# Generation of a repulsive dynamic polarization potential by transfer couplings

N. Keeley and N. Alamanos
*C.E.A. Centre de Saclay, DSM/DAPNIA/SPhN,*
*Orme des Merisiers, 91190 Gif-sur-Yvette, France*

K. Rusek
*Department of Nuclear Reactions, The Andrzej Sołtan Institute for Nuclear Studies, ul. Hoża 69, 00-681 Warsaw, Poland and*
*Departamento de Fisica Aplicada, Universidad de Huelva, E-21819, Huelva, Spain*

K.W. Kemper
*Department of Physics, The Florida State University, Tallahassee, Florida 32306-4350*
(Dated: October 19, 2004)

A series of coupled reaction channels calculations for the $^9$Be + $^{209}$Pb system at near barrier energies is presented. Single neutron stripping couplings leading to several states in $^{209}$Pb together with coupling to the direct breakup of $^9$Be using a $^5$He + $\alpha$ cluster model are included. We find that the transfer couplings give rise to a dynamic polarization potential with the same characteristics in the nuclear surface region as that produced by breakup.

PACS numbers: 25.70.Bc, 25.70.Hi, 24.10.Eq, 21.60.Gx

## I. INTRODUCTION

Interest in the influence of breakup on the elastic scattering of weakly bound nuclei dates back to the discovery that the double-folding model using the M3Y interaction [1], hitherto highly successful for many different heavy-ion projectiles [2], had to be renormalized by a factor of order 0.5 in order to fit the elastic scattering of the weakly bound $^6$Li [3], $^7$Li [4] and $^9$Be [5] nuclei. This was subsequently demonstrated to be due to a large positive real dynamic polarization potential produced by coupling to breakup [6–9]. However, although ground state reorientation couplings were found to have an important influence on the elastic scattering of $^7$Li and $^9$Be for relatively high bombarding energies with respect to the Coulomb barrier [10], there has been little investigation of the effect of coupling to transfer reactions on the elastic scattering of such nuclei.

The effect of coupling to transfer channels with negative $Q$-values on the elastic scattering of systems involving a weakly bound projectile has been previously investigated for the $^{208}$Pb($^7$Li,$^6$Li)$^{209}$Pb single neutron stripping reaction [11]. These couplings were found to induce negative real and imaginary dynamic polarization potentials, contributing to the "threshold anomaly" observed for this system [12]. We note that while coupling to the ground state reorientation and excitation of the first excited state of $^7$Li was found to have a negligible effect at near barrier energies for the $^7$Li + $^{208}$Pb system [13], Lubian *et al.* [14] found that these couplings had a significant effect on the elastic scattering of $^7$Li by $^{138}$Ba. However, coupling to excited states of the target nucleus was found to have a negligible influence for both systems [11, 14].

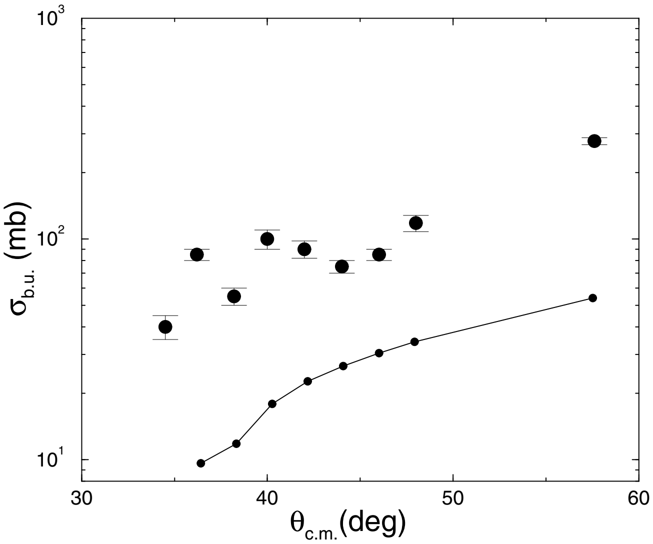
For the interaction of these weakly bound nuclei with heavy targets, where breakup should have its maximum influence due to the large Coulomb breakup contribution, there are also transfer reactions with positive $Q$-values that could play an important role at near and sub barrier energies. In this paper, prompted by the recent availability of precision elastic scattering data for the $^9$Be + $^{208}$Pb system [15], we investigate the influence of one such reaction, the $^{208}$Pb($^9$Be,$^8$Be)$^{209}$Pb single neutron stripping, on elastic scattering through coupled reaction channels (CRC) calculations. Total transfer yield data are also available for this system at several energies [16], providing a check on the transfer coupling strengths used in the calculations. This transfer may be expected to be particularly important due to the presence of several states in the residual $^{209}$Pb nucleus at excitation energies such that the effective $Q$-value will be approximately zero, and which should consequently be strongly populated.

## II. THE CALCULATIONS

The calculations employed a two-body $^5$He+$\alpha$ cluster picture of $^9$Be in order to model the breakup within the coupled discretized continuum channels (CDCC) formalism (see Sakuragi *et al.* [9] for a convenient summary of the CDCC method as applied to light heavy ions.) While $^9$Be is best described as a three-body $\alpha$+$\alpha$+$n$ object, at present CDCC has not been completely implemented for four-body breakup (although progress is being made in this area, see Matsumo *et al.* [17]). The two-body model of $^9$Be has been found to work rather well for the elastic and inelastic scattering (breakup) to the 2.43 MeV $5/2^-$ resonance of $^9$Be from a $^{12}$C target [18].

Structure calculations suggest that the $^9$Be ground state is largely of $^5$He+$\alpha$ cluster nature [19], thus one may reasonably suppose that coupling to the $^5$He+$\alpha$ breakup mode will have most influence on the elastic scattering despite its higher (2.37 MeV) threshold compared to that of the $^8$Be+$n$ mode (1.67 MeV). We note that the as-

FIG. 1: Calculated $^9$Be $\rightarrow$ $^5$He+$\alpha$ breakup cross sections compared with the data of Wooliscroft *et al.* [16].




sumption of a $^5$He+$\alpha$ cluster structure in our calculations does not rule out the possibility of a significant contribution to the total breakup cross section from $^8$Be+$n$ breakup; we merely make the tacit assumption that coupling to this mode will have a small effect on the elastic scattering due to the non-orthogonality of the $^9$Be ground state with this clustering mode.

The $^5$He+$\alpha$ continuum was included in the calculations exactly as described in [18], with the exception that coupling to the 1.68 MeV $1/2^+$ state, poorly described by a $^5$He+$\alpha$ cluster, was omitted and the continuum model space was limited to $0.0 \leq k \leq 0.8$ fm$^{-1}$ with $\Delta k = 0.2$ fm$^{-1}$, $\hbar k$ being the momentum of the $^5$He+$\alpha$ relative motion. Test calculations with $\Delta k = 0.15$ fm$^{-1}$ gave similar results. All partial waves up to $\ell = 150$ were included and the matching radius was set equal to 130 fm, while the radius limiting the range of the continuum bins was 80 fm. The $\alpha$+$^{208}$Pb optical potentials required as input to the cluster-folding $^9$Be potentials were taken from Goldring *et al.* [20], while the $^5$He+$^{208}$Pb potentials used the same parameters with the real and imaginary diffuseness increased by 0.1 fm in order to take account of the larger radial extent of the $^5$He resonance. All calculations described here were carried out using the code FRESCO [21], version FRXY.1i.

In Fig. 1 we compare the calculated $^9$Be $\rightarrow$ $^5$He+$\alpha$ integrated breakup cross sections with the values of Wooliscroft *et al.* [16], extracted from their total $\alpha$ yield measurements. The calculated $^9$Be $\rightarrow$ $^5$He+$\alpha$ breakup accounts for between a half and a third of the measured total breakup yield.

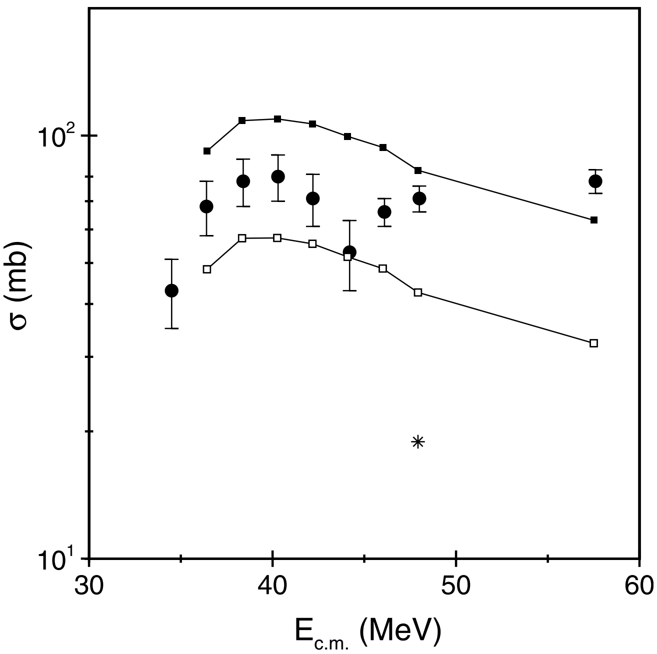
Other reaction processes besides breakup may have an important influence on the near barrier elastic scattering. The $^{208}$Pb($^9$Be,$^8$Be)$^{209}$Pb single neutron stripping reaction has a $Q$-value of +2.27 MeV and may be expected to play a significant role for near barrier energies. In order to investigate the effect of this reaction on the elastic scattering, transfers leading to the following states of $^{209}$Pb were included in the calculations: 0.0 MeV $9/2^+$, 0.78 MeV $11/2^+$, 1.57 MeV $5/2^+$, 2.03 MeV $1/2^+$, 2.49 MeV $7/2^+$, and 2.54 MeV $3/2^+$. These states were assumed to be of pure single particle nature with the configurations of Kovar *et al.* [22]. The $^8$Be+$^{209}$Pb optical model parameters in the exit channels were taken from fits to the $^9$Be+$^{208}$Pb elastic scattering using Woods-Saxon [23] form real and imaginary potentials.

Two sets of calculations including the single neutron stripping were carried out. The first set took the Cohen and Kurath [24] value for the $^9$Be/$^8$Be overlap spectroscopic factor of $C^2S = 0.58$, with the $1p_{1/2}$ neutron being bound in a Woods-Saxon potential well with the standard parameters $R = 1.25 \times 8^{1/3}$ fm, $a = 0.65$ fm, the depth being adjusted to obtain the correct binding energy. The corresponding spectroscopic factors for the $^{208}$Pb/$^{209}$Pb overlaps were set equal to 1.0, the neutron being again bound in a Woods-Saxon well with standard parameters, $R = 1.25 \times 208^{1/3}$ fm, $a = 0.65$ fm. A similar procedure was found to give a good description of the $^{208}$Pb($^7$Li,$^6$Li)$^{209}$Pb single neutron stripping reaction [25]. The calculations were performed using the post form of the coupled reaction channels (CRC) formalism and included the full complex remnant term and non-orthogonality correction.

A comparison of the calculated angular distributions with the data of Stahel *et al.* [26] for the $^{208}$Pb($^9$Be,$^8$Be)$^{209}$Pb reaction at an incident $^9$Be energy of 50 MeV found that they overpredicted the measured values by a factor of approximately five. However, we note that the DWBA analysis of Stahel *et al.*, also using the Cohen and Kurath spectroscopic factor for the $^9$Be/$^8$Be overlap, extracted spectroscopic factors for the $^{209}$Pb/$^{208}$Pb overlaps that were smaller than those obtained from $^{208}$Pb($d$,$p$)$^{209}$Pb analyses by an average factor of about 5.2.

We therefore performed a second set of calculations including the single neutron stripping, with the form-factors for the $^9$Be/$^8$Be and $^{209}$Pb/$^{208}$Pb overlaps being taken from Lang *et al.* [27] and Kovar *et al.* [22], respectively. The latter set of form-form factors were taken to be those obtained from the adiabatic model analysis of the 20 MeV $^{208}$Pb($d$,$p$)$^{209}$Pb data. Lang *et al.* obtained a $^9$Be/$^8$Be spectroscopic factor of $C^2S = 0.42$ for the $1p_{1/2}$ neutron bound in a Woods-Saxon potential well with parameters $R = 1.15 \times 8^{1/3}$ fm, $a = 0.57$ fm with the depth adjusted to give the correct binding energy and a spin-orbit component with the same geometry parameters and a fixed depth of 5.5 MeV. The form-factors of Kovar *et al.* bound the neutron in a Woods-Saxon potential well with parameters $R = 1.23 \times 208^{1/3}$ fm, $a = 0.65$ fm with the depth adjusted to give the correct binding energy and a spin-orbit component with the same geometry parameters and a fixed depth of 6.0 MeV. These calculations

FIG. 2: Calculated total $^{208}$Pb($^{9}$Be,$^{8}$Be)$^{209}$Pb cross sections for the first (filled squares) and second (open squares) sets of calculations compared with the data of Wooliscroft *et al.* [16] (filled circles). The asterisk denotes the summed integrated cross section for the DWBA fits of Stahel *et al.* [26]. See text for details.




overpredict the data of Stahel *et al.* [26] by a factor of approximately three.

This discrepancy between the two sets of calculations, both with physically reasonable choices for the $^{9}$Be/$^{8}$Be and $^{209}$Pb/$^{208}$Pb form-factors, and the data of Stahel *et al.* [26] could be due to one of two possibilities: either the data are incorrectly normalized or the mechanism of the $^{208}$Pb($^{9}$Be,$^{8}$Be)$^{209}$Pb reaction is more complicated than direct single neutron stripping. Fortunately, Wooliscroft *et al.* [16] have extracted total integrated cross sections for the $^{208}$Pb($^{9}$Be,$^{8}$Be)$^{209}$Pb reaction at several incident energies. The total cross sections predicted by the two sets of calculations described above are compared with these data in Fig. 2. We see that the first set of calculations somewhat overpredict these data (by a factor of $\sim 1.4$ at $E_{\mathrm{c.m.}} = 40$ MeV) while the second set slightly *underpredict* the data (by a factor of $\sim 0.8$ at $E_{\mathrm{c.m.}} = 40$ MeV). We also plot on Fig. 2 the summed integrated cross section of the DWBA fits of Stahel *et al.* [26]. It is a factor of $\sim 4$ below the equivalent data point of Wooliscroft *et al.* [16]. We therefore conclude that the $^{208}$Pb($^{9}$Be,$^{8}$Be)$^{209}$Pb reaction does indeed largely proceed via direct single neutron transfer and that the data of Stahel *et al.* [26] are incorrectly normalized. The second set of calculations could be modified to fit the total cross section data of Wooliscroft *et al.* [16] by a slight increase in the $^{9}$Be/$^{8}$Be spectroscopic factor and/or the radius parameter of the potential well used to bind the $1p_{1/2}$ neutron to the $^{8}$Be core, although we have chosen to keep the values obtained from the literature.

We have discussed the question of the $^{208}$Pb($^{9}$Be,$^{8}$Be)$^{209}$Pb coupling strengths at some length as we found that the effect of this transfer coupling on the elastic scattering was sensitive to the values chosen for these strengths. In Figs. 3 and 4 we present the results of the second set of calculations compared with the elastic scattering data of Wooliscroft *et al.* [15]. Note that the effect of the breakup coupling is to reduce the Coulomb rainbow while increasing the cross section at backward angles, characteristic of this type of coupling. However, rather surprisingly, we note that the $^{208}$Pb($^{9}$Be,$^{8}$Be)$^{209}$Pb single neutron stripping coupling acts in the *same* sense as the breakup, further reducing the Coulomb rainbow and improving the agreement with the data. This is particularly so for the lowest incident $^{9}$Be energies, and we show a detail of the Coulomb rainbow region at a $^{9}$Be incident energy of 44 MeV in Fig. 5 to better illustrate this. The first set of calculations (with single neutron stripping coupling strengths that are somewhat too large) show a similar but somewhat larger effect, the full calculations rather underpredicting the elastic scattering data in the Coulomb rainbow region.

The effect of the single neutron stripping on the calculated elastic scattering leads us to expect that the dynamic polarization potential (DPP) induced by these couplings should be similar to that induced by coupling to breakup, i.e. the real part of the DPP should be positive (repulsive) in nature. In Fig. 6 we confirm this by plotting the strength of the trivially equivalent local potential, calculated according to the method of Thompson *et al.* [28], evaluated at a radius of 12.3 fm, taken as the radius of sensitivity by Wooliscroft *et al.* [15].

One may observe that coupling to the single neutron stripping does indeed induce a DPP that is qualitatively similar to that induced by the breakup coupling, although the energy dependence of the surface strength is somewhat different. The real part of the DPP induced by breakup becomes steadily more positive (repulsive) as the $^{9}$Be incident energy is reduced towards the Coulomb barrier, while the reverse is true for that induced by the stripping. However, the imaginary part of the DPP becomes more negative (absorptive) for both couplings as the incident energy is reduced. We also note that the two sets of CRC calculations yield DPPs that are very close in strength in the surface region, the main effect of the larger coupling strength in the first set being to slightly increase the absorption at all energies.

## III. DISCUSSION

We have shown that the $^{208}$Pb($^{9}$Be,$^{8}$Be)$^{209}$Pb single neutron stripping reaction has a significant effect on the near barrier elastic scattering of $^{9}$Be by $^{208}$Pb. We have

FIG. 3: Calculated angular distributions for $^{9}$Be + $^{208}$Pb elastic scattering at $E_{\rm lab}$ = 38, 40, 42, 44, and 46 MeV. The data are taken from [15]. Calculations with no coupling, coupling to $^{9}\rm{Be} \rightarrow {}^{5}\rm{He} + \alpha$ breakup only and breakup plus $^{208}$Pb($^{9}$Be,$^{8}$Be)$^{209}$Pb transfer are denoted by the dotted, dashed and solid curves, respectively.

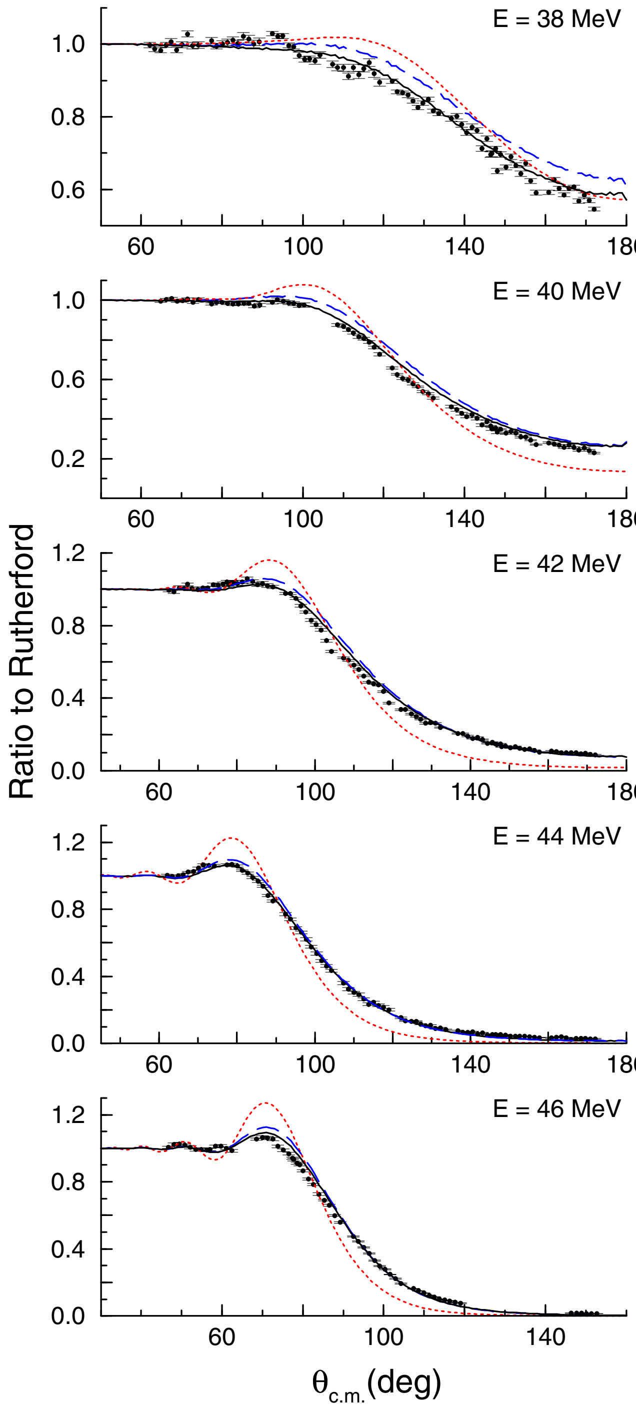



FIG. 4: Calculated angular distributions for $^{9}$Be + $^{208}$Pb elastic scattering at $E_{\rm lab}$ = 48, 50, 60, 68 and 75 MeV. The data are taken from [15]. Calculations with no coupling, coupling to $^{9}\rm{Be} \rightarrow {}^{5}\rm{He} + \alpha$ breakup only and breakup plus $^{208}$Pb($^{9}$Be,$^{8}$Be)$^{209}$Pb transfer are denoted by the dotted, dashed and solid curves, respectively.

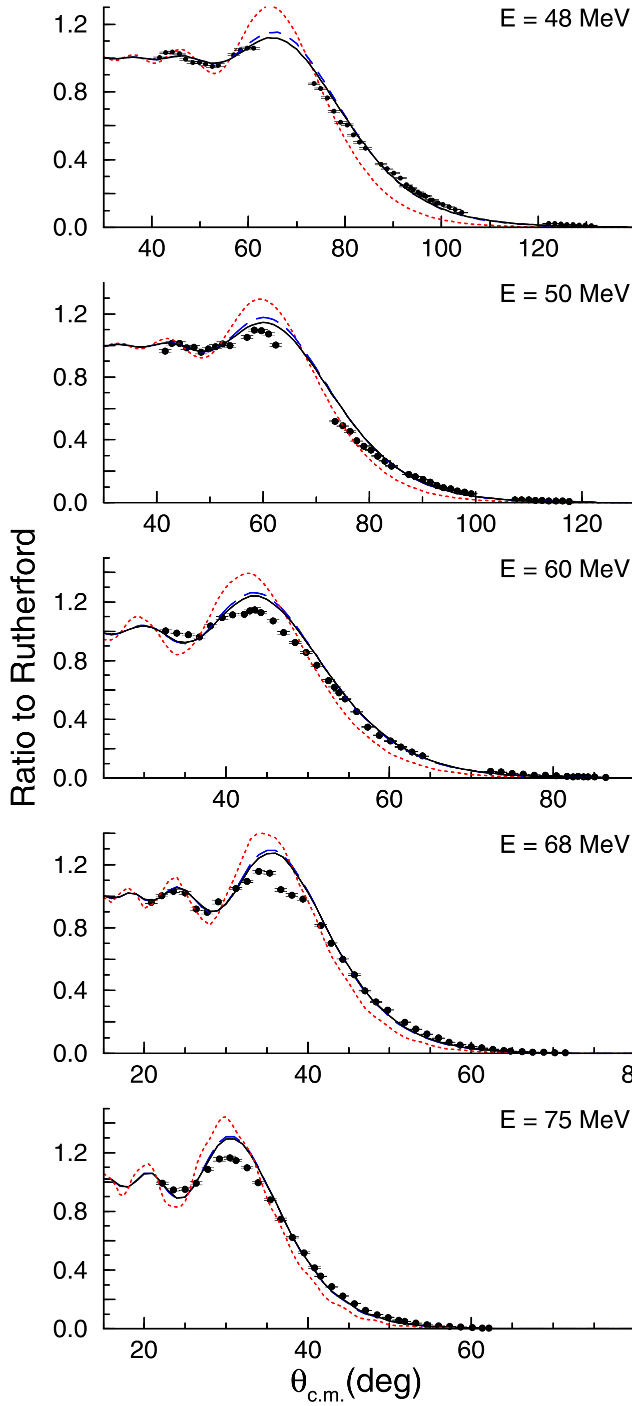


FIG. 5: Detail of the Coulomb rainbow region for $^{9}$Be+$^{280}$Pb elastic scattering at an incident $^{9}$Be energy of 44 MeV. The dotted, dashed and solid curves denote the results of calculations with no coupling, coupling to breakup only and coupling to both breakup and single neutron stripping, respectively.

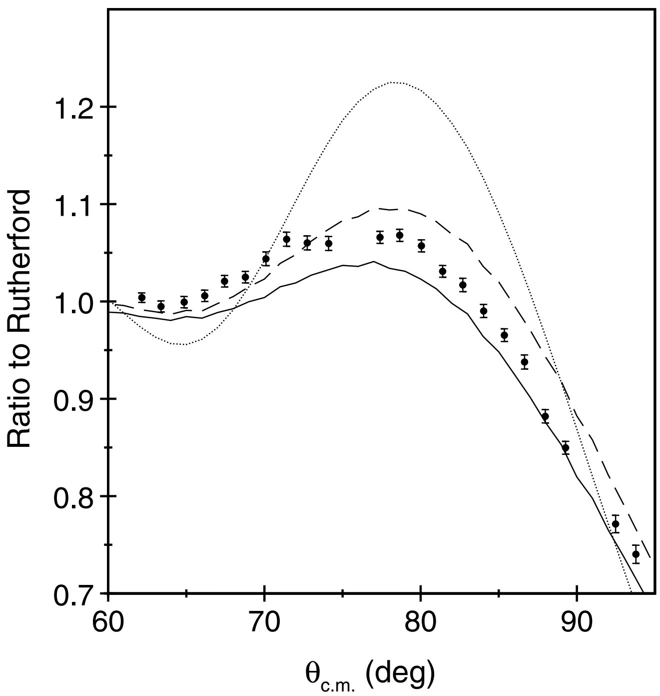
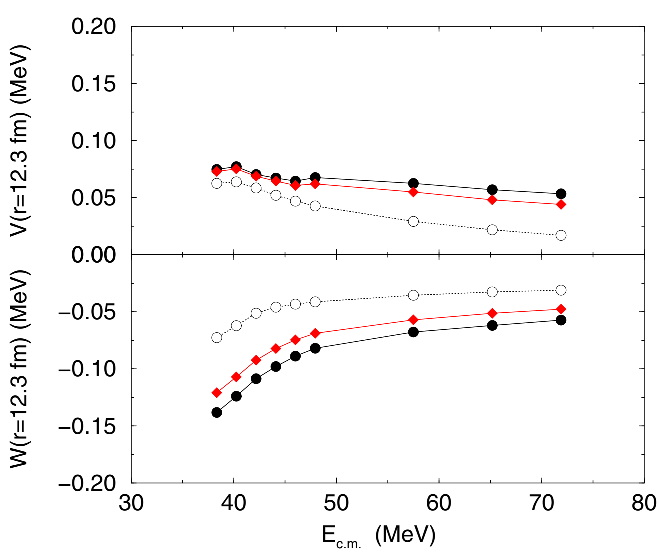



FIG. 6: Dynamic polarization potentials (DPPs) derived from the present calculations evaluated at a radius of 12.3 fm. The open circles denote the DPPs derived from the calculations including breakup only, the filled circles those derived from the first set of calculations including the single neutron stripping and the filled diamonds those derived from the second set of calculations including the single neutron stripping.




further demonstrated that, unlike coupling to transfer channels with relatively large negative $Q$-values [11], coupling to these transfers with $Q$-values that are either positive or very close to zero generates a DPP that is qualitatively similar to that induced by breakup. This DPP has a positive (repulsive) real part and a negative (absorptive) imaginary part, the latter steadily increasing in strength as the incident energy is reduced towards the Coulomb barrier.

The nature of the DPP induced by the $^{208}$Pb($^{9}$Be,$^{8}$Be)$^{209}$Pb stripping reaction has important implications for the question of the presence or absence of a threshold anomaly in near barrier $^{9}$Be elastic scattering. The threshold anomaly is a channel coupling effect that manifests itself as a pronounced rise in the surface strength of the real part of the optical model potential, associated with a sharp drop in the imaginary part as the incident energy is reduced towards the Coulomb barrier, see e.g. [29, 30] and references therein. The threshold anomaly has been found to be present for $^{7}$Li but to be absent from $^{6}$Li elastic scattering [12, 31–33], the lower breakup threshold of $^{6}$Li being found to play a major role in this difference [13].

For $^{9}$Be elastic scattering the situation is less clear. Wooliscroft *et al.* [15] found a threshold anomaly in the $^{9}$Be+$^{208}$Pb system, whereas Signorini *et al.* [34] found hybrid behavior in the neighboring $^{9}$Be+$^{209}$Bi system. The surface strength of the real part of the optical model potential showed the rapid increase with decreasing incident energy characteristic of the threshold anomaly, while that of the imaginary part continued to rise as the incident energy decreased below the Coulomb barrier. Moraes *et al.* [35] obtained conflicting results for the $^{9}$Be+$^{64}$Zn system; with one form of the optical potential they obtained a weak threshold anomaly, while with an alternative form no significant energy dependence of the surface strength of the potential was observed. A later analysis by the same group [14] concluded that this system does not exhibit a threshold anomaly.

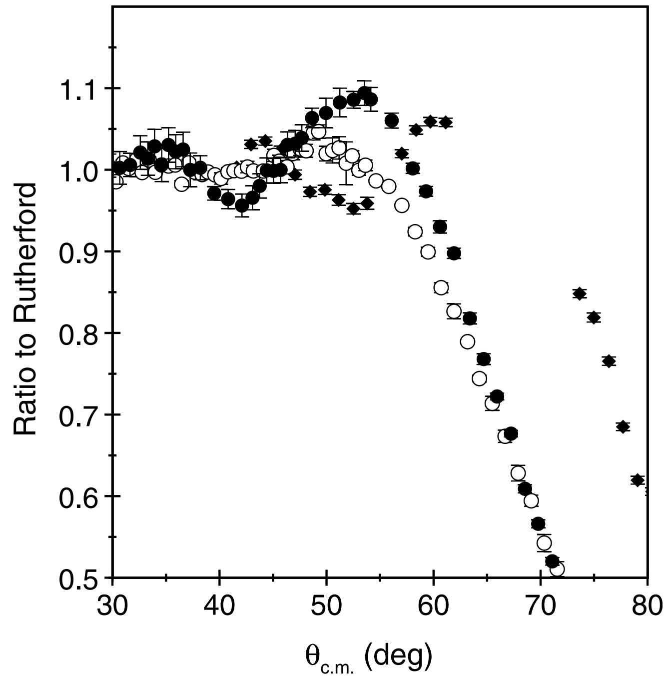
As the bare cluster-folded potential used in our calculations is energy independent, the optical potential parameters of Goldring *et al.* [20] used as input not varying with energy, the DPP obtained from our CRC calculations would appear to contradict the observation of a threshold anomaly for the $^{9}$Be+$^{208}$Pb system by Wooliscroft [15] and be more in accord with the behavior observed by Signorini *et al.* [34] for the $^{9}$Be+$^{209}$Bi system or Moraes *et al.* [35] for the $^{9}$Be+$^{64}$Zn system. However, we note that the real part of the DPP is only on average of order 5 % of the strength of the bare real potential at the same radius, thus allowing the DPP induced by coupling to other channels, such as transfer reactions with negative $Q$-values, to induce the classic threshold anomaly behavior observed for $^{7}$Li. The same applies to the imaginary part of the DPP, although its surface strength is much larger relative to the bare potential than for the real part, particularly so for the lowest incident energies considered here.

It is clear that in contrast to the $^7$Li+$^{208}$Pb system the threshold anomaly observed by Wooliscroft *et al.* [15] for the $^9$Be+$^{208}$Pb system is not explained by single neutron stripping, rather the reverse. It is therefore possible that the apparently contradictory behavior observed for the $^9$Be+$^{209}$Bi and $^9$Be+$^{64}$Zn systems could be explained by the dominance of the effect of coupling to the stripping channels in these systems. However, the $Q$-value for the $^{64}$Zn($^9$Be,$^8$Be)$^{65}$Zn reaction is +6.31 MeV, favoring transfers to states in $^{65}$Zn at around 6 MeV excitation energy. Such states exist, but little is known about their structure. The $Q$-value for the $^{209}$Bi($^9$Be,$^8$Be)$^{210}$Bi transfer is +2.94 MeV, similar to that for $^{208}$Pb($^9$Be,$^8$Be)$^{209}$Pb, suggesting that the effect should be similar, although the transfer strength is highly fragmented in $^{210}$Bi, making calculation difficult.

There is, however, an empirical argument in favor of a threshold anomaly for the $^9$Be+$^{208}$Pb system. If one compares the elastic scattering angular distributions for $^6$Li and $^7$Li+$^{208}$Pb at the same near barrier energies on a linear cross section (ratio to Rutherford) scale, one immediately notices that the Coulomb rainbow for $^7$Li is considerably more pronounced than that for $^6$Li, which is hardly present at all in comparison, indicating a larger $V/W$ ratio for $^7$Li. This difference diminishes with increasing incident energy, thus providing an empirical illustration of the contrasting near barrier behavior of the two isotopes. In Fig. 7 we plot the measured elastic scattering angular distributions for $^6$Li, $^7$Li and $^9$Be+$^{208}$Pb at incident energies of 39, 39 and 48 MeV, respectively, approximately the same center of mass energies with respect to the appropriate Coulomb barriers. It will be observed that the Coulomb rainbow for $^9$Be is similar to that for $^7$Li, showing the marked minimum just before the rainbow peak that is absent for $^6$Li, suggesting that the $^9$Be+$^{208}$Pb system should exhibit similar near barrier behavior to that of the $^7$Li+$^{208}$Pb system and show a threshold anomaly.

This empirical argument in favor of a threshold anomaly for the $^9$Be+$^{208}$Pb system also lends support to our assumption that the $^5$He+$\alpha$ breakup of $^9$Be is more important with regard to its effect on the elastic scattering than the $^8$Be+$n$ mode, despite its higher threshold energy. Calculations comparing the $^7$Be+$^{208}$Pb and $^7$Li+$^{208}$Pb systems [36] suggest that our previous conclusion [13] as to the importance of the breakup threshold energy in explaining the presence in the $^7$Li+$^{208}$Pb and the absence in the $^6$Li+$^{208}$Pb system of a threshold anomaly may be generalized, and that a strong experimental signature of the absence of a threshold anomaly is the suppression of the Coulomb rainbow in the near barrier elastic scattering. The presence of a strong Coulomb rainbow in the measured near barrier $^9$Be+$^{208}$Pb elastic scattering strongly supports the view that the $^5$He+$\alpha$ breakup with its threshold energy of 2.37 MeV, close to that of the $\alpha$+$t$ breakup in $^7$Li (2.47 MeV), is the important mode for determining the influence of breakup on the elastic scattering of $^9$Be. In contrast, as Fig. 1 makes clear, the $^9$Be $\rightarrow$ $^8$Be+$n$ mode provides the major contribution to the total breakup yield, as might be expected due to its lower threshold energy (1.67 MeV).

FIG. 7: Measured elastic scattering angular distributions for $^6$Li (open circles), $^7$Li (filled circles) and $^9$Be (filled diamonds) at incident energies of 39, 39 and 48 MeV, respectively. See text for details.




## IV. SUMMARY

A series of CRC calculations for the $^9$Be+$^{208}$Pb system using a $^5$He+$\alpha$ cluster picture of $^9$Be to model the effect of breakup using the CDCC formalism and including couplings to the $^{208}$Pb($^9$Be,$^8$Be)$^{209}$Pb single neutron stripping reaction have been presented. Good fits to the elastic scattering data of Wooliscroft *et al.* [15] were obtained with no adjustable parameters.

We have shown that coupling to the single neutron stripping has a significant effect on the calculated elastic scattering angular distributions, acting to reduce the Coulomb rainbow in the same way as couplings to breakup. Furthermore, DPPs derived from the CRC calculations demonstrated that the transfer coupling gives rise to a DPP of the same type as that due to breakup, i.e. it has a positive (repulsive) real part and a negative (absorptive) imaginary part. We have therefore shown for the first time that couplings to transfer reactions with $Q$-values that are positive or close to zero affect the elastic scattering in the same way as breakup, in contrast to couplings to transfer reactions with relatively large negative $Q$-values, which induce a DPP with a negative (attractive) real part (see e.g. [11]).

This has interesting implications for the question of the presence or absence of a threshold anomaly in $^9$Be elastic scattering. Unlike the $^7$Li+$^{208}$Pb system where the single neutron stripping contributed to the presence of a threshold anomaly, for $^9$Be+$^{208}$Pb the reverse is true; coupling to the single neutron stripping channels tends to suppress threshold anomaly type behavior. Thus, for the $^9$Be+$^{208}$Pb system the explanation of the observed threshold anomaly [15] must be sought in couplings to other channels, such as negative $Q$-value transfers. As the positive DPPs induced by the $^5$He+$\alpha$ breakup and single neutron stripping are relatively weak the calculations presented here are consistent with this possibility.

Previous work comparing $^6$Li and $^7$Li+$^{208}$Pb [13] and $^7$Li and $^7$Be+$^{208}$Pb [36] suggests that for weakly bound systems the breakup threshold energy plays an important role in determining whether a threshold anomaly is present or not, and that suppression of the Coulomb rainbow at near barrier energies is an experimental signature of the absence of a threshold anomaly. A comparison of the measured angular distributions for $^6$Li, $^7$Li and $^9$Be+$^{208}$Pb elastic scattering at similar center of mass energies with respect to their appropriate Coulomb barriers reveals that the $^9$Be+$^{208}$Pb angular distribution shows a pronounced Coulomb rainbow, similar to that for $^7$Li+$^{208}$Pb. This is consistent with the observation of a threshold anomaly for the $^9$Be+$^{208}$Pb system by Wooliscroft *et al.* [15] and supports the suggestion that the $^5$He+$\alpha$ breakup mode with a threshold energy only 0.1 MeV lower than the $\alpha$+$t$ threshold of $^7$Li has the greatest influence on the $^9$Be elastic scattering. Thus, comparison of near barrier elastic scattering angular distributions in the region of the Coulomb rainbow provides an empirical means of determining whether breakup and/or positive $Q$-value transfer channels dominate the effects of channel coupling on the elastic scattering, provided that the data have sufficient angular definition to unambiguously trace the form of the Coulomb rainbow.

**Acknowledgments**

This work was supported by the State Committee for Scientific Research of Poland (KBN), Grant No. POLONIUM 4335.III/2004, the U.S. National Science Foundation and the State of Florida.

[1] G.Bertsch, J.Borysowicz, H.McManus, and W.G.Love, Nucl. Phys. **A284**, 399 (1977).
[2] G.R. Satchler and W.G. Love, Phys. Rep. **55**, 183 (1979).
[3] G.R. Satchler and W.G. Love, Phys. Lett. **76B**, 23 (1978).
[4] M.F. Steeden, J. Coopersmith, S.J. Cartwright, M.D. Cohler, N.M. Clarke, and R.J. Grifffiths, J. Phys. **G6**, 501 (1980).
[5] G.R. Satchler, Phys. Lett. **83B**, 284 (1979).
[6] R.S. Mackintosh and A.M.Kobos, Phys. Lett. **116B**, 95 (1982)
[7] M.A. Nagarajan, I.J. Thompson, and R.C. Johnson, Nucl. Phys. **A385**, 525 (1982).
[8] Y. Hirabayashi, S. Okabe, and Y. Sakuragi, Phys. Lett. **221B**, 227 (1989).
[9] Y. Sakuragi, M. Yahiro, and M. Kamimura, Prog. Theor. Phys. Suppl. **89**, 136 (1986).
[10] V. Hnizdo, K.W. Kemper, and J. Szymakowski, Phys. Rev. Lett. **46**, 590 (1981).
[11] N. Keeley and K. Rusek, Phys. Rev. C **56**, 3421 (1997).
[12] N. Keeley, S.J. Bennett, N.M. Clarke, B.R. Fulton, G. Tungate, P.V. Drumm, M.A. Nagarajan, and J.S. Lilley, Nucl. Phys. **A571**, 326 (1994).
[13] N. Keeley and K. Rusek, Phys. Lett. B **427**, 1 (1998).
[14] J. Lubian, I. Padron, P.R.S. Gomes, A.M.M. Maciel, R.M. Anjos, S.B. Moraes, J.J.S. Alves, C. Muri, R. Liguori Neto, and N. Added, Phys. Rev. C **64**, 027601 (2001).
[15] R.J. Wooliscroft, B.R. Fulton, R.L. Cowin, M. Dasgupta, D.J. Hinde, C.R. Morton, and A.C. Berriman, Phys. Rev. C **69**, 044612 (2004).
[16] R.J. Wooliscroft, N.M. Clarke, B.R. Fulton, R.L. Cowin, M. Dasgupta, D.J. Hinde, C.R. Morton, and A.C. Berriman, Phys. Rev. C **68**, 014611 (2003).
[17] T. Matsumoto, E. Hiyama, M. Yahiro, K. Ogata, Y. Iseri, and M. Kamimura, Nucl. Phys. **A738**, 471 (2004).
[18] N. Keeley, K.W. Kemper, and K. Rusek, Phys. Rev. C **64**, 031602(R) (2001).
[19] K. Arai, Y. Ogawa, Y. Suzuki, and K. Varga, Phys. Rev. C **54**, 132 (1996).
[20] G. Goldring, M. Samuel, B.A. Watson, M.C. Bertin, and S.L. Tabor, Phys. Lett. **32B**, 465 (1970).
[21] I.J. Thompson, Comput. Phys. Rep. **7**, 167 (1988).
[22] D.G. Kovar, N. Stein, and C.K. Bockelman, Nucl. Phys. **A231**, 266 (1974).
[23] R. D. Woods and D.S. Saxon, Phys. Rev. **95**, 577 (1954).
[24] S. Cohen and D. Kurath, Nucl. Phys. **101**, 1 (1967).
[25] K. Rusek, C.O. Blyth, N.M. Clarke, P.R. Dee, B.R. Fulton, J.A.R. Griffith, S.J. Hall, N. Keeley, I. Martel-Bravo, G. Tungate, N.J. Davis, K.A. Connell, J.S. Lilley, M.W. Bailey, J. Gómez-Camacho, Nucl. Phys. **A575**, 412 (1994).
[26] D.P. Stahel, G.J. Wozniak, M.S. Zisman, B.D. Jeltema, and J. Cerny, Phys. Rev. C **16**, 1456 (1977).
[27] J. Lang, R. Müller, J. Unternährer, L. Jarczyk, B. Kamys, and A. Strzałkowski, Phys. Rev. C **16**, 1448 (1977).
[28] I.J. Thompson, M.A. Nagarajan, J.S. Lilley, and M.J. Smithson, Nucl. Phys. **A505** (1989) 84.
[29] G.R. Satchler, Phys. Rep. **199**, 147 (1991).
[30] B.R. Fulton, in *Heavy Ion Collisions at Energies Near the Coulomb Barrier*, ed. M.A. Nagarajan, Inst. Phys. Conf. Ser. 110 (IOP, Bristol, 1990).
[31] A.M.M. Maciel, P.R.S. Gomes, J. Lubian, R.M. Anjos, R.

Cabezas, G.M. Santos, C. Muri, S.B. Moraes, R. Liguori Neto, N. Added, N. Carlin Filho, and C. Tenreiro, Phys. Rev. C **59**, 2103 (1999).

[32] M.A. Tiede, D.E. Trcka, and K.W. Kemper, Phys. Rev. C **44**, 1698 (1991).

[33] A. Pakou, N. Alamanos, G. Doukelis, A. Gillibert, G. Kalyva, M. Kokkoris, S. Kossionides, A. Lagoyannis, A. Musumarra, C. Papachristodoulou, N. Patronis, G. Perdikakis, D. Pierroutsakou, E.C. Pollacco, and K. Rusek, Phys. Rev. C **69**, 054602 (2004).

[34] C. Signorini, A. Andrighetto, M. Ruan, J.Y. Guo, L. Stroe, F. Soramel, K.E.G. Löbner, L. Müller, D. Pierroutsakou, M. Romoli, K. Rudolph, I.J. Thompson, M. Trotta, A. Vitturi, R. Gernhäuser, and A. Kastenmüller, Phys. Rev. C **61**, 061603(R) (2000).

[35] S.B. Moraes, P.R.S. Gomes, J. Lubian, J.J.S. Alves, R.M. Anjos, M.M. Sant'Anna, I. Padron, C. Muri, R. Ligouri Neto, and N. Added, Phys. Rev. C **61**, 064608 (2000).

[36] N. Keeley, K.W. Kemper, and K. Rusek, Phys. Rev. C **66**, 044605 (2002).