UNIVERSIDADE DE SÃO PAULO

PUBLICAÇÕES

INSTITUTO DE FÍSICA
CAIXA POSTAL 20516
01498 - SÃO PAULO - SP
BRASIL

IFUSP/P-811



# COLOR VAN DER WAALS FORCE ACTING IN HEAVY-ION SCATTERING AT LOW ENERGIES

**M.S. Hussein, C.L. Lima and M.P. Pato**
Instituto de Física, Universidade de São Paulo

and

**C.A. Bertulani**
Instituto de Física, Universidade Federal do Rio de Janeiro
21945 Rio de Janeiro, RJ, Brasil

Novembro/1989

# COLOR VAN DER WAALS FORCE ACTING IN HEAVY-ION SCATTERING AT LOW ENERGIES*

*M.S. Hussein, C.L. Lima and M.P. Pato*
Instituto de Física da Universidade de São Paulo
Caixa Postal 20516 - 01498 São Paulo, SP - Brasil

and

*C.A. Bertulani*
Instituto de Física da Universidade Federal do Rio de Janeiro
21945 Rio de Janeiro, RJ - Brasil

ABSTRACT:

The influence of the color Van der Waals force in the elastic scattering of $^{208}$Pb on $^{208}$Pb at subbarrier energies is studied. The conspicuous changes in the Mott oscillation found here is suggested as a possible experimental test.

* Supported in part by the CNPq

NOVEMBER/1989



Several theoretical investigations have considered the possible existence of strong color Van der Waals forces between hadrons[1-6]. Just as the usual electromagnetic Van der Waals force between neutral atoms arises from two-photon exchange, the color VDW force comes about from two and multi-gluons exchange between color singlet hadrons. There are of course important differences between the QED-VDW force and the QCD-VDW one. Most notable of these differences are related to confinement, (in the MIT bag model this force does not exist) and the non-linear structure of the Yang-Mills gluon fields. It is important therefore to set experimental limits on these forces. Estimates of the strength of the color VDW force have been made. We summarize these in the following[4,5]

$$V^{C,6}_{VDW}(r) = -\alpha_6 \frac{\hbar c}{r_o}\left(\frac{r_o}{r}\right)^6 \qquad (1a)$$

$$V^{C,7}_{VDW}(r) = -\alpha_7 \frac{\hbar c}{r_o}\left(\frac{r_o}{r}\right)^7 \qquad (1b)$$

where $r_o \approx 1$fm. $\alpha_6 \cong 8$ and $\alpha_7 \cong 100$.

The phenomenological consequences of the existence of the color VDW interaction have been looked for in different systems and the results are not conclusive[4].

The purpose of the present paper is to suggest a physical system where the color VDW is enhanced and consequently its effect on the system can be less ambiguously studied. Specifically, owing to the fact that in the collision between two heavy nuclei the effective interaction is obtained by double folding hadronic densities with the effective nucleon-nucleon interaction, any color VDW force between the constituent hadrons, such as 1a or 1b, leads to a color nucleus-nucleus VDW force which at large separations goes as $A_1 A_2 \times$(1a) or (1b), where $A_i$ is the atomic number of nucleus i.

We therefore propose to look for the color VDW force in the low energy scattering of $^{208}Pb+^{208}Pb$. By low energy we mean low enough to avoid the action of the strong short-range nuclear interaction. At these energies, the Coulomb repulsion completely dominates the scattering and consequently the cross-section is structureless and almost entirely Rutherford. Small perturbations such as the color VDW force, have to be looked for in quantum interference effects which would arise from e.g. the identity of the projectile and the target. Thus our choice of $^{208}PB+^{208}Pb$. We proceed now to describe our calculation.

We first remind the reader that other small effects, besides the VDW interaction, have to be taken into account. These include QED vacuum polarization, $V_{VP}$ (Uehling potential[7]), nuclear dipole, and quadrupole polarizabilities, $V_D$ and $V_Q$, respectively[8-10], electron screening $V_{ES}$[11], and relativistic corrections, $V_R$, arising from using the Darwin Hamiltonian[10]. The sum of all these corrections and the VDW one is denoted by $\Delta V \equiv \sum_i V_i$. Thus the interaction potential felt by the two nuclei is

$$V_{A_1A_2}(r) = \frac{Z_1Z_2e^2}{r} + \Delta V(r) \tag{2}$$

The Coulomb barrier of Pb+Pb is about 600 MeV. We take for the CM energy 500 MeV as a representative case. At this energy the classical distance of closest approach is 25 fm, at which the short-range nuclear interaction is negligible. So we are fully justified in taking (2) for an interaction.

At 500 MeV, the Sommerfeld parameter $\eta = \frac{Z_1Z_2e^2}{\hbar v}$ is about 480 which is large enough to guarantee that a semiclassical description of the scattering is quite adequate[8-10]. with the aid of the stationary phase approximation, we obtain for the elastic scattering amplitude



$$f(\theta) = \frac{1}{k\sqrt{\sin\theta}}\sqrt{\frac{\lambda_i}{|\Theta'(\lambda_i)|}}\exp\left[2i\delta(\lambda_i) - i\lambda_i\theta\right] \tag{3}$$

$$\sqrt{\frac{d\sigma_{cl}}{d\Omega}}\exp\left[2i\delta(\lambda_i) - i\lambda_i\theta\right],$$

where $\frac{d\sigma_{cl}}{d\Omega} \equiv \frac{1}{k\sin\theta}\frac{\lambda_i}{|\Theta'(\lambda_i)|}$, is the classical cross-section, $\delta(\lambda_i)$ is the total phase shift, $\lambda_i = \ell_i + \frac{1}{2}$, with $\ell_i$ being the orbital angular momentum of the stationary phase defined by

$$2\frac{d}{d\lambda}\delta(\lambda)\Big]_{\lambda_i} \equiv \Theta(\lambda_i) = \theta,$$

and $\Theta$ is the classical deflection function. In Eq. (3) $\Theta' = \frac{d}{d\lambda}\Theta\Big]_{\lambda_i}$.

The phase $\delta(\lambda_i)$ is written as

$$\delta(\lambda_i) = \sigma(\lambda_i) + \Delta\delta \equiv \sigma(\lambda_i) + \sum_j \Delta\delta_j(\lambda_i) \tag{4}$$

where $\sigma$ is the Coulomb phase and $\Delta\delta_j(\lambda_i)$ is the change in the phase due to the perturbing potential $V_j$. The classical cross section, $\frac{d\sigma_{cl}}{d\Omega}$ can be calculated to first order in $\Delta\Theta \equiv 2\frac{d}{d\lambda}\Delta\delta$, as[8-10]

$$\frac{d\sigma_{cl}}{d\Omega} = \frac{d\sigma_{Ruth}}{d\Omega}\left[1 + \frac{1}{2}\Delta\theta\tan\frac{\theta}{2} + \frac{3}{2}\Delta\theta\cot\frac{\theta}{2} - \frac{d}{d\theta}\Delta\theta\right], \tag{6}$$

where $\frac{d\sigma_{Ruth}}{d\Omega} \equiv a^2/\left(4\sin^4\frac{\theta}{2}\right)$ is the Rutherford cross-section and

$a \equiv \frac{Z_1 Z_2 e^2}{2E_{CM}}$. With the above preliminaries, we can finally write the summetrized cross-section in the following form

$$\frac{d\sigma}{d\Omega} = |f(\theta) + f(\pi-\theta)|^2 = \frac{d\sigma_{cl}}{d\Omega}\left[\theta\right] + \frac{d\sigma_{cl}}{d\Omega}\left[\pi-\theta\right] + 2\sqrt{\frac{d\sigma_{cl}}{d\Omega}\left[\theta\right]\frac{d\sigma_{cl}}{d\Omega}\left[\pi-\theta\right]}$$

$$\times \cos\left[2\eta \ln\cot\frac{\theta}{2} + 2\left[\Delta\delta\left[\lambda_1(\theta)\right] - \Delta\delta\left[\lambda_1(\pi-\theta)\right]\right]\right] \quad (7)$$

In obtaining the phase in (7) the formula[12]

$$2\sigma(\lambda_1(\theta)) - 2\sigma(\lambda_1(\pi-\theta)) = 2\eta \ln\cot\frac{\theta}{2},$$

has been used (this formula is valid as long as $\eta^{-1} \ll 1$).

The numerical results presented below are obtained by calculating $\Delta\sigma$ using first order perturbation theory, which should be quite adequate considering the smallness of the perturbations involved. The quantity

$$\Delta \equiv \frac{\frac{d\sigma}{d\Omega} - \frac{d\sigma_{Mott}}{d\Omega}}{\frac{d\sigma}{d\Omega} + \frac{d\sigma_{Mott}}{d\Omega}}$$

is then evaluated with $\frac{d\sigma_{Mott}}{d\Omega}$ being the Mott cross-section. In figure 1 we summarize our results for $E_{CM}$ = 500 MeV which is slightly below the Coulomb barrier.

For $V^{C,6}_{VDW}(r)$, Eq. (1a), with $\alpha_6$ = 8.0, the effect is extremely small (Fig. 1a). However, when $V^{C,7}_{VDW}(r)$, Eq. (1b), is used with $\alpha_7$ = 100.0, the effect on the Mott cross-section is quite conspicuous, as can be seen in Fig. 1b. Notice that an angle precision of 0.0001 degrees is required in order to confirm our finding. Recently, Vetterli et al.[13] have studied QED vacuum polarization effects in $^{12}C+^{12}C$ at $E_{LAB}$ = 4 MeV with a precision which is slightly smaller than the one required in our test case.

In summary, we have studied in this paper the influence of the Color Van der Waals force on the low energy elastic scattering of identical heavy nuclei. With a precision in angle measurement of about $10^{-4}$ degrees one should be able to set an upper limit on the strength of the $r^{-7}$ CVDW force.



ACKNOWLEDGEMENTS:

M.S.H. would like to thank Kenneth Johnson and Arthur Kerman for useful discussions.

## REFERENCES:


1. T. Appelquist and W. Fischler
   Phys. Lett. 77B, 405 (1978).

2. G. Feinberg and J. Sucher
   Phys. Rev. 20D, 1717 (1979).

3. T. Sawada
   Phys. Lett. 100B, 50 (1981).

4. C.J. Batty
   Phys. Lett. 115B, 278 (1982).

5. G. Feinberg
   Comments Nucl. Part. Phys. 19, 51 (1989); a general formula which contains the two limits, Eqs. 1a at 1b, depending on the value of r, is given by $V^{C}_{VDW} = \frac{2\alpha_6}{\pi r^6} \tan^{-1} \frac{d}{r}$ with $d = \frac{23\alpha_D^A \alpha_D^B \hbar c}{16\pi\alpha_6}$ and $\alpha_D$ is the dipole polarizability. See H.B.G. Casimir and D. Polder, Phys. Rev. 73, 360 (1948).

6. S.J. Brodsky, I. Schmidt and G.F. Téramond
   SLAC - PUB - 5102 (1989).

7. E.A. Uehling
   Phys. Rev. 48, 55 (1935).

8. G. Baur, F. Rösel and D. Trautmann
   Nucl. Phys. A288, 113 (1977).

9. M.S. Hussein, V.L.M. Franzin, R. Franzin and A.J. Baltz
   Phys. Rev. 30C, 184 (1984).

10. M.S. Hussein, A.J. Baltz and B.V. Carlson
    Phys. Rep. 113, 133 (1984).

11. K. Alder and A. Winther
    Electromagnetic Excitations (North-Holland, Amsterdam, 1975).

12. M. Abramowitz and I.A. Stegun
    Handbook of Mathematical Functions (Dover, N.Y., 1968).

13. D. Vetterli, W. Boeglin, P. Egelhof, R. Henneck, M. Jaskóla, A. Klein, H. Mükry, G.R. Plattner, I. Sick, D. Trautmann, G. Baur and A. Weller
    Phys. Rev. Lett. 62, 1453 (1989).




## FIGURE CAPTIONS:

Figure 1a. Calculated $\frac{\sigma-\sigma_{Mott}}{\sigma+\sigma_{Mott}}(\theta)$ for $^{208}Pb+^{208}Pb$ at $E_{CM}$ = 500 MeV. Full curve includes all effects including $V^{C,6}_{VDW}(r)$. Dashed curve corresponds to no color Van der Waals force. The value $\alpha_6$ = 8.0 was used.

Figure 1b. Same as figure 1 for $V^{C,7}_{VDW}(r)$ (Eq. 1b) with $\alpha_7$ = 100.0.

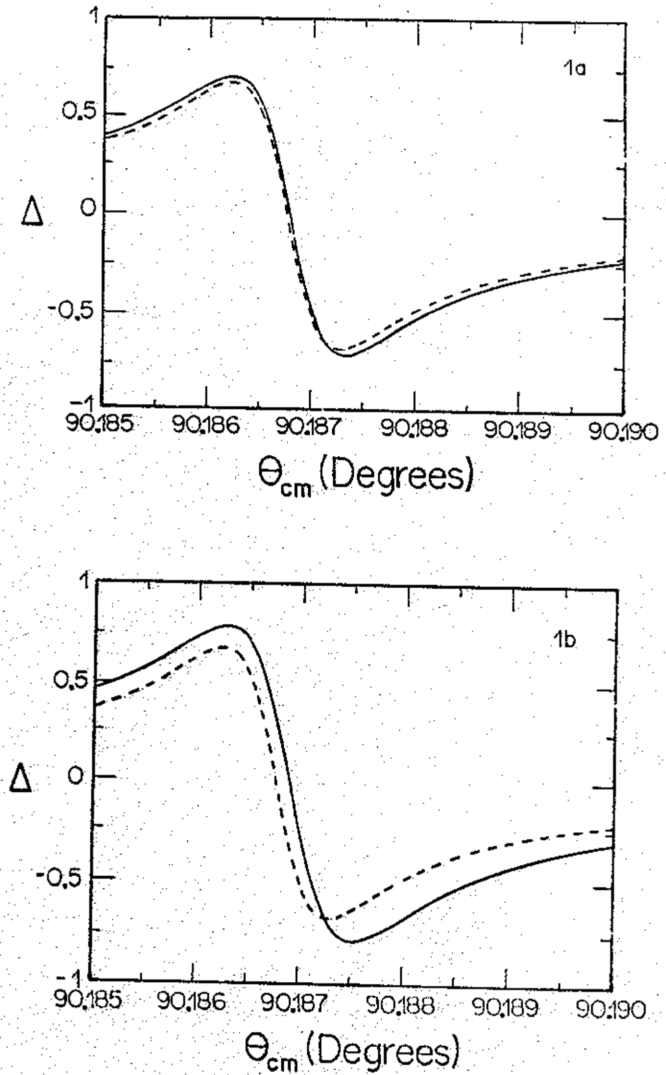
1a
1
0.5
0
-0.5
-1
Δ
90.185
90.186
90.187
90.188
90.189
90.190
Θcm (Degrees)
1b
1
0.5
0
-0.5
-1
Δ
90.185
90.186
90.187
90.188
90.189
90.190
Θcm (Degrees)

Fig. 1