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THE THRESHOLD ANOMALY FOR HEAVY-ION SCATTERING*

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THE THRESHOLD ANOMALY FOR HEAVY-ION SCATTERING*

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ABSTRACT

The real parts of optical potentials deduced from heavy-ion scattering measurements become rapidly more attractive as the bombarding energy is reduced close to the top of the Coulomb barrier. This behavior is explained as a coupled-channels effect, and is related to the corresponding reduction in the absorptive potential through a dispersion relation which expresses the consequences of causality. Another manifestation of this "anomaly" is the striking enhancement observed for the near- and sub-barrier fusion of two heavy ions. The barrier penetration model of fusion is examined critically in this context. It is also stressed that similar anomalies could appear in the energy dependence of nonelastic scattering.

1. The Threshold Anomaly

The term "threshold anomaly" refers to the rapid, localized variation of the optical potential $U(E) = V(E) + iW(E)$ with energy E at low energies in the vicinity of the top of the Coulomb barrier. This was first noted for heavy ions by Baeza et al.[1] from analyses of the scattering of $^{32}S + ^{40}Ca$, although the corresponding behavior for nucleon scattering had been known for some time[2]. The anomaly was first mapped out[3] for $^{16}O + ^{208}Pb$, as shown in fig. 1, and then[4] for $^{16}O + ^{60}Ni$. Indications of similar behavior have now been seen for ^{32}S scattering from several targets[1,5,6], as well as in α-particle scattering[7]. However, there is still a need for a more precise and

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definitive mapping to test various aspects of the theory. It is not easy to obtain this information from elastic scattering because, of course, it tends toward Rutherford scattering as the energy drops below the barrier and optical model analyses become more and more ambiguous in this energy region.

The main features of the anomaly are that the strength of the imaginary potential, in the surface region to which the elastic scattering is sensitive, increases rapidly as the energy rises above the Coulomb barrier and then saturates at a more-or-less constant value, while at the same time the real, attractive potential in the same region decreases rapidly and then remains more-or-less constant. The behavior of the absorptive potential W(E) is easy to understand because the Coulomb barrier effectively closes the nonelastic channels at the lower energies, but increasing the energy above the barrier allows absorption to take place. Hence the word "threshold". The term "anomaly" applies to the real potential V(E), whose behavior was unexpected.

The above explanation for W(E) implies that it is a coupled-channels (CC) effect, and this has been confirmed[9,10] by explicit and extensive CC calculations for $^{16}O + ^{208}Pb$. These reproduced the V(E) behavior also. Such CC calculations are complicated. Roughly speaking, the coupling to other channels happens suddenly at high energies and mainly results in absorption from the elastic channel, whereas at energies near and below the barrier the processes are more adiabatic and give rise to a large "polarization potential" which is real.

Such CC calculations are complicated and specific to each system. A more general, but more implicit, approach includes all the CC dispersive effects "exactly" by using a dispersion relation[7,11] between V(E) and W(E). This ensures that, if the absorption varies in the way just described, there will be a corresponding anomaly in the real potential. Thus it should be a universal phenomenon.

2. The Dispersion Relation (DR)

Although dispersion relations have a long history[12], Feshbach[13] seems to have been the first to point out their application to relate the real and imaginary parts of the optical potential as derived from the analytic properties of the propagators that appear in his reaction theory. Later, this relation was derived[14] in a time-dependent framework as a consequence of causality: a scattered wave cannot be emitted before the arrival of the incident wave. The two derivations are equivalent.

If the real potential is written $V(E) = V_o + \Delta V(E)$, where V_o is independent of E (but may be nonlocal) and ΔV has been called a dynamical polarization potential, then the dispersion relation (DR) is

$$\Delta V(E) = \frac{P}{\pi} \int_{-\infty}^{\infty} \frac{W(E')}{E'-E} \, dE', \tag{1}$$

where P denotes principal value. We see immediately that if U is complex ($W \neq 0$), then V <u>must</u> depend upon E. Further, any localized rapid increase in $|W(E)|$ (where $W < 0$), such as we have postulated near the Coulomb barrier, <u>must</u> be accompanied by a similarly localized attractive contribution to ΔV in that same energy region. Since the absorption described by W(E) arises from couplings to nonelastic channels, we see that $\Delta V(E)$ arises from the same source.

Now V_o and W, hence ΔV, are generally nonlocal[13], but in practice model potentials are taken to be local equivalents to these. Consequently, such models will include some "spurious" energy dependence that arises from modeling the nonlocality (momentum dependence) of the more fundamental potentials. Such a spurious E-dependence should not be included in the DR integral (1). This distinction is made routinely in discussions of nucleon potentials[2], but for heavier ions it is usually assumed that the nonlocality correction is small and can be ignored (but see[7] for some discussion).

The DR (1) is obeyed by the potential at each radial point r. It will also be obeyed by any radial moment, such as the volume integral, which may be better determined by the scattering data[7,15].

A simple analytic expression can be given[7] for $\Delta V(E)$ when $W(E)$ is represented by straight-line segments; such a fit is shown in fig. 1, and it reproduces the anomaly in both shape and magnitude. More realistic smooth functions for $W(E)$ do not produce[7] large changes in $\Delta V(E)$. An important feature is that $|\Delta V(E)|$ begins to decrease again as the energy is lowered further; there is some indication of this behavior from the analyses of the data for $^{16}O + {}^{60}Ni, {}^{208}Pb$.

3. Heavy-Ion Fusion

The enhancement of heavy-ion fusion cross sections (over what is expected from simple penetration of a constant, energy-independent Coulomb barrier) at near- and sub-barrier energies has also been explained in terms of CC effects[16]. Clearly this fusion "anomaly" could be removed by making the ion-ion potential more attractive at the lower energies, thus lowering the barrier and easing fusion. Hence we are led to ask whether the anomaly in the optical potential just discussed provides an alternative explanation of the fusion enhancement. The answer appears to be yes[17], although it remains to be seen whether it is a <u>useful</u> alternative.

The total absorption (reaction) cross section for the optical potential $U(E)$ is given by

$$\begin{aligned}\sigma_A(E) &= -\frac{2}{\hbar v}\langle \chi_E | W(E) | \chi_E \rangle, \\ &= -\frac{2}{\hbar v}\int | \chi_E(\underline{r}) |^2 W(r;E) d\underline{r},\end{aligned} \tag{2}$$

where $\chi_E(r)$ is the elastic scattering distorted wave;

$$[K + U(r;E) - E]\chi_E(\underline{r}) = 0 \tag{3}$$

if K is the kinetic energy operator. Now σ_A consists of fusion plus other, more peripheral, nonelastic processes,

$$\sigma_A(E) = \sigma_F(E) + \sigma_D(E). \tag{4}$$

("D" stands for "direct", but need not be taken too literally.)

Equation (2) suggests a similar decomposition of W, and indeed this can be done formally[17,18], so we have

$$W(E) = W_F(E) + W_D(E). \tag{5}$$

Then an <u>exact</u> expression for the fusion cross section is

$$\sigma_F(E) = -\frac{2}{\hbar v} \langle \chi_E \,|\, W_F(E) \,|\, \chi_E \rangle. \tag{6}$$

Clearly the threshold anomaly in U(E) affects $\sigma_F(E)$ through the distorted waves χ_E. Underlying most models of fusion is the idea that fusion occurs after penetration of a potential barrier; if this intuition is correct, the W_F that describes this process will be a short-ranged potential confined inside the barrier. Then the detailed shape and strength of W_F is of little concern, provided it leads to 100% absorption in the inner region. In this view, the entire energy dependence of $\sigma_F(E)$ occurs through the χ_E, and hence the U(E). (We remember that U(E) is the same potential that describes the elastic scattering.) Both the increased attraction and the reduced peripheral absorption in U(E) enhance $\sigma_F(E)$ in the barrier region, compared to what would be obtained if U were taken unchanged from, say, analysis of elastic scattering at higher energies. It turns out that the extra attraction is the dominant feature, and can increase σ_F by two orders of magnitude or more. The example shown in fig. 2 is one of the less striking cases, but it is one for which elastic scattering is available, as shown in fig. 1.

4. The Barrier Penetration Model (BPM)

The widely used BPM simply calculates the penetration through a real potential barrier, often in a semi-classical approximation[16]. This corresponds to the approximate expression

$$\sigma_F^{\,B}(E) = -\frac{2}{\hbar v} \langle \chi_E^{\,B} \,\big|\, W_F \,\big|\, \chi_E^{\,B} \rangle \tag{7}$$

where now

$$[K - V_B - i\, W_F - E]\chi_E^{\ B}(r) = 0 \tag{8}$$

and W_F is the short-ranged absorptive potential just discussed. Usually V_B is chosen to be energy independent and either some "typical" potential, such as the proximity one, or based upon elastic scattering at higher energies. Even if V_B is chosen to equal the true $V(E)$, $\sigma_F^{\ B}$ still differs from the exact σ_F because the $\chi_E^{\ B}$ differ from χ_E by the omission of the peripheral absorption W_D from eq. (8). However, model calculations[17] suggest that the W_D effect is very small compared to the large enhancement factors induced by using the proper $V(E)$ (only ~7% for the case in fig. 2 compared to factors of ~30; as much as 40% compared to a factor of 70 in another case). Although eqs. (3) and (6) are as easy to compute as eqs. (7) and (8), use of the former does require knowledge of $W_D(E)$ which may not be available. Hence the BPM with $V_B = V(E)$ can provide a very useful first approximation to σ_F.

Because of this, it is tempting to use the BPM to extract information on the behavior of $V(E)$ when elastic data are not available. Figure 3 shows an example where an optical potential was found by fitting elastic scattering at an energy well above the anomaly, and then its real part was simply renormalized so as to reproduce the fusion measurements[19] at lower energies. Later work[6] has done this for ^{32}S + Ni, and compared the results with elastic measurements at the lower energies; the results are encouraging.

5. Spin Distributions in Fusion

A more stringent test of models of fusion is provided by the partial-wave decomposition, or spin distribution,

$$\sigma_F(E) = \sum_L \sigma_F(L;E). \tag{9}$$

Some measurements on these are becoming available[16] and a general conclusion is that CC effects change the shape of the distribution and increase the average L. One implication for the optical model description (6) is that it is not sufficient to simply renormalize the

strength of the real potential in the vicinity of the anomaly, but its radial shape must also be changed[7,17]. That is, the $\Delta V(r;E)$ of (1) has a different radial shape from $V_o(r)$. This should not be surprising, since $W(r;E)$ will generally have a different shape from $V_o(r)$. Some model calculations[17] suggest that CC effects make $V(r;E)$ more steep for radii in the vicinity of the top of the Coulomb barrier. It will be difficult to obtain confirmation of this from elastic scattering measurements.

This conclusion also reminds us that it may not be sufficient to represent the nonlocality of ΔV by an energy-dependent local potential, but some L dependence of ΔV may also be required. Clearly this can affect the spin distributions.

6. Anomalies in Nonelastic Scattering

Nonelastic scattering may be treated as a coupled-channels problem where the one-channel optical potential is replaced by a potential matrix $U_{\beta\alpha}(E)$. Arguments parallel to those that led to eq. (1) show[20] that each element of this matrix satisfies a corresponding DR, where now the imaginary parts $W_{\beta\alpha}(E)$ account for the loss of flux out of the explicitly coupled set of channels into all other open nonelastic channels. Since the effective number of the latter that contribute will also increase with energy at the low energies, we may anticipate a threshold anomaly (perhaps reduced in magnitude) for the real parts of the off-diagonal coupling potentials which parallels that for the diagonal optical potential. There is some evidence for this from both inelastic[5,21] and transfer[8] measurements, but the effect is much less well established than in the case of elastic scattering. Important for inelastic scattering is the interference between Coulomb and hadronic interactions[21] which provides a sensitive probe of any energy dependence in the hadronic coupling. Figure 4 shows an example[21] of an excitation function with various choices for the hadronic part of the interaction.

7. Final Remarks

We have reviewed the existence of an "anomaly" in the optical potentials for heavy-ion scattering at energies in the vicinity of the top of the Coulomb barrier, and its use as an alternative description of the near- and sub-barrier fusion anomaly. Studies of the existence and properties of similar behavior in the energy dependence of non-elastic couplings are only just beginning. One open question is the relative importance of inelastic scattering and transfer reactions as a source of these "anomalies".

It is difficult to obtain complete and detailed information from one type of measurement at these energies. It seems that a complete picture will emerge only from a coherent study of a number of processes, such as elastic and inelastic scattering, transfer reactions and fusion (including the spin distributions).

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Figure Captions

Fig. 1. Values of the optical potental for $^{16}O + ^{208}Pb$ at r = 12.4 fm, as a function of bombarding energy, obtained from a systematic reanalysis of many sets of elastic scattering data[3] (full circles), as well as reaction cross section measurements (open circles) at energies near the Coulomb barrier[8].

Fig. 2. Fusion cross sections for $^{16}O + ^{208}Pb$. The dashed curve is predicted using the BPM and a fixed real potential, while the solid curve uses this potential with an energy-dependent renormalization that follows fig. 1.

Fig. 3. Renormalization of real potential that fits elastic scattering at 74 MeV needed in order to reproduce fusion cross sections measured at lower energies.

Fig. 4. Excitation functions for 3^- state of ^{208}Pb: comparison of measurements with predictions for several assumptions[21] about the energy dependence of the hadronic coupling.

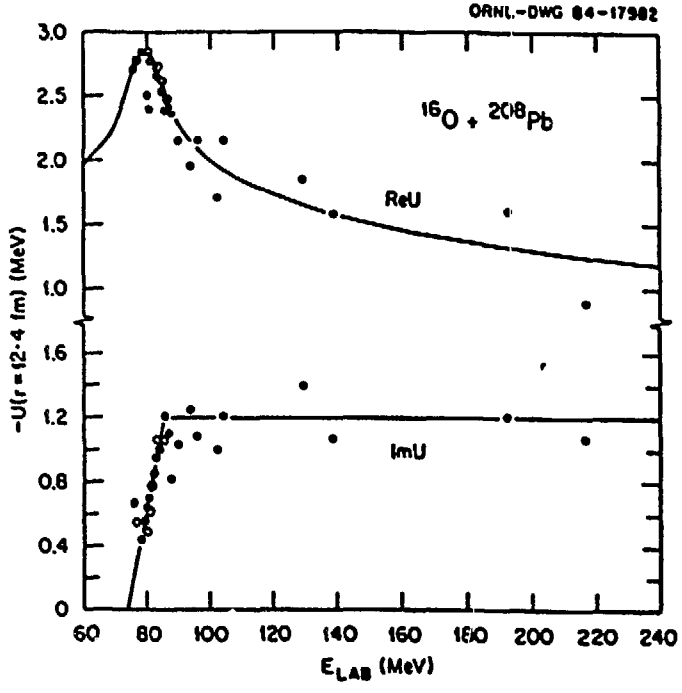
ORNL-DWG 84-17982
$^{16}O + ^{208}Pb$
ReU
ImU
-U(r = 12·4 fm) (MeV)
E_{LAB} (MeV)

Fig. 1

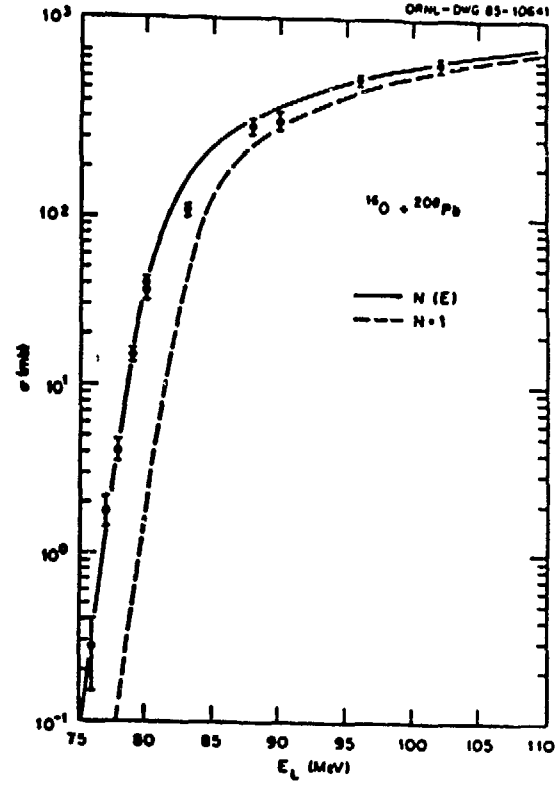
ORNL-DWG 83-10641
$^{16}O + ^{208}Pb$
N (E)
N+1
σ (mb)
E_L (MeV)

Fig. 2

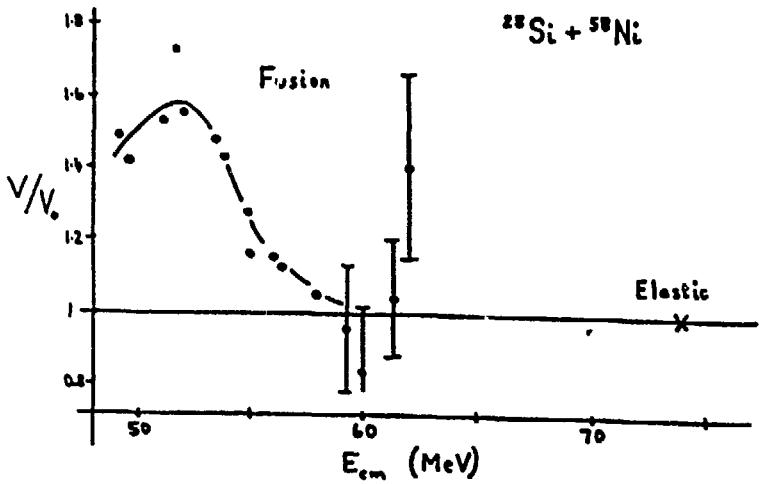
$^{28}Si + ^{58}Ni$
Fusion
Elastic
V/V₀
1.8
1.6
1.4
1.2
1
0.8
50
60
70
E_{cm} (MeV)

Fig. 3

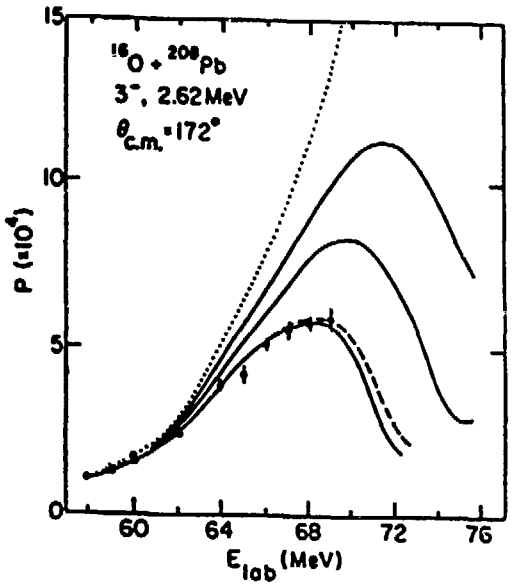
$^{16}O + ^{208}Pb$
3^-, 2.62 MeV
$\theta_{c.m.} = 172°$
P (×10⁴)
15
10
5
0
60
64
68
72
76
E_{lab} (MeV)

Fig. 4