is sufficiently damped that the elastic scattering is similar to that for $^6$Li from the same target (provided due account is taken of the difference in projectile charge and thus in the interaction Coulomb barriers). The energy of the projectile with respect to the Coulomb barrier can also be important, as calculations predict that even for a $^{208}$Pb target if the incident energy is sufficiently high the $^6$He elastic scattering should show a classic Fresnel pattern.

Figure 1 also shows the value of obtaining precise data (of the order of ± 2-3 %) for both radioactive and stable beams. Data at this level of precision enable differences in the angular distributions to be established unambiguously as real effects dependent on the specific properties of the nuclei under investigation.

Not all nuclei are so easily understood. Recent elastic scattering data for $^8$B from a $^{58}$Ni target at several near-barrier energies [7] present “a riddle, wrapped in a mystery, inside an enigma” [8] or, alternatively, “the curious incident of the dog in the night-time” [9]. Figure 2 shows the data together with the results of CDCC calculations modelling the effect of the $^8$B → $^7$Be + p breakup coupling. It might be argued that the data of Ref. [7] are far from our ideal of precision. However, it should be recalled that $^8$B is a difficult beam to produce so that the
available intensities are low, and these data represent the greatest precision that can realistically be obtained with current facilities. While data of greater precision would of course be welcome, the existing angular distributions are already sufficient to establish an unexpected phenomenon.

The CDCC calculations presented in Figure 2 are briefly described in Ref. [10]. They employ a simplified cluster model of $^8$B which treats the $^7$Be core as inert but retains its non-zero intrinsic spin. Despite very large breakup cross sections (much larger than those for $^6$Li, say, at similar energies with respect to the Coulomb barrier) it is obvious that for $^8$B, coupling to the $^7$Be + $p$ continuum has very little influence on the elastic scattering. This is, to say the least, unusual behaviour, especially when it is recalled that $^8$B has the lowest known threshold against breakup ($S_p = 0.1375$ MeV). While it has long been known that a large cross section for a given reaction channel or set of channels is not a reliable guide as to the importance of coupling to those channels on the elastic scattering, $^8$B appears to offer an extreme example of this phenomenon.

It remains an enigma why coupling to channels that have such large cross sections (ranging from 108 mb at the lowest to 160 mb at the highest incident energy) should have little or no apparent effect on the elastic scattering, but it is surely linked to some subtlety in the nuclear structure of $^8$B. Calculations for a $^{208}$Pb target presented in Ref. [11] exhibit similar behaviour to those in Figure 2, thus suggesting that it is not an effect linked to Coulomb excitation. To add further to the mystery, calculations [11] also suggest that the influence of coupling to the
Figure 3. Adapted from Ref. [13]. Open circles denote the $^{11}\text{Be} + ^{64}\text{Zn}$ quasi-elastic data of Ref. [12], the dashed curve the quasi-elastic scattering predicted by a calculation including only coupling to the first excited state of $^{11}\text{Be}$. The solid curve denotes the quasi-elastic scattering predicted by the full CDCC calculation while the dot-dashed curve denotes the result of a similar calculation where the Coulomb excitation has been switched off.

$^{58}\text{Ni}(^{8}\text{B},^{7}\text{Be})$ proton stripping reaction on the elastic scattering is at least as large as that due to the $^{8}\text{B} \rightarrow ^{7}\text{Be} + p$ breakup and perhaps even larger, in spite of an almost negligible cross section. In $^{8}\text{B}$ we therefore have the apparent paradox of a nucleus whose elastic scattering is exotic because it is not particularly exotic . . .

We have thus far considered two different radioactive beams where specific nuclear structure properties affect the near-barrier elastic scattering angular distributions in a striking manner ($^{6}\text{He}$) and much more subtly ($^{8}\text{B}$). In considering $^{11}\text{Be}$ we shall find additionally that apparently similar effects may be due to different causes.

A recent measurement of the $^{11}\text{Be} + ^{64}\text{Zn}$ quasi-elastic scattering angular distribution at $E_{c.m.} = 24.5$ MeV [12] found, in contrast to the $^{6}\text{He} + ^{64}\text{Zn}$ data which showed a conventional Fresnel scattering distribution, a similar pattern to that seen for $^{6}\text{He} + ^{208}\text{Pb}$, see Figure 3. The data are quasi-elastic as it was impossible to separate inelastic scattering to the low-lying ($E_x = 0.32$ MeV) bound first excited state of $^{11}\text{Be}$ from the elastic scattering. However, the data may be taken as pure elastic scattering for most practical purposes.

It is natural to assume that this non-Fresnel pattern is again due to the effect of strong Coulomb excitation to the continuum. It is somewhat surprising to see such a strong effect for a target with a relatively small charge ($Z = 30$) but $^{11}\text{Be}$ does after all have twice the charge
of $^6$He and it is the product of the projectile and target charges that is the relevant quantity here. However, CDCC calculations described in Ref. [13] suggest that in fact the cause is strong nuclear excitation to the continuum. The curves in Figure 3 show that while switching off the Coulomb excitation (but retaining the diagonal Coulomb terms) does have some influence on the result, the bulk of the effect is due to the nuclear breakup coupling alone, an unexpected result.

Why the nuclear excitation to the continuum should be more important than the Coulomb for $^{11}$Be remains to be elucidated by more detailed model calculations (those presented in Ref. [13] are somewhat simplified as they treat the $^{10}$Be core as inert). What is clear, and independent of any model, is that in spite of the largest known $B(E1)$ for excitation of a bound state, coupling to the 0.32 MeV 1/2$^-$ first excited state of $^{11}$Be is not responsible for the non-Fresnel scattering pattern. This conclusion is model independent, as the data being quasi-elastic the “add back” effect would have given rise to a standard Fresnel angular distribution for this observable if the inelastic excitation did have a significant influence on the elastic scattering.

It is hoped that this brief summary of coupling effects on near-barrier elastic scattering has shown that it can be a useful probe of nuclear structure, provided care is taken to obtain precise angular distribution data and some thought given to the choice of target and incident energy. It has concentrated on light radioactive beam data, mainly due to the availability of suitable measurements. Although we have focussed on the influence of coupling to the continuum — breakup — stripping reactions can also have a significant influence on the elastic scattering and in some cases this may be dominant, e.g. the predictions for the ($^{12}$C,$^{14}$C) stripping reaction of Ref. [14]. Further examples are given in the review article Ref. [11].

As more exotic and heavier radioactive beams become available with the new generation of facilities who can tell what surprises elastic scattering may have in store for us a century after Rutherford?

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