A Study of Semi-Classical Processes in the Elastic Scattering of $^{32}$S by $^{64}$Ni and $^{58}$Ni by $^{27}$Al

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Abstract. In order to determine the extent of the presence of semi-classical phenomena such as Fresnel and Fraunhofer patterns etc., we have analyzed the elastic scattering of $^{32}$S by $^{64}$Ni and $^{58}$Ni by $^{27}$Al using the McIntyre parametrization at several energies. The theoretical approach can reasonably account for the general pattern of the data, thus allowing us to extract the parameters pertinent to these semi-classical processes. The scattering of $^{58}$Ni by $^{27}$Al at 220, 185, 170, 160 and 155 MeV laboratory energies, exhibits features expected from the strong absorption model (SAM). However, the features of the scattering of $^{32}$S by $^{64}$Ni at 150, 108, 98, 93, 91, 88 and 82 MeV laboratory energies have significant deviation from the expected pattern of SAM.

Keywords: low and intermediate energy heavy-ion reactions, elastic and quasielastic scattering

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1. Introduction

The elastic scattering of $^{32}$S by $^{64}$Ni and $^{58}$Ni by $^{27}$Al at several incident energies above the Coulomb barrier have been measured and analyzed by optical model in [1] and [2], respectively, and they have also been analyzed using complex molecular potential [3]. At these energies, the angular distributions may manifest such classical features as rainbow scattering, Fresnel diffraction and Fraunhofer oscillation etc., and it is interesting to analyze the data within the context of a semi-classical theory, which allows us to extract the characteristic features associated with these physical phenomena. The McIntyre parametrization [4,5] of the data is a very useful tool for this purpose. It has already been applied to analyze heavy-ion scattering and to provide guidance to phase shift analysis of angular distributions [6,7,10]. This parametrization has also been useful in analyzing several transfer reactions [7–9] within the context of the Austern and Blair model [11].

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Frahn and Venter have introduced a detailed understanding of the relation between the semi-classical features of the scattering cross-section and the properties of the S-matrix by means of an analytic treatment [12,13]. In this treatment the sum in the partial wave expansion is written in the form of an integral over a continuous angular momentum variable. The \( l \)-dependence of the S-matrix is expressed in the form of a generalized continuous function, which has the strong absorptive profile characteristic of heavy-ion elastic scattering. This strong absorption model (SAM) of Frahn and Venter, which has its roots in the earlier work of Blair [14,15], manifests itself in a closed analytical expression for the elastic scattering cross-section which explains the mechanism and criteria for the diffractive aspects of elastic scattering, as well as the refractive effects of the Coulomb and nuclear fields. Although the numerical model of McIntyre parametrization is used in this work, SAM will be used as a physical guide to it. In particular, the initial choice of the S-matrix parameters and the understanding of the physical relationships between these parameters and of the qualitative features of observed elastic scatterings would be guided by the prescriptions of SAM model.

The theory behind the McIntyre parametrization is presented in the next section. It has the roots in the earlier work of Ford and Wheeler [16]. It has been applied to the elastic scattering of \(^{58}\text{Ni}\) by \(^{27}\text{Al}\) at incident laboratory energies of 220, 185, 170, 160 and 155 MeV and of \(^{32}\text{S}\) by \(^{64}\text{Ni}\) at incident laboratory energies of 150, 108, 98, 93, 91, 88 and 82 MeV. The application and discussion are presented in Section 3. Conclusion has been drawn in Section 4.

2. Theory

The differential elastic scattering cross-section is the absolute square of the scattering amplitude, \( f(\theta) \), where \( \theta \) is the scattering angle in the center-of-mass (c.m.) system. \( f(\theta) \) can be expressed in terms of the Coulomb scattering amplitude \( f_c(\theta) \), S-matrix \( (S_{l,N}) \) of the scattering by the nuclear potential for a partial wave \( l \), wave number \( k \) and a Coulomb phase shift \( \sigma_l \) as follows [6,10]:

\[
f(\theta) = f_c(\theta) + \frac{1}{2ik} \sum_{l=0}^{\infty} (2l + 1) \exp(2i\sigma_l)(S_{l,N} - 1) P_l(\cos \theta), \tag{1}
\]

where

\[
f_c(\theta) = \frac{1}{2ik} \sum_{l=0}^{\infty} (2l + 1)[\exp(2i\sigma_l) - 1] P_l(\cos \theta). \tag{2}
\]

The complex \( S_{l,N} \) can be expressed in terms of real quantities \( \eta_l \) and \( \delta_{l,N} \) as follows:

\[
S_{l,N} = \eta_l \exp(2i\delta_{l,N}), \tag{3}
\]

where \( \eta_l \) plays the role of reflection coefficient and \( \delta_{l,N} \) is the nuclear phase shift [10]. The Coulomb phase shifts are given by the exact solution of the Rutherford
scattering problem:

\[ \sigma_l = \text{arg } \Gamma(l + 1 + in), \]  

(4)

where \( n \) is the Sommerfeld parameter, defined as:

\[ n = (0.1575)Z_PZ_T\sqrt{\frac{M \text{ (MeV)}}{E_{\text{c.m.}} \text{ (MeV)}}}, \]  

(5)

\( Z_P \) and \( Z_T \) are the nuclear charges of the incident and target ions, respectively. \( M \) is the reduced mass of the system and \( E_{\text{c.m.}} \) is the energy in the c.m. system.

The McIntyre parametrization [4, 5, 10] uses special functional forms for \( \eta_l \) and \( \delta_{L,N} \) as defined in Eqs. (4) and (5) of Ref. [10]. In these equations the five parameters \( l_g, \Delta, l'_g, \Delta' \) and \( \mu \) are involved. In the McIntyre numerical model three parameters may be used if the assumption is made that \( l_g = l'_g \) and \( \Delta = \Delta' \) [6, 8–10]. In the WKB approximation, the deflection function is given by the formula [6]:

\[ \Theta_l = \Theta_R + \Theta_{\text{Nucl}}. \]  

(6)

where \( \Theta_R(= 2\delta \sigma_l/\partial l) \) is the contribution to the deflection function from Coulomb scattering. The nuclear deflection function \( \Theta_{\text{Nucl}}(= 2\delta \delta_{L,N}/\partial l) \) can be calculated from Eq. (7) of Ref. [10] and is given by:

\[ \Theta_{\text{Nucl}} = -\frac{2\mu}{\Delta'} \frac{\exp\left(\frac{l - l'_g}{\Delta'}\right)}{1 + \exp\left(\frac{l - l'_g}{\Delta'}\right)^2}. \]  

(7)

For positive \( \mu \), the deflection function \( \Theta_{\text{Nucl}} \) is always negative because the exponential in (7) cannot be negative. However, at the rainbow scattering the derivative of the deflection function in (6) with respect to \( l \) must be zero. The above-mentioned features of heavy-ion collisions result in characteristic qualitative features, which are observed in measured angular distributions of elastic scattering. The observed angular distributions are mainly determined by the interplay between the (quantal) diffractive effects of strong absorption and the (semi-classical) refractive effects produced by the repulsive long range Coulomb field and the attractive, short range nuclear field.

3. Results and Discussion

In this section we present the analysis of the data of Refs. [1] and [2] within the context of the above model.

3.1. The scattering of \(^{58}\text{Ni} \) by \(^{27}\text{Al} \)

The elastic angular distribution for \(^{58}\text{Ni} \) by \(^{27}\text{Al} \) measured at five energies \( E_{\text{lab}} = 220, 185, 170, 160 \) and 155 MeV by Brandon et al. [1] has been studied using the
above-mentioned McIntyre parametrization. A Fortran code [8–10] is used to fit the experimental data at different energies. The first step towards the validation of the model is to be able to fit the data. In Fig. 1 we present the fits to the 220, 185, 170, 160 and 155 MeV data using 3 parameters. The fit to the 220 and 185 MeV data using 5 parameters is also shown. The parameters are listed in Table 1. The quality of the fits using both 3 and 5 parameters are reasonable and about the same. Since the use of 5 parameters does not improve the fits significantly compared to the results obtained with 3 parameters, we have analyzed the data at 170, 160 and 155 MeV with only 3 parameters. In the five-parameter model, the phase shift radius \( r_0 \) is smaller than the radius \( r_0 \) in both cases. This consequently leads to a value of \( l_0 \) less than that of \( l_0 \). The values of the parameters \( r_0 \), \( d \) and \( \mu \) are not very much different from those in the three-parameter model at incident energies of \( E_{\text{lab}} = 220 \) and 185 MeV. The minimum of the deflection angle located at very small values \( (l < l_0) \), where the S-matrix elements are very small. This is shown in Fig. 2, for the five-parameter case. This indicates that the refractive phenomenon

![Graph](image-url)

**Fig. 1.** Calculated angular distributions for the three-parameter model (solid curve) are compared to corresponding data for elastic scattering differential cross-sections expressed in terms of Rutherford cross-sections [1] for \( ^{58}\text{Ni} + ^{27}\text{Al} \) at \( E_{\text{lab}} \): 220, 185, 170, 160 and 155 MeV. Calculated angular distributions for the five-parameter model (dashed curve) at \( E_{\text{lab}} = 220 \) and 185 MeV are also presented.
Table 1. Elastic scattering parameters of $^{58}\text{Ni} + ^{27}\text{Al}$ at different laboratory energies

<table>
<thead>
<tr>
<th>$E_{\text{lab}}$ (MeV)</th>
<th>$r_0$ (fm)</th>
<th>$d$ (fm)</th>
<th>$\mu$ (rad.)</th>
<th>$r_o'$ (fm)</th>
<th>$d_o'$ (fm)</th>
<th>$l_o$</th>
<th>$\Delta$</th>
<th>$l_o'$</th>
<th>$\Delta'$</th>
<th>$\theta_\text{C}$ (rad.)</th>
<th>$\theta_\text{Nucl}$ (rad.)</th>
<th>$n$</th>
<th>$\chi^2$</th>
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<td>0.15</td>
<td>4.85</td>
<td>–</td>
<td>–</td>
<td>38</td>
<td>1.48</td>
<td>–</td>
<td>–</td>
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<td>–1.64</td>
<td>29.52</td>
<td>0.03</td>
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<tr>
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<td>0.11</td>
<td>4.51</td>
<td>1.12</td>
<td>0.013</td>
<td>39</td>
<td>1.02</td>
<td>8</td>
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<td>1.30</td>
<td>–6.24</td>
<td>29.52</td>
<td>0.04</td>
</tr>
<tr>
<td>185</td>
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<td>0.02</td>
<td>0.60</td>
<td>–</td>
<td>–</td>
<td>28</td>
<td>0.24</td>
<td>–</td>
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<td>1.71</td>
<td>–1.23</td>
<td>32.23</td>
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<td>0.01</td>
<td>0.55</td>
<td>1.48</td>
<td>0.200</td>
<td>28</td>
<td>0.11</td>
<td>24</td>
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<td>–0.12</td>
<td>32.23</td>
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<td>170</td>
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<td>1.00</td>
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<td>–</td>
<td>15</td>
<td>7.89</td>
<td>–</td>
<td>–</td>
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<tr>
<td>160</td>
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<td>0.21</td>
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<td>–</td>
<td>–</td>
<td>6</td>
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<tr>
<td>155</td>
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<td>–</td>
<td>7</td>
<td>3.86</td>
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<td>–</td>
<td>2.75</td>
<td>–0.010</td>
<td>35.23</td>
<td>0.046</td>
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</table>

is not important because $l_o'$ is much less than $l_o$ and $\eta$ is too small. The set of parameters for each energy is chosen using the best $\chi^2$ value. The values of $\chi^2$ listed in Table 1 are comparable to those of [1]. However, for the five parameters case, the minimum of nuclear angles changes from $-6.24$ to $-0.117$ radians resulting in a shift of rainbow angles from $-3.629$ to $1.74$ radians as the energy is decreased from $E_{\text{lab}} = 220$ to $185$ MeV. This indicates that the Coulomb effect starts to become dominant at energies lower than $220$ MeV.

Fig. 2. The modulus $\eta$ of the S-matrix (upper part) and Coulomb, nuclear and total (Coulomb + nuclear) deflection angles (lower part), as obtained from the semi-classical relations that are described in the text, are plotted against the orbital angular momentum for the elastic scattering $^{58}\text{Ni} + ^{27}\text{Al}$ at $E_{\text{lab}} = 220$ MeV by using the five parameters in Table 1.
Both the calculations and data indicate very little oscillations in the illuminated as well as in the shadow region. However, some structures start to appear with the increase of energy. This is expected since the Coulomb parameter $n$ listed in Table 1 is very large compared to unity. This hinders the occurrence of Fraunhofer diffraction. The parameter $n$, however, diminishes with increasing energy and, as such, the Fraunhofer phenomenon starts to appear in the illuminated region at higher energies. Another measure of the degree of Fresnel scattering is to calculate the pattern parameter given by

$$p = \frac{2n}{1 + (n/l_g)^2}.$$  

The value of $p$ is $36.8$, $27.7$, $11.16$, $2.0$ and $2.67$ for incident laboratory energies of $220$, $185$, $170$, $160$ and $155$ MeV, respectively. A value of $p > 1$ usually signifies Fresnel scattering. Thus, Fresnel scattering dominates this elastic scattering at different energies.

The rainbow deflection angles are $-0.32$, $0.48$, $2.24$, $2.92$ and $2.74$ radians for energies of $220$, $185$, $170$, $160$ and $155$ MeV, respectively, when 3 parameters are used. When 5 parameters are used the rainbow angles are $-4.94$ and $1.76$ radians for energies of $220$ and $185$ MeV, respectively. This again implies the dominance of Fresnel-type regime in these reactions. However, some small Fraunhofer oscillations damped by Coulomb effect appear at the shadow region for energy of $220$ MeV, where the value of $n$ is very large compared to the values at other energies. The calculated values of $\Delta R = (r_0 - 1.1)(58)^{1/3} + (27)^{1/3}$ are $3.3$, $2.95$, $2.75$, $2.95$ and $2.4$ fm for energies $155$, $160$, $170$, $185$ and $220$ MeV, respectively, i.e. it approximately decreases with increasing energy, as expected from SAM. This decrease in $\Delta R$ or $r_0$ results in pushing the highest peak in the oscillatory structure towards backward angles. According to SAM when $n \ll kR$, the ratio of diffusivity parameter $d$ to interaction radius $R$, provides the measure of Coulomb damping of Fraunhofer oscillations in the shadow region, where $\theta > \theta_R$. At all energies the ratio of elastic to the Rutherford scattering, $\sigma_{\text{elast}}/\sigma_{\text{Ruth}}$, at angles $\theta > \theta_R$ falls off nearly exponentially which is an indication of strong Coulomb damping of Fraunhofer oscillations. In this region, the scattering is dominated by Fresnel diffraction.

Measured as well as calculated cross-sections exhibit no glory or orbiting effect. However, SAM usually damps the effect of these effects in the cross-section.

There are some interesting factors pointing towards the deviation from SAM. Our values of $\Delta$, $d$ and $\mu$ are at variance with the expected ones discussed in [12]. However, the normal diffraction behavior of the scattering process dominates at forward angles and can be described by the strong absorption model and this is shown in all figures at all energies.

3.2. The scattering of $^{32}S$ by $^{64}Ni$

The fits to the elastically scattered $^{32}S$ by $^{64}Ni$ [2] for $150$, $108$, $98$, $93$, $91$, $88$ and $82$ MeV incident laboratory energies are shown in Fig. 3. Except for the $150$ MeV
Fig. 3. The ratio of calculated elastic scattering angular distribution to Rutherford cross-section for $^{32}$S + $^{64}$Ni at $E_{\text{lab.}}$ = 150, 108, 98, 93, 91, 88 and 82 MeV using the three-parameter model (solid curve) is shown. The same at $E_{\text{lab.}}$ = 150 MeV using the five parameter model (dashed curve) is also shown. These results are compared to the corresponding available experimental data of [2], shown as symbols in all inserts.

In Fig. 4, a typical example of the dependence of $\eta$ and deflection angle on orbital angular momentum for the energy of 150 MeV is exhibited. Here, 5 parameters are used. The parameter $n$ is large and hence, one expects the dominance of Fresnel scattering in these cases. However, the calculated values of $p$ defined above are 35.0, 26.9, 18.1, 14.1, 10.1, 6.4 and 0.63 at incident energies of 150, 108, 98, 93, 91, 88 and 82 MeV, respectively, when 3 parameters are used. Thus, at 82 MeV, $p$ is less than one which implies lack of Fresnel scattering. Other features of these reactions, which are not characteristics of SAM, are that $r_0$ does not decrease with
Table 2. Elastic scattering parameters of $^{32}$S + $^{64}$Ni at different laboratory energies

<table>
<thead>
<tr>
<th>$E_{\text{lab.}}$ (MeV)</th>
<th>$r_\text{o}$ (fm)</th>
<th>$d$ (fm)</th>
<th>$\mu$ (rad)</th>
<th>$r'_\text{o}$ (fm)</th>
<th>$d'_\text{o}$ (fm)</th>
<th>$l_\text{p}$</th>
<th>$\Delta$</th>
<th>$l'_\text{p}$</th>
<th>$\Delta'$</th>
<th>$\theta_\text{b}$ (rad)</th>
<th>$\theta_{\text{total}}$ (rad)</th>
<th>$n$</th>
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<td>28</td>
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<td>-</td>
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<td>2.93</td>
<td>-0.009</td>
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</table>

the increase of energy in any significant way, and $l_\theta$ are very small for lower energies. However, the ratio, $\sigma_{\text{elast}}/\sigma_{\text{Ruth}}$, exhibits approximately exponential drops with angles, but there are oscillations present at higher energies in the shadow region. The Coulomb damping of Fraunhofer oscillations is, therefore, not complete. Although the data can be reasonably fitted with the McIntyre parametrization, the values and trends of these parameters point to the features not completely expected in SAM.

There are no structures in the cross-section that have a characteristic of glory or orbiting effect.

Fig. 4. The modulus $|\eta|$ of the S-matrix (upper part) and Coulomb, nuclear and total (Coulomb + nuclear) deflection angles (lower part), as obtained from the semi-classical relations that are described in the text, are plotted against the orbital angular momentum for the elastic scattering $^{32}$S + $^{64}$Ni at $E_{\text{lab.}} = 150$ MeV by using the five parameters in Table 2.
Our analysis indicates a possible existence of a threshold anomaly, which may point to the fact that the couplings to other non-elastic channels are important. The values of unrealistic combination of parameters (especially $d$ and $\mu$) obtained for energies near and below 93 MeV, as indicated in Table 2, are indicative that the system deviates from the expected pattern of SAM as the energy approaches the Coulomb barrier energy. Also at this range of energies it becomes very difficult to obtain outstanding fit with a better realistic set of parameters.

Tables 1 and 2 show that the values of $\mu$ and $\theta_{\text{Nucl.}}$ decrease with the decrease in incident energy. The analysis shows that higher values of $\mu$ are required for deeper minima of diffraction oscillations. However, an increased value of $\mu$ enhances the diffraction structure of the calculated angular distributions as evidenced by the deepening of the minima of the diffraction oscillations. Both the experimental and theoretical results show that the oscillations start to disappear as the incident energy decreases. An increase in the value of $d$ has the effect of increasing the slope of the envelope for the calculated Fraunhofer oscillations. The values of $r_0$ indicate the typical slow decrease with increasing energy. The decrease in the value of $r_0$ leads to push the highest peak in the oscillatory structure towards backward angles.

4. Conclusions

The elastic scattering data of $^{58}\text{Ni} + ^{27}\text{Al}$ and $^{32}\text{S} + ^{64}\text{Ni}$ systems can be parametrized in the McIntyre model at different laboratory energies. The quality of theoretical fits obtained by using three parameters is found fairly comparable to the optical model and the molecular potential fits obtained by other authors to the same data. In both cases, the scattering is predominantly of Fresnel type except at lower energy for the $^{32}\text{S} + ^{64}\text{Ni}$ system. The Coulomb damping of Fraunhofer oscillations is evident in the $^{58}\text{Ni} + ^{27}\text{Al}$ system but not that pronounced in the $^{32}\text{S} + ^{64}\text{Ni}$ system. At low energies, i.e. at energies slightly above the Coulomb barriers, the values of the parameters particularly for the $^{32}\text{S} + ^{64}\text{Ni}$ system, deviate from those expected from SAM. In particular, the behavior of the radius parameter for the $^{58}\text{Ni} + ^{27}\text{Al}$ system is consistent with that expected from the SAM but for the $^{32}\text{S} + ^{64}\text{Ni}$ system, it deviates from the pattern expected from the SAM.

Dedicated to the memory of George Marx

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