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ANALYSIS OF THE ELASTIC SCATTERING OF THE $^{12}C+^{28}Si$ SYSTEM USING THE SÃO PAULO POTENTIAL AND REGGE POLES

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ABSTRACT

The angular distributions of the $^{12}C+^{28}Si$ system have been measured at the Pelletron Laboratory of the Institute of Physics of the São Paulo University. The data were obtained at center of mass energies close and above the Coulomb barrier ($V_{CB}=14.3MeV$). The analysis of the angular distributions was performed using an Optical Potential, where the real and imaginary parts of the potential are described through the Non-local Interaction Model, called São Paulo Potential. A strong oscillatory behavior was observed in the angular distributions of the $^{12}C+^{28}Si$ system at energies above $E_{c.m}=16.1MeV$. To describe such oscillatory behavior Regge Poles were introduced in the *S*-matrix. In order to fit these data, a Monte Carlo C/C++ code, named "POLODSA", was developed. The energies above $E_{c.m.}=16.1MeV$ were fitted introducing two Regge Poles, one with $l=l_g$ and the other with $l=10$. One can observe that the $l=10$ resonance reproduces the main behavior of the angular distributions, however the fit becomes better adding small contributions due to grazing angular momentum. The clear presence of a resonance around $E_{c.m.}=19\text{-}20MeV$ is observed, which would correspond to an excited state with $J=10$ and $^{12}C+^{28}Si$ cluster structure in the ^{40}Ca at $E_{exc}\cong 33MeV$.

1. INTRODUCTION

The Non-local Interaction Model, called São Paulo Potential [1,2], has been used to study many systems. The angular distributions of the $^{12}C+^{24}Mg$ system [3] exhibit strong oscillations for the energies $E_{cm}=11\text{-}16MeV$ ($V_{CB}=12.56MeV$). The angular distributions of the $^{12}C+^{24}Mg$ system, were successfully analyzed using the São Paulo Potential and Regge poles[4,5] to describe the oscillatory behavior. In order to fit these data, a Monte Carlo *C/C++* code, named "POLODSA"[6], was developed. This code fits the angular distributions via the χ^2 minimization using the *Downhill Simplex Method* coupled with the *Annealing Process*. The basic idea of the simulated annealing method is also applicable to optimization problems with continuous *N*-dimensional control spaces, e.g., finding the (ideally, global) minimum of some function *f(x)*, in the presence of many local minima, where *x* is an *N*-dimensional vector.

All angular distributions of the $^{12}C+^{24}Mg$ system were fitted with an $l=6$ resonance. The energy independence of the l value indicates the existence of a resonance in the compound system ^{36}Ar. The purpose of this work is to study the $^{12}C+^{28}Si$ system in the same context.

2. EXPERIMENTAL METHOD AND RESULTS

The measurements were performed at the Pelletron Laboratory of the University of São Paulo, using a ^{28}Si beam and a ^{12}C target. The data were obtained at center of mass energies close and above the Coulomb barrier ($V_{CB}=14.3MeV$), namely $E_{c.m.}$= *12.4, 13.3, 14.0, 14.7, 16.1, 16.8, 17.5, 18.9, 19.6, 20.3, 20.9* and *21.9MeV*. Three telescopes, consisting of proportional gas counters followed by ^{28}Si surface barrier detectors, allowed the detection and identification of the scattered particles. The simultaneous measurement of the ^{28}Si and the recoiling ^{12}C, permitted us to cover the angular range from $\theta_{cm}=27^o$ *to* 164^o.

The elastic angular distributions are shown in Fig. 1 and 2. A strong oscillatory behavior was observed in the angular distributions of $^{12}C+^{28}Si$ system at energies above $E_{c.m}=16.1MeV$.

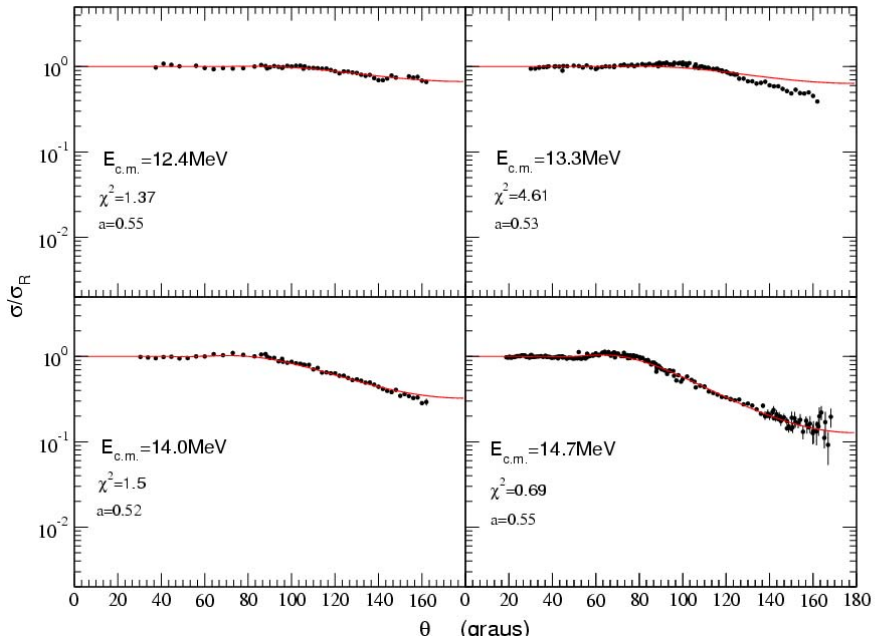

Figure 1. The $^{12}C+^{28}Si$ system elastic angular distributions, measured at the indicated energies, are represented by dots. The solid lines are optical model calculations using the São Paulo Potential without pole.

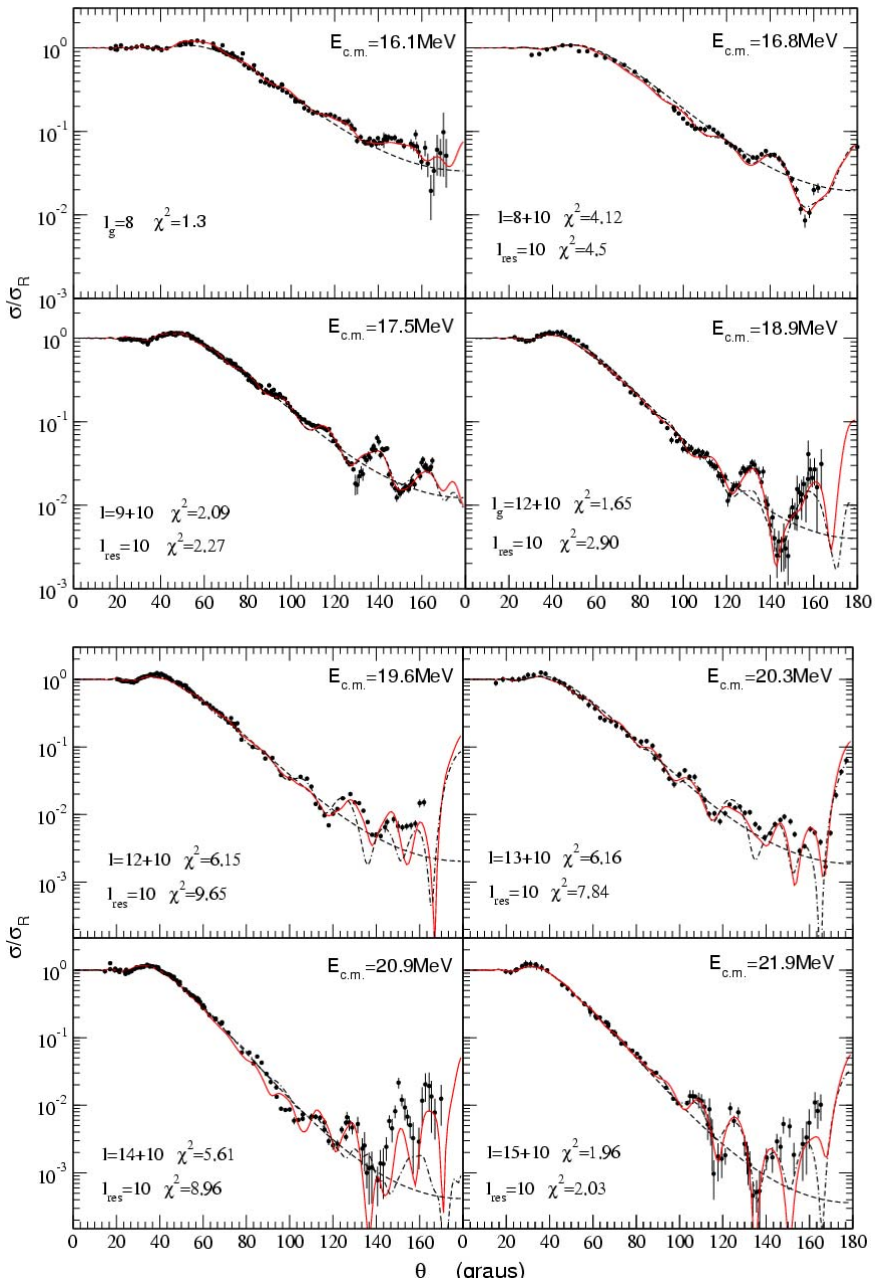

Figure 2. The $^{12}C+^{28}Si$ system elastic angular distributions, measured at the indicated energies, are represented by dots. The fits obtained using the São Paulo Potential (dashed line), introducing only one Regge Pole whith l=10 (dashed dotted line) and with two Regge Poles (solid line).

3. ANALYSIS

3.1. Theoretical Aspects – interaction

The elastic scattering for the $^{12}C+^{28}Si$ system was analyzed using the so-called São Paulo Potential [1,2], which has the following properties:

1. Takes into account the effects of the Pauli non-locality. The local-equivalent potential is energy dependent:

$$V(r,E) \approx V_{fold}(r) e^{-[4v^2/c^2]} \tag{1}$$

where: $V_{fold}(r)$ is the double-folding potential, c is the speed of light and v is the local relative velocity between the nuclei:

$$v^2 = \frac{2}{\mu} E_k = \frac{2}{\mu}[E - V_C - V_N], \tag{2}$$

where: E_k is the kinetic energy, V_C is the Coulomb potential and V_N is the nuclear potential.

2. The double-folding potential has the form:

$$V_{fold}(r) = \int d\vec{r}_p \int d\vec{r}_a \rho_p(\vec{r}_p)\rho_a(\vec{r}_a) \mathrm{v}(\vec{r}_{pa}) \tag{3}$$

where: ρ_p and ρ_a are the projectile and target nuclear densities, respectively; $\mathrm{v}(r_{pa})$ is the zero-range effective interaction, with V_O=*-456MeVfm*^{3}:

$$\mathrm{v}(\vec{r}_{pa}) = V_o \delta(\vec{r}_{pa}) \tag{4}$$

The nucleon coordinates r_p, r_a and r_{pa} are defined in Fig. 3.

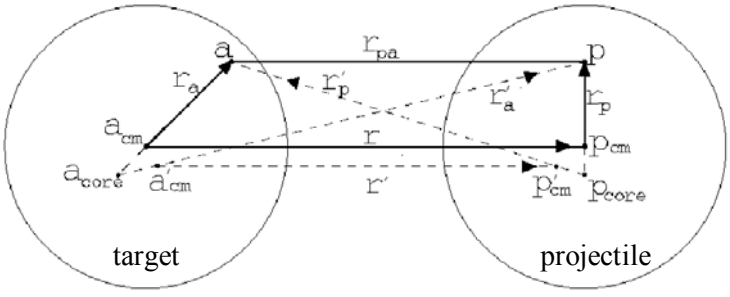

Figure 3. Non-local Folding Potential coordinate system. The dotted lines represent the exchange of nucleons between the target and the projectile.

3. The fermi distribution is assumed in the description of the nuclear densities:

$$\rho(r) = \frac{\rho_o}{1 + e^{(r-R_o)/a}} \tag{5}$$

where a is the diffuseness and the radius R_o is:

$$R_o = 1.31A^{1/3} - 0.84\,fm \tag{6}$$

The parameter ρ_o is obtained by the normalization condition:

$$4\pi \int_0^{+\infty} \rho(r) r^2 dr = A \tag{7}$$

4. The imaginary part of the potential is:

$$W(r,E) = N_i V(r,E) \tag{8}$$

where: $V(r,E)$ is the real potential and $N_i=0.78$ is the factor of normalization used for all energies. This value is the same for other heavy ions systems providing good results [1,2].

5. Regge poles [4,5] were introduced in the S-matrix form to describe the oscillatory behavior in the angular distributions:

$$S_l = S_l^o \left[1 + \frac{D(l) e^{2i\phi}}{(l - l_o) - i\Gamma(l)/2} \right] \tag{9}$$

where: S_l^o is the optical model S-matrix and, $D(l)$, ϕ, $\Gamma(l)$ are the amplitude, phase and width of a pole centered at l_o .

3.2. Results

The elastic angular distributions are shown in Fig.1 and 2. In order to fit these data, a Monte Carlo *C/C++* code, named "POLODSA" [5] was developed. For the energies $E_{c.m.}$= *12.4, 13.3, 14.0* and *14.7MeV* no oscillations were observed in the angular distributions, which could be fitted without the introduction of Regge poles, as shown in Fig. 1.

A strong oscillatory behavior was observed in the angular distributions of $^{12}C+^{28}Si$ system at energies above $E_{c.m}=16.1MeV$. To describe such oscillatory behavior Regge Poles were introduced in the S-matrix [3,4]. The Fig. 2 shows the fits obtained for the $^{12}C+^{28}Si$ system using the São Paulo Potential (dashed line), introducing only one Regge Pole with $l=10$ (dashed dotted line) and with two Regge Poles (solid line). In Fig. 4 we show the S -matrix elements for $l=10$ and for $l=l_g$ a function of energy, divided by S_l^0 which are the S -matrix elements without the Regge Poles. The clear presence of a resonance around $E_{c.m.}=19$-$20MeV$ is visible in this figure.

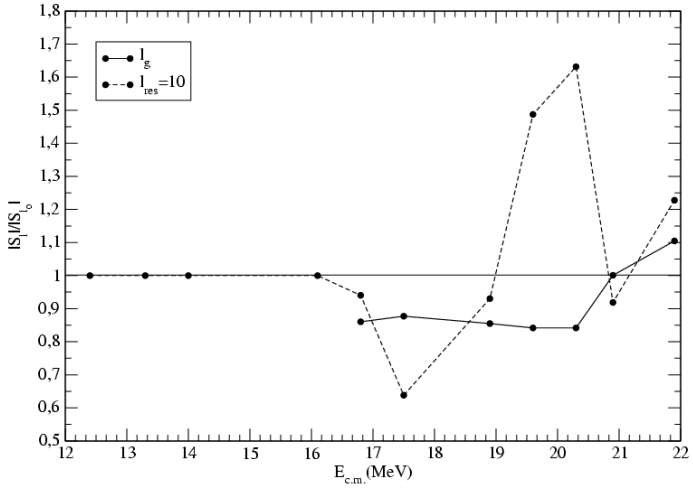

Figure 4. The *S*-matrix elements of the Regge Poles are shown as a function of energy. They are calculated as $|S_l|/|S_l^0|$, where: $|S_l|$ and S_l^0 are the *S*-matrix elements with and without Regge Poles respectively.

3. CONCLUSIONS

With the inclusion of Regge poles for the $^{12}C+^{28}Si$ system for energies between $E_{c.m.}=16.1$ and $21.9MeV$, the angular distributions are well reproduced. One can observe that the $l=10$ resonance reproduces the main behaviors of the angular distributions, however the fit becomes better adding small contributions due to grazing angular momentum. In Fig. 4 we show the *S*-matrix elements for $l=10$ and for $l=l_g$ a function of energy, divided by S_l^0 which are the *S*-matrix elements without the Regge Poles. The clear presence of a resonance around $E_{c.m.}=19$-$20MeV$ is visible in this figure, which would correspond to an excited state with $J=10$ a $^{12}C+^{28}Si$ cluster structure in the ^{40}Ca at $E_{exc}\cong 33MeV$. The l value obtained have a behavior very different from that observed in the $^{12}C+^{24}Mg$ system [6], where a constant l value was found between $E_{cm}=11$-$16MeV$. All angular distributions of $^{12}C+^{24}Mg$ system were fitted only with the $l \sim 6$ resonance. This energy independence indicates the existence of a resonance in the compound system ^{36}Ar. This result is very interesting, because we cannot interpret this state as a quasi-molecular resonance with $l \sim$ lg. The search for higher spin resonances is in progress for the $^{12}C+^{28}Si$ system.

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