Study of the elastic scattering of ^{6}He on ^{208}Pb at energies around the Coulomb barrier

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Abstract

The elastic scattering of ^{6}He on ^{208}Pb has been measured at laboratory energies of 14, 16, 18 and 22 MeV. These data were analyzed using phenomenological Woods-Saxon form factors and optical model calculations. A semiclassical polarization potential was used to study the effect of the Coulomb dipole polarizability. Evidence for long range absorption, partially arising from Coulomb dipole polarizability, is reported. The energy variation of the optical potential was found to be consistent with the dispersion relations which connect the real and imaginary parts of the potential.

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1 Introduction

We report here on new measurements of the angular distributions of the elastic scattering of ^{6}He projectiles on a ^{208}Pb target at the laboratory energies of E_{lab} = 14, 16, 18 and 22 MeV. The aim is to investigate the effect of the dipole polarizability and the energy dependence of the nuclear optical potential in the scattering of ^{6}He by heavy targets at energies around the Coulomb barrier. It is well known that the weakly bound nucleus ^{6}He has an extended neutron distribution, the so called "neutron halo", and a relatively low 2n-binding energy. These particular features favour the process of breakup and neutron transfer, and should affect the angular distribution of the elastic cross sections.

In an optical model description, the contributions of the inelastic, break-up and transfer processes are usually included using a local dynamic polarization potential (DPP) which represents the effect of the relevant reaction channels on the elastic cross sections. A number of techniques to generate the DPP make use of coupled channel calculations to produce the S matrix for the elastic channel, and a suitable inversion method to obtain the polarization potential [1–3]. Another option is to use a semiclassical model to generate the DPP, and this technique has been extensively used to investigate these contributions [4–10].

At energies around the Coulomb barrier, the dipole component of the Coulomb interaction should play an important role by coupling the ground state to the continuum states of the projectile. In this case a simple adiabatic form of the DPP was derived in the past [4], and more recently an analytical expresion beyond the adiabatic limit has been proposed [7]. Previous studies on the effect of the Coulomb dipole polarizability (CDP) in the scattering of ^{6}He at near-barrier energies have been reported in [2,3,11]. In ref. [12–14] evidences of long range absorption were found, and this effect was partially attributed to the Coulomb dipole polarizability. Here we extend this study to a range of energies around the Coulomb barrier.

Another important aspect is the behaviour of the nuclear optical potential

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at near-barrier energies. In this energy range, the strong coupling between intrinsic degrees of freedom and reaction dynamics might produce a strong energy dependence on the strength of the real part of the nuclear optical potential. This effect is called the "Threshold Anomaly" [15]. This behaviour can be understood by means of a dispersion relation between the real and the imaginary parts of the optical potential [16,17]. Although the appearance of the Threshold Anomaly has been studied to some extend in the scattering of light stable nuclei like ^{6,7}Li [18–24] there are very few works done with ^{6}He projectiles [25,26]. In the present work we also investigate the presence of a Threshold Anomaly in the scattering of ^{6}He on ^{208}Pb.

2 Experimental method

The measurements were carried out using the ^{6}He beam provided by the radioactive beam facility of the Cyclotron Research Center (CRC) at Louvain-la-Neuve (Belgium). The exotic beam was produced using the proton beam from the cyclotron Cyclone-30 impinging on a LiF powder target via the reaction ^{7}Li(p,2p)^{6}He [27]. The atomic beam was ionized in an ECR ion source, purified by magnetic separation and post accelerated by a second cyclotron Cyclone-110 of the CRC facility. The ^{6}He beam was produced at laboratory energies of 14, 16, 18 MeV (1^+ charge state) with a typical intensity of 4×10^{6} ions per second and at 22 MeV (2^+ charge state) with 1.5×10^{5} ions per second. A high intensity beam of ^{4}He at a laboratory energy of 12 MeV was used for the normalization of the elastic cross sections. The targets used were in the form of self supporting foils of ^{208}Pb with a thickness of 0.950 mg/cm^2. In order to increase the counting rate at the highest laboratory energy of 22 MeV a target foil of 2.080 mg/cm^2 was used. The targets had the following isotopic composition: ^{208}Pb 87(2)%, ^{207}Pb 1.20(2)%, ^{206}Pb 11.4(2)%.

A schematic lay-out of the experimental setup is shown in Figure 1. The reaction products were measured in a detection system consisting of two LEDA detector arrays in standard (LEDA, Fig. 1) and "lamp" (LAMP, Fig. 1) configurations [28], covering forward scattering angles (5°-65°), and the DINEX telescope array [13] covering backward scattering angles (135°-170°). The angular resolution of the detector setup, considering the size of the beam and the angular coverage, was approximately two degrees in the DINEX array, and below one degree in the LEDA array.

The Master Trigger was built as a common "OR" so that events firing any of the detectors were included. For each accepted trigger a common gate was sent to all ADC modules connected in a daisy chain. For every valid event, both the energy and the time-of-flight (TOF), measured with respect to the cyclotron frequency, were recorded.

In the case of the LEDA detector array, the different reaction fragments were identified using TOF techniques. An Energy - TOF spectrum obtained at E_{lab} = 22 MeV and $\theta_{lab} = 42°$ is shown in Figure 2a. For the DINEX detector array mass and charge separation of reaction fragments could be easily achieved by means of standard energy loss techniques used with charged particle telescopes. A typical particle identification spectrum (ΔE, E_t) obtained with the DINEX array at E_{lab} = 22 MeV and $\theta_{lab} = 147°$ is shown in Figure 2b. The total energy E_t of the detected particle was obtained as $E_t = E + \alpha(\theta)\Delta E$, where $\alpha(\theta)$ is a constant that depends on the relative gain of the different electronic chains processing ΔE and E signals. This constant was obtained by minimizing the width of the elastic peak. A typical value was $\alpha = 0.5$. We obtained an average energy resolution for the LEDA array of 150 keV and of 250 keV for the DINEX array, depending on detector strip.

The elastic scattering yield was corrected for the beam misalignment using a standard method described in [29]. This method provides an "effective" position of the beam spot on target by minimizing the difference between the measured and calculate elastic yields in the angular region corresponding to the Rutherford elastic cross sections. The effective position is used to introduce a correction in the elastic yields due to the variation of the solid angles.

Throughout the data analysis, it was also found that the detection system was not 100% efficient, which could be attributed to defects in some electronic channels and the presence of low amplitude electronic noise. The final values of the yields were corrected for these effects using the TOF spectra and the signal of a low rate pulser.

Finally, for each collision energy, E, the angular distribution of the elastic cross sections was obtained by

$$\frac{\sigma_{el}}{\sigma_R}(E,\theta) \equiv \frac{\frac{d\sigma_{el}}{d\Omega}(E,\theta)}{\frac{d\sigma_R}{d\Omega}(E,\theta)} = C(E) \times \frac{N_{el}(E,i)}{N_R(E_0,i)} \times F(E,i), \tag{1}$$

where $C(E)$ is a normalization constant, $N_{el}(E,\theta)$ is the yield of ^{6}He elastic events at the laboratory energy E and detector strip i, corresponding to laboratory angle θ, and $N_R(E_0,i)$ is the elastic yield of ^{4}He+^{208}Pb at the laboratory energy $E_0 = 12$ MeV in the same strip. $F(E,i)$ accounts for the correction due to beam misalignment.

The constant $C(E)$ depends on the collision energy E and the total charge collected during the measurements. This constant is just a global normalization factor of the angular distributions of the elastic cross sections. It was determined by imposing that, for small scattering angles, the ratio of elastic and Rutherford cross sections should be independent of θ and equal to unity.

This method for obtaining the elastic cross sections does not require the measurement of the total accumulated beam charge and the target thickness, and it has the advantage of avoiding the systematic errors arising from the calculation of the solid angles. However, it has the disadvantage that the cross sections should be measured at small scattering angles in order to provide Rutherford scattering data.

In Figures 3 and 4 we present the angular distributions of the elastic scattering at the laboratory energies of 14, 16, 18 and 22 MeV resulting from our data analysis. In Figure 4 we also show recent data on the elastic cross section for the same system at $E_{lab} = 27$ MeV [12].

3 Theoretical interpretation

Our general motivation is to understand the reaction mechanisms which are specific of the scattering of weakly bound nuclei, such as ^{6}He. When two "normal" heavy nuclei collide, the elastic scattering is determined by the phenomenon of strong absorption [30]. There is a grazing angular momentum L_g defined by the modulus of the scattering amplitude $|S(L_g)| = 1/2$. For the values of L smaller than L_g, the modulus of the S-matrix becomes very small, while for $L > L_g$, $|S(L)|$ becomes practically 1. Associated to the grazing angular momentum, there is a grazing angle θ_g given by the relation $L_g + 1/2 = \eta \cot(\theta_g/2)$, and a strong absorption radius r_{sa}, given by the distance of closest approach of the Coulomb trajectory for L_g.

$$r_{sa} = \frac{1}{2}\frac{Z_t Z_p}{E}e^2\left(1 + \frac{1}{\sin(\theta_g/2)}\right) \tag{2}$$

For $r = r_{sa}$, the elastic differential cross section for θ_g is just 1/4 times the Rutherford cross section.

The strong absorption radius has a special significance in the study of nuclear collisions. The scattering data are sensitive to the values of the potentials in the range of the strong absorption radius. Moreover, as the diffuseness parameter of the optical potentials is typically about 1 fm, one does not expect to have nuclear effects well beyond r_{sa}.

In order to obtain the strong absorption radius from the experimental data, we have plotted in Figure 5 the elastic cross section divided by Rutherford, as a function of the distance of closest approach r_{max} of the Coulomb trajectory. For the energies above the barrier we have only included data points beyond the rainbow angle, which has been estimated to be $\theta_{rb} \approx 90°$ for $E_{lab} = 22$ MeV, and $\theta_{rb} \approx 60°$ for $E_{lab} = 27$ MeV. These values have been obtained from an optical model calculation that reproduces the observed angular distributions, by varying the imaginary part of the optical potential.

We can see that the experimental points fall approximately along a line, suggesting a value of $r_{sa} = 12.5$ fm for the strong absorption radius of this system. This value is in accordance with those obtained from ^{7}Li + ^{208}Pb or ^{16}O + ^{208}Pb scattering data. However, at much larger distances, up to 20 fm, there is still a significant reduction of the cross sections with respect to the Rutherford values. This is a clear indication of the presence of reaction mechanisms that remove flux from the elastic channel in situations in which the nuclei stay well separated. This is called long range absorption, and it is associated to the scattering of weakly bound nuclei.

The concept of absorption, in nuclear collisions, corresponds strictly to the fact that the modulus of the S-matrix deviates from unity. To investigate this, we have also studied the dependence of the $|S_L|^2$, as a function of the Coulomb turning point, $r(E,L) = (\eta + \sqrt{\eta^2 + L(L+1)})/k$. We find that, for all the energies studied, there is a significant deviation of $|S_L|^2$, corresponding to turning points as large as 20 fm.

3.1 Optical model calculations

We have performed optical model calculations to understand the nature of the long range absorption. Throughout the present work the optical model (OM) calculations have been performed with the code ECIS [31].

The potential describing the interaction between ^{6}He and ^{208}Pb is the sum of a monopole Coulomb potential and a phenomenological nuclear potential.

The monopole Coulomb potential is determined by the charges of projectile and target. The only parameter is the Coulomb radius, which we define as $R_c = r_c\ (A_p^{1/3} + A_t^{1/3})$. The value of the radius parameter was $r_c = 1.3$ fm.

We have used phenomenological volume Woods-Saxon potentials for both the real and imaginary parts of the nuclear potential. The total nuclear potential is given by the expressions:

$$\begin{aligned} U(r) &= V(r) + i\,W(r), \\ V(r) &= -\,V_0\,\frac{1}{1+\exp\left(\frac{r-R_r}{a_r}\right)}, \\ W(r) &= -\,W_0\,\frac{1}{1+\exp\left(\frac{r-R_i}{a_i}\right)}. \end{aligned} \quad (3)$$

The choice of Woods-Saxon shapes instead of folding potentials simplifies the study of the dispersion relations and the comparison with previous analysis performed in ref. [12–14] for the scattering of ^{6}He on heavy targets.

As a starting point we have used global parameters [32] found for ^{6}Li elastic scattering: R_r = 7.856 fm; R_i= 9.090 fm; a_r = 0.811 fm; a_i = 0.884 fm. These parameters define the shape (or geometry) of the Woods-Saxon form factors. They have been obtained by fitting a large set of ^{6}Li elastic scattering data for a wide range of laboratory energies (E = 5-156 MeV) and targets (A = 6-209).

Having fixed the geometry of the form factors, the only free parameters are the depths V_0, W_0 of the real and imaginary parts of the nuclear potential. They have been varied in order to optimize the fits of the angular distributions.

The results of this search are given in columns 2-4 of Table 1 and the elastic cross section is shown with the dashed lines in Figures 3 and 4. Under this prescription we obtained a rather poor description of the elastic scattering of ^{6}He with a large value of the χ^2. Note that for E_{lab}= 22 and 27 MeV the fits predict also a rainbow structure that seems to be absent from the data, in particular at 27 MeV. This effect is seen in the scattering of ^{6}Li at energies around the Coulomb barrier [18], but our results suggest that this might not be the case for the scattering of the halo nucleus ^{6}He.

The absence of the rainbow in the case of ^{6}He might be related to greater absorption for $L > L_g$ due to the tail (halo) of the ^{6}He density distribution. Therefore although both ^{6}Li and ^{6}He have some structural similarities, their response to external fields seem to be different. Deviations from pure Coulomb scattering above the grazing angle have also been reported in the past by Thorn et al. [33] for the low energy scattering of ^{18}O on ^{184}W. In this work the elastic data exhibit strong absorption at small scattering angles and the characteristic rise above Rutherford does not appear. Using coupled channels calculations the authors show that the effect is associated with the strong Coulomb coupling to low lying excited states in ^{18}O. For the case of the elastic scattering of ^{6}He similar effects are discussed in [34], where the Coulomb couplings are found to suppress the Coulomb rainbow. Their results confirm the conclusions of Kakuee et al. [12] and the findings of our present analysis.

To achieve a satisfactory description of the scattering of ^{6}He we must use values for the radius and diffuseness different from those obtained from ^{6}Li scattering. Therefore a new search was performed where the values of the depth and diffuseness for the real and imaginary parts of the potential were varied simultaneously. The radius parameter was kept fixed to the same value $R_r = R_i$ = 7.856 fm. In this four parameter search we only included the data at the two highest collision energies available, E_{lab} = 22 and 27 MeV, where

Table 1
Results of the analysis using an energy independent geometry. N_f is the number of degrees of freedom. For all the fits the free parameters are the real and imaginary depths of the Woods-Saxon potential. The radius parameter is fixed to $R_r = R_i =$ 7.856 fm. The real and imaginary diffuseness are fixed to the values obtained in a simultaneous fit of the data at E_{lab} = 22 MeV and E_{lab} = 27 MeV. See text for further details.

E_{lab} (MeV)	V_0 (MeV)	W_0 (MeV)	χ^2	Vp (MeV)	Wp (MeV)	χ^2	N_f
27	22(2)	5.5(3)	34	24(1)	8.5(5)	27	30
22	13(1)	5.8(5)	21	6(4)	12(2)	20	29
18	30(20)	3.7(8)	36	50(20)	7(1)	28	30
16	30(50)	2.8(8)	13	80(70)	6(2)	13	30
14	30(80)	1.4(5)	16	30(70)	0(6)	19	30

we expected the elastic scattering to be most sensitive to the geometry of the nuclear potential. We obtained the values $a_r = 1.15$ fm and $a_i = 1.89$ fm.

Having found the new geometry, the real and imaginary depths of the optical potential V_0, W_0 have been varied to reproduce the data at E_{lab} = 14, 16 and 18 MeV. The results of this analysis are shown with a solid line in Figures 3 and 4, and the potential depths are given in columns 2-4 of Table 1. The uncertainties in the OM parameters extracted from the fits were estimated from the corresponding covariance matrix.

Therefore our data sets can be properly reproduced by using an energy independent geometry for the optical potential (radius and diffuseness). One should notice that the diffuseness of the imaginary part of the potential is much larger than the values used for light stable nuclei as ^{6}Li. This confirms the presence of long range absorption mechanisms in the scattering of ^{6}He discussed in [12,14,35].

3.2 Dipole polarizability

We have also investigated the role played by the Coulomb dipole polarizability (CDP) in the scattering of ^{6}He at energies around the barrier. The CDP accounts for the coupling to break-up states induced by the dipole component of the Coulomb force between projectile and target.

The effects due to the CDP have been explicitly included in the OM calculations by means of a parameter-free polarization potential derived in a semiclassical framework [7]. This potential is complex and energy dependent, and it is completely determined by the energy distribution of the Coulomb dipole strength B(E1). For the actual calculations we have used the theoretical distribution predicted in [36]. The polarization potential is local, and L-independent, and its radial dependence is determined so that the first order amplitude of the polarization potential gives, for all the scattering angles, the same value as the second order amplitude corresponding to Coulomb dipole excitation and de-excitation to all the excited states. The potential so obtained is purely real, in the limit of high dipole excitation energy, and purely imaginary for low dipole excitation energy. The range of the imaginary potential is larger as the dipole excitation energy is lower.

We have performed new fits to the data including the CDP potential, in the same manner as explained in last subsection. The diffuseness parameters were obtained by fitting the data at $E_{lab} = 27$ and 22 MeV. In this case we obtained $a_r = 0.985$ fm and $a_i = 1.451$ fm.

The potential depths V_p, W_p were obtained using this geometry, by fitting all data sets. The results are listed in columns 5-7 of Table 1. The calculated cross sections are depicted in figures 3 and 4 with a dot-dashed line. To illustrate the effect of the CDP potential we have also included in the same figures an OM calculation where the CDP potential has been suppressed (dotted line). The difference in reaction cross sections calculated with and without DPP are around 3% for energies higher than the Coulomb barrier and about 20% for energies below.

By including the polarizability we get an overall improvement of the fits. The general effect in the scattering of ^{6}He on ^{208}Pb is a reduction of the elastic cross sections, which become particularly important at energies below the barrier and at backward angles. The diffuseness of the real part is close to the value given in [32]. However the diffuseness of the imaginary part is still high. Thus, the dipole polarizability is only partly responsible for the long range absorption. This suggests the presence of important reaction channels [14,37] which do not originate from Coulomb dipole couplings, and produce absorption at large distances.

The Coulomb dipole polarization potential used in this work describes accurately the effect of purely Coulomb dipole coupling in the elastic scattering, as it is shown in [38]. However, it does not include the effect of dipole nuclear excitation, or Coulomb-nuclear interference effects.

The imaginary part of the polarization potential, including both Coulomb and nuclear couplings has been derived, for high incident energies, in [9,10]. It is shown that the effect of break up gives rise to long range imaginary potentials, for weakly bound projectiles. The range of the imaginary potential due to Coulomb coupling is larger than that of nuclear coupling. In particular the effect of the breakup channel on the polarization potential obtained from the elastic data can be understood in terms of the small binding energy of valence nucleons and the long range of the Coulomb potential. In ref. [9] the diffuseness parameter of the imaginary potential is approximated in terms of the imaginary momentum of the bound halo wavefunction as $\alpha \simeq (2\gamma_i)^{-1}$, where $\hbar^2\gamma_i^2/2\mu = E_B$ and E_B is the binding energy. If this expression is applied to ^{6}He, one gets $\alpha \simeq 2$ fm, which is in good agreement with the phenomenologically determined diffuseness parameter. In ref. [10] an expression is derived for the diffuseness parameter β of the imaginary potential due to Coulomb excitation, in the high energy limit. The authors obtain $\beta \simeq \hbar v/E_d$, where E_d is the typical excitation energy of dipole states. This would give, for $E_d = 4$ MeV, a diffuseness parameter of about $\beta \simeq 4$ fm. Thus, the arguments used in [9,10] lead to the presence of long range absorption, in agreement with the present data.

The role of dipole Coulomb + nuclear polarizability and higher order contributions have been recently studied using CDCC calculations by Rusek et al. [34]. Here the authors perform continuum discretized coupled channel calculations (CDCC) for the scattering of ^{6}He on ^{208}Pb, ^{209}Bi and ^{197}Au targets and the results are compared with available data. It is found that dipole couplings with the continuum play an important role by generating a long-range absorption that suppresses the Coulomb rainbow. However they also show that quadrupole couplings are also important, as they are responsible for the enhancement of the differential cross-section values at backward-scattering angles and have to be taken into account to obtain good agreement with the experimental data. On the other hand, very recently it has been also shown the importance of the 2n transfer channels in the scattering of ^{6}He with heavy targets at Coulomb barrier energies [39,40].

The effect of the breakup and transfer channels on the elastic cross sections can also be investigated by the use of DPPs obtained from CDCC calculations [1,3]. This technique was recently applied to describe the effect of the breakup channels in the elastic scattering of ^{6}He on ^{208}Pb at E_{lab}=27 MeV [2]. Here the authors found a remarkable long range tail in the DPP potential originated from breakup couplings, extending at radial distances beyond 40 fm. This effect might be related to the strong absorption phenomena found for this system, as it was also discussed in [40].

4 Energy dependence of the optical potential and dispersion relations

One of the main objectives of the present work is to determine the energy dependence of the OM potential and to test its consistency by using the dispersion relations. In this section we obtain a fit to the data using the same geometry parameters (R, a) for the real and imaginary parts of the Woods-

Saxon potentials, so that the energy dependence of the optical potential can be analyzed independently of the radial distance. In this study we have also included the CDP potential, which satisfies the dispersion relations by construction.

The energy dependent nucleus-nucleus optical potential can be expressed in a local and angular momentum independent form as:

$$V(r,E) = V_R(r) + iW(r,E) + \Delta V(r,E) \ . \tag{4}$$

In this equation $\Delta V(r,E)$ is the polarization potential arising from the excitations (second order term in Feshbach formalism) which are also at the origin of the energy dependent imaginary part $W(r,E)$.

Both parts are connected through the dispersion relation [17]. For a given value r of the relative coordinate, it can be written as:

$$\Delta V(E) = \Delta V(E_R) + (E - E_R)\frac{P}{\pi}\int_0^{\infty} \frac{W(E')}{(E' - E_R)(E' - E)} \ dE \ . \tag{5}$$

where P is the principal value of the integrand and E_R is an arbitrary reference energy. Note that any energy independent contribution to the imaginary potential will not affect the value of $\Delta V(E)$. To obtain meaningful optical potentials, that can be compared to check the validity of the dispersion relation, it is necessary to use fits to the elastic data using energy-independent geometries. Moreover, the application of dispersion relations to imaginary potentials with a certain geometry would lead to a dispersive contribution to the real potential with the same geometry. On the other hand, when using Woods-Saxon potentials to analyze the data, it is possible to find a family of potentials producing fits of similar quality. The value of the radial coordinate at which these potentials cross is defined as the sensitivity radius. At this point the OM potential is determined without ambiguity and it is where the dispersion relation is usually evaluated.

Previous studies of the ^{6}He + ^{208}Pb reaction at E_{lab} = 27 MeV [14] and ^{17}F + ^{208}Pb at E_{lab} = 90.4 MeV [41] suggest different radial regions of sensitivity for the real and imaginary parts of the OM potential for these weakly bound nuclei. In this work we have investigated this effect and its energy dependence. Several calculations were carried out by varying the parameters $(V_0, W_0, a_{r,i})$ maintaining a similar value of the total χ^2 (10% of minimum) [42]. This analysis reveals that the radial region of sensitivity is different for the real and imaginary parts of the potential, and depends also on the energy of the collision. For the real part, the region of sensitivity varies from about 11 to 13 fm, whereas for the imaginary part it changes from 13 to about 16 fm. This result brings new evidence to the energy variation of interaction radii for scattering of light weakly bound nuclei reported in [22,41].

We have noticed that we can analyze our data using energy-independent geometries if we separate the potential in two parts, one with long range and one with short range. In this approach the OM potential is divided in two components with different diffuseness and energy dependence,

$$
\begin{aligned}
U(r,E) &= (V_S + iW_S) f_S(r) + (V_L(E) + iW_L(E)) f_L(r) \ , \\
f_S(r) &= \frac{1}{1+\exp\frac{r-R}{a_S}} \ , \\
f_L(r) &= \frac{1}{1+\exp\frac{r-R}{a_L}} \ .
\end{aligned}
\tag{6}
$$

where $f_S(r), f_L(r)$ are the short-range and long-range Woods-Saxon form factors, and V_S, W_S, V_L, W_L, the corresponding potential depths.

As the data have large error bars we have performed here a relatively simple analysis. For the short range part we have chosen standard energy independent Woods-Saxon potentials with parameters $V_S = 50$ MeV, $W_S = 30$ MeV, $R =$ 7.86 fm, and a value of $a_S = 0.811$ fm taken from ^{6}Li scattering results [12]. On the other hand, the long range part was defined by a very diffuse shape with a value of $a_L = 2.0$ fm taken from previous analysis of ^{6}He scattering on Pb and Au targets [12,14]. Thus for each collision energy the search was only performed on the depths $V_L(E), W_L(E)$ of the long range component. The CDP potential was also included in the OM calculations.

The results of this analysis are listed in Table 2. It should be noticed that we do not list the value of the potential at some radius, but the coefficients $V_L(E)$ and $W_L(E)$, defined in eq. (6) above. These satisfy the subtracted dispersion relations, and therefore the real and imaginary parts of $U(r,E)$ will satisfy dispersion relations for any radius r. At E = 14 MeV the data is weakly sensitive to the imaginary part of the potential. Therefore we have fixed W_L = 0 so that only the real part V_L is fitted to the elastic data.

The energy dependence of the OM potential extracted from this analysis is shown Figure 6. Despite the size of the error bars, we find that the energy dependence is consistent with a reduction of the imaginary part $W_L(E)$ as the collision energy decreases below the Coulomb barrier.

The presence of short and long range components in the OM potential with different energy dependence can be related to the interplay between fusion and direct reaction channels in the scattering of light nuclei at Coulomb barrier energies [26,43,44]. Our results provide new evidence for the need of such a

Table 2
Results of the analysis using the sum of a long and short range nuclear potentials. N_f is the number of degrees of freedom. See text for details.

E (MeV)	V_L (MeV)	W_L (MeV)	χ^2	N_f
27	1.0(4)	1.8(2)	28	30
22	-0.3(3)	2.0(3)	16	29
18	0(2)	2.6(6)	29	30
16	6(5)	0.7(7)	14	30
14	1(2)	0	18	31

decomposition.

The energy variation of the OM potential has been studied by using the dispersion relations. The dependence of $W_L(E)$ on the laboratory collision energy has been parameterized using simple straight lines:

$$\begin{aligned} 0,&\quad E \leq 14\,\mathrm{MeV}, \\ 2.89\,\frac{E-14}{2},&\quad 14\,\mathrm{MeV} \leq E \leq 18\,\mathrm{MeV}\ , \\ 2.89\,\frac{38.4-E}{20.4},&\quad 18\,\mathrm{MeV} \leq E \leq 38.4\,\mathrm{MeV}\ , \\ 0,&\quad E \geq 38.4\,\mathrm{MeV}\ . \end{aligned} \tag{7}$$

The results are presented in Figure 6 with a solid line. The data are well reproduced by the calculation, showing a clear consistency with the dispersion relations. Note that $W_L(E)$ is chosen to vanish above $E_{lab} = 38.4$ MeV. This limit of $W_L(E)$ is chosen as it provides a reasonable description of the data.

It is tempting to interpret the decreasing W_L with increasing energy in connection with the variation of the (direct part) of the reaction cross section. However we did not measured the breakup cross section, and although the 2n transfer data show an increase of the cross section from 14 to 22 MeV [40], we do not have any data at 27 MeV. Therefore it is difficult for us to relate the decrease of W_L to decreasing cross section for direct reactions. On the other hand data at 18, 22 and 27 MeV would be also consistent with a constant W_L. Therefore we cannot claim from our data that there is a decrease of W_L for higher excitation energies. The ”fit” with a decreasing straight line is just to obtain a closed expression for the dispersion relation integral. The important message from our analysis is that there are indications that the long absorption decreases for low energies (16 and 14 MeV), and it is accompanied by an increase in the real potential. This would be consistent with dispersion relations.

In the present work the experimental uncertainties make it difficult to conclude whether ^{6}He+^{208}Pb scattering exhibits a Threshold Anomaly. According to recent studies [26] the existence of an Anomaly is equivalent to very large fusion cross section compared to direct reaction channels. However, Bychowski *et al.* [45] and De Young *et al.* [39] have found that for ^{6}He+^{209}Bi scattering the cross section for neutron-transfer reactions is larger that the fusion cross section reported in [46]. Therefore more experimental data from 24 to 50 MeV, with sufficient statistics and covering a wide angular range, is needed to obtain a clear picture of the energy variation of the optical potential for this system.

5 Summary and outlook

New elastic scattering measurements are reported for the system ^{6}He+^{208}Pb at collision energies above and below the Coulomb barrier. The data indicate the presence of long range absorption mechanisms, both above and below the Coulomb barrier.

The data have been analyzed using optical model calculations with potentials having an energy-independent geometry, where only the depth of the real and imaginary parts were allowed to vary with collision energy. The Coulomb dipole polarizability has been included by means of a dynamic polarization potential.

The calculations using nuclear potential shapes that describe the elastic scattering of ^{6}Li cannot reproduce the measured angular distributions for ^{6}He. This suggests that the dynamics of the collision is rather different for these two weakly bound nuclei. It is found that the long range absorption present in the ^{6}He scattering data can only be reproduced using large values for the diffuseness of the imaginary part of the potential.

The Coulomb dipole polarizability produces an important reduction of the elastic scattering cross section at all collision energies reported in this work. This reaction mechanism can account for only a part of the long range absorption found in this system.

It is observed that the elastic data are sensitive to the values of the real and imaginary potentials in different radial ranges. In general, the sensitivity to the real potential corresponds to the region of the strong absorption radius, which is r_{sa} = 12.5 fm. However, the sensitivity to the imaginary potential occurs at much larger radii. Under these circumstances the application of dispersion relations has to be made with caution.

The data can be described with OM calculations using an optical potential made of long range and a short range component, and keeping the same geometry for the real and imaginary parts. This results in an energy variation consistent with the dispersion relations.

The study of low energy scattering of halo nuclei is revealing new and exciting aspects of this exotic systems. Some of these features are the Coulomb dipole polarizability and the long range absorption mechanisms. Detailed and high quality data on the scattering of halo systems such as ^{6}He or ^{11}Be can already be obtained at present radioactive ion beam facilities with very competitive intensities. The analysis of this data can provide very important information to interpret the behaviour of more exotic systems, such as ^{11}Li or ^{8}He.

Detailed microscopic calculations [47], including explicitly the coupling to fusion, transfer, and break-up channels, would be needed to understand the origin of long range absorption in the scattering of weakly bound nuclei.

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Figure Captions

Figure 1 Schematic layout of the experimental setup. All distances are in *mm*.

Figure 2 (a) Energy -Time of Flight (TOF) spectrum for LEDA detector at E_{lab} = 22 MeV and a typical angle of $\theta_{lab} = 42°$. (b) Particle identification spectrum for DINEX detector array obtained at E_{lab} = 22 MeV and $\theta_{lab} = 147°$.

Figure 3 Angular distributions for the elastic scattering of ^{6}He on ^{208}Pb at the laboratory energies of 14, 16 and 18. The dashed line indicates the fit with normal diffuseness parameters, coming from ^{6}Li scattering data. The full line is the fit with large diffuseness ($a_r = 1.15$ fm, $a_i = 1.89$ fm). The dot dashed line is the fit with large diffuseness ($a_r = 0.985$ fm, $a_i = 1.451$ fm), including the Coulomb Dipole Polarizability (CDP) potential. The dotted line is obtained removing the CDP potential from the previous calculation.

Figure 4 Angular distributions for the elastic scattering of ^{6}He on ^{208}Pb at the laboratory energies of 22 and 27 MeV. Data at E_{lab} = 27 MeV has been taken from [12]. The meaning of the lines is the same as in Figure 3.

Figure 5 Present experimental data plotted as a function of the classical distance of closest approach r_{max} for a Coulomb trajectory. See text for details.

Figure 6 The energy dependence of the real (V_L) and imaginary (W_L) parts of the optical potential obtained in this work. The solid lines are calculations using the dispersion relations. See text for details.