bB

GANIL

Elastic scattering of ^{6}He and its analysis within a four-body eikonal model

J.S. Al-Khalili[1], M.D. Cortina-Gil[2], P. Roussel-Chomaz[2], N. Alamanos[3], J. Barrette[4], W. Mittig[2], F. Auger[3], Y. Blumenfeld[5], J.M. Casandjian[2], M. Chartier[2], V. Fekou-Youmbi[3], B. Fernandez[3], N. Frascaria[5], A. Gillibert[3], H. Laurent[5], A. Lepine-Szily[6], N.A. Orr[7], V. Pascalon[5], J.A. Scarpaci[5], J.L. Sida[3], T. Suomijarvi[5]

[1] *Southern Centre for Nuclear Physics, Department of Physics, University of Surrey, Guildford GU2 5XH, U.K.*

[2] *GANIL, BP 5027, 14021 Caen Cedex, France*

[3] *CEA/DSM/DAPNIA/SPhN Saclay, 91191 Gif-sur-Yvette Cedex, France*

[4] *McGill University, Montreal, Canada*

[5] *IPN, IN2P3-CNRS, 91406 Orsay, Cedex, France*

[6] *IFUSP, DFN, CP 20516, 01498, Sao Paulo, Brasil*

[7] *LPC-ISMRA, 14050 Caen Cedex, France*

Submitted for publication in Physics Letters B

GANIL P 96 01

Elastic scattering of ^{6}He and its analysis within a four-body eikonal model

J.S. Al-Khalili[1], M.D. Cortina-Gil[2], P. Roussel-Chomaz[2], N. Alamanos[3], J. Barrette[4], W. Mittig[2], F. Auger[3], Y. Blumenfeld[5], J.M. Casandjian[2], M. Chartier[2], V. Fekou-Youmbi[3], B. Fernandez[3], N. Frascaria[5], A. Gillibert[3], H. Laurent[5], A. Lepine-Szily[6], N.A. Orr[7], V. Pascalon[5], J.A. Scarpaci[5], J.L. Sida[3], T. Suomijarvi[5]

[1)] *Southern Centre for Nuclear Physics,*
Department of Physics, University of Surrey, Guildford GU2 5XH, U.K.
[2)] *GANIL, BP 5027, 14021 Caen Cedex, France*
[3)] *CEA/DSM/DAPNIA/SPhN Saclay, 91191 Gif-sur-Yvette Cedex, France*
[4)] *McGill University, Montreal, Canada*
[5)] *IPN, IN2P3-CNRS, 91406 Orsay, Cedex, France*
[6)] *IFUSP, DFN, CP 20516, 01498, Sao Paulo, Brasil*
[7)] *LPC-ISMRA, 14050 Caen Cedex, France*

(January 25, 1996)

Abstract

We have measured the elastic scattering of a ^{6}He secondary beam on a ^{12}C target at 41.6 MeV/u. The secondary beam was produced by fragmentation with SISSI, and transported to SPEG. The combined use of SISSI and SPEG allows very good quality data to be obtained in terms of energy and angular resolution. The cross section is analysed within a 4-body (α+n+n+^{12}C) eikonal scattering model which is completely parameter-free. Very good agreement with the data is found.

PACS numbers: 29.25.Rm, 29.30.-h, 25.45.De, 24.10.Ht, 25.10.+s

Elastic scattering measurements provide unique information on the nuclear matter density distributions [1,2]. These have become particularly important in the study of light unstable nuclei. However, recent measurements of angular distributions for the scattering of ^{8}B [3], ^{11}Li [4,5] and ^{14}Be [6] have been unable to distinguish between elastic and inelastic scattering due to the overall poor energy resolution in the detectors.

We have started an experimental programme at GANIL for the study of elastic scattering induced by light unstable nuclei. These experiments benefit from the high resolution energy loss spectrometer SPEG and from the high quality secondary beams that are provided using the double superconducting solenoid SISSI [7]. The energy resolution ($\Delta E/E=10^{-3}$) allows the measurement of elastic scattering angular distributions of halo nuclei without contaminations from target excitations. The angular resolution is of the order of 0.3°. We present here the first measurements of the ^{6}He+^{12}C elastic scattering angular distribution at 41.6 MeV/nucleon.

The ^{6}He secondary beam was produced by fragmentation of a 75 MeV/nucleon primary ^{13}C beam, delivered by the GANIL accelerator, on a 1155 mg/cm^2 carbon production target, located between the two superconducting solenoids of SISSI. The position of SISSI at the exit of the second cyclotron and at the entrance of the beam analysing α-spectrometer allows for an improved collection of secondary beams and transmission to the different experimental areas. The momentum acceptance of the system SISSI+α-spectrometer was of the order of 0.6% and the angular acceptance was around 100 mrad in the horizontal and vertical directions. This results in roughly one order of magnitude increase in beam intensity with respect to the use of the α-spectrometer alone.

The total intensity of the secondary beam was of the order of 10^7 particles/second for a primary intensity of 2×10^{12} particles/second. The intensity for the more neutron-rich nuclei ^{6}He and ^{11}Be was of the order of a few percent of the total intensity, whereas the intensity for the nuclei closer to the stability valley such as ^{7}Li and ^{10}Be were around 15 - 20% of the total intensity. We ran the experiment with the composite beam (instead of using an achromatic degrader to purify the secondary beam) in order to avoid any additional loss of beam quality and intensity.

The secondary reaction target was a foil of 100μm thick polypropylene, $(CH_2)_3$. The scattered particles were identified in the focal plane of SPEG by the energy loss measured in an ionisation chamber and the residual energy measured in a plastic scintillator. All the particles could thus be unambiguously identified. The momentum and scattering angle were obtained by track reconstruction of the trajectory as determined by two drift chambers placed 70 cm apart and located near the focal plane of the spectrometer. The elastic scattering of the secondary beam was measured on ^{1}H, ^{12}C and ^{208}Pb targets in the range $\theta_{\rm lab} = 0.7° - 6.0°$. Fig.(1) shows a two-dimensional spectrum measured in the focal plane of SPEG for the scattering of ^{6}He on the $(CH_2)_3$ target. The straight line to the right corresponds to the elastic scattering on ^{12}C, whereas the broad curve corresponds to the elastic scattering on the protons. The shape and the width of this structure are related to the strong kinematics of the reaction.

As we did not measure the number of incident particles on the target in this experiment, it was not possible to obtain the absolute normalisation in a direct way. Preliminary calculations showed that the angular distribution for the elastic scattering on the ^{12}C target is not very sensitive to the interaction potential, and hence the normalisation of the data could be obtained very precisely from the value on the first maximum of the angular distribution.

The theoretical cross section was calculated within a few-body eikonal model [8]. To a good approximation, ^{6}He can be regarded as a three-body system of α+n+n [9] which has the interesting feature that none of its binary subsystems are bound. Such nuclei have been dubbed 'Borromean'. Other examples of Borromean nuclei are ^{11}Li and ^{14}Be which can also be modeled as core+n+n. It has been shown that for such weakly bound systems the reaction mechanisms are strongly influenced by the dynamic polarisation of the projectile [10,11]. Similar large effects should be anticipated for the scattering of ^{6}He which has a two-neutron separation energy of 0.975 MeV. The analysis of ^{6}He induced reactions thus requires an explicitly four-body model of α+n+n+target. Such a model, based on eikonal and adiabatic methods, was presented and evaluated for the case of ^{11}Li [8] and ^{14}Be [12] quasielastic scattering.

This model makes two assumptions. Firstly, that the valence neutrons' separation energy is small relative to the beam energy and, secondly, that an eikonal approximation may be used for scattering at forward angles ($< 20°$). To calculate ^{6}He elastic scattering the model requires three inputs: the ^{6}He three-body wave function plus the α+^{12}C and n+^{12}C optical potentials at the relevant energy per nucleon. Once these are chosen the calculation is completely parameter-free. At 41.6 MeV/nucleon we require an α+^{12}C optical potential at 166 MeV. Data exist at this energy [13] and a good fit was obtained with the Woods-Saxon parameters: V=100 MeV, r_V=1.117 fm, a_V=0.82 fm, W=35 MeV, r_W=1.355 fm, a_W=0.65 fm. The n+^{12}C potentials were derived from a Schrödinger reduction [14] of the global Dirac nucleon optical potential parameterisation of Cooper *et al.* [15].

A particular feature of interest in Borromean nuclei is the role of the pairing correlations of the valence neutrons. This is a feature not reflected strongly in single-particle densities. In our model we use a three-body Faddeev wave function for ^{6}He in which these correlations are included explicitly. The sensitivity of the cross section to the ^{6}He wave function, and in particular to the strength of the valence neutron correlations was thus studied. The wave functions used were those of Zhukov *et al.* [9] calculated within the coordinate space Faddeev approach (CSF) with a realistic NN interaction and Woods-Saxon for the αN interaction. In the limit of no correlation between the valence neutrons the NN interaction was switched off and the αN interaction increased in strength to retrieve the correct binding energy. It was found that this had very little effect on the elastic angular distribution.

For the case of maximally correlated valence neutrons we used a two-body wave function based on the di-neutron model. Here, the two neutrons are treated as a single structureless entity. A relative S-wave α-nn cluster wave function was obtained via a Woods-Saxon interaction whose parameters were chosen to give the correct separation energy and ^{6}He rms radius. The parameters used were V=172 MeV, r_V=0.8 fm, a_V=0.3 fm. Here the calculations were performed assuming three-body α+nn+target dynamics, where the di-neutron-target interaction was taken to be twice the neutron-target interaction used in the earlier four-body model.

Fig.(2) shows the measured angular distribution plotted against the result of the four-body calculation using a realistic Faddeev model wave function for ^{6}He (solid curve). The dashed curve was obtained from the three-body calculation using a di-neutron model wave function. The cross section obtained using the uncorrelated wave function for ^{6}He was almost identical, over the angular region shown, to the solid curve and was thus not plotted.

Clearly, the elastic cross-section is not very sensitive to the strength of the valence neutron correlations in ^{6}He. Whereas in the corresponding study of ^{11}Li scattering [8] using similar model wave functions, there did appear to be greater sensitivity. The dotted curve in Fig.(2) is the result obtained by folding the ^{6}He density of Sagawa *et al.* [16] and a 2-parameter Fermi density for ^{12}C with the density-dependent DDM3Y interaction [17,2]. The parameters of the imaginary part were taken from the systematics given in Ref. [18]. This kind of calculation has been successful in describing elastic scattering of light stable beams on a ^{12}C target in the same energy range [18], and it is interesting to see how it compares with data with unstable neutron rich beams. However the present data do not extend far enough to distinguish unambiguously between the results. The deep minimum in the dotted curve at 7° may be due to ambiguities in the imaginary potential in this kind of calculation.

For the case of ^{11}Li+^{12}C quasielastic scattering, all attempts to describe the small angle behaviour of the cross section within semi-microscopic [19] and few-body models [8,20] have so far failed. A common feature of all these calculations is the presence of a sharp minimum at 4°, whereas the measured cross section has a much shallower minimum at around 5°. It should also be emphasised that, in all the above calculations, the inelastic cross sections due to target excitation were added to the elastic cross sections in order to compare with the quasielastic data. But this did not shift the position of the first minimum at all. However, within a purely phenomenological analysis, Mermaz [21] found that to obtain a fit to the small angle data requires the presence of significant attractive, surface peaked, real and imaginary terms in the phenomenological ^{11}Li–^{12}C optical potential. This could be achieved only by addition of derivative Woods-Saxon terms, of large radius, to both the real and imaginary parts of volume Woods-Saxon central potentials.

No such discrepancy between theory and data exist for ^{6}He+^{12}C scattering. Since both ^{11}Li and ^{6}He are assumed to have two-neutron halos surrounding an inert core, this leads us to speculate that it may well be the ^{9}Li core that requires a better treatment. The effects of core excitation and spin-dependence may well need to be included in future models of ^{11}Li. Whereas ^{6}He, with its spinless and inert α core, appears not to require such considerations. In order to progress in these studies, besides theoretical developments, high quality data for ^{9}Li+^{12}C and ^{11}Li+^{12}C elastic scattering are urgently needed, at the same energy per nucleon.

Fig.(3) shows the effective optical potential [10] for the ^{6}He+^{12}C system extracted from the 4-body model. Clearly, a long-range tail, of the type proposed for ^{11}Li, is not required for ^{6}He. The potential is compared with that used in the double folding model and which produced the dotted curve in Fig.(2).

In summary, we have shown that the combined use of SISSI and SPEG offers new opportunities for measuring elastic scattering cross sections of neutron-rich nuclei to high accuracy. These are the first data on nucleus-nucleus elastic scattering with exotic beams without contributions from inelastic scattering. For the limited angular range covered by the present data, a three-body model for ^{6}He of α+n+n describes the data very well. In the same angular domain, it was not possible to fit the ^{11}Li data, using similar models (even allowing for inelastic excitations of the target). Thus ^{6}He appears to offer a better testing ground for studying the properties of Borromean systems due to its inert α core. It would be extremely valuable for new data to be obtained at larger angles to discriminate further between theoretical model wave functions of ^{6}He.

The authors are indebted to Dr I.J. Thompson for providing the three-body ^{6}He wave functions, and to H. Sagawa for providing the ^{6}He density distribution in a tabulated form. One of the authors (J.A-K) acknowledges the financial support of the Engineering and Physical Sciences Research Council (UK) in the form of an Advanced Fellowship.

REFERENCES

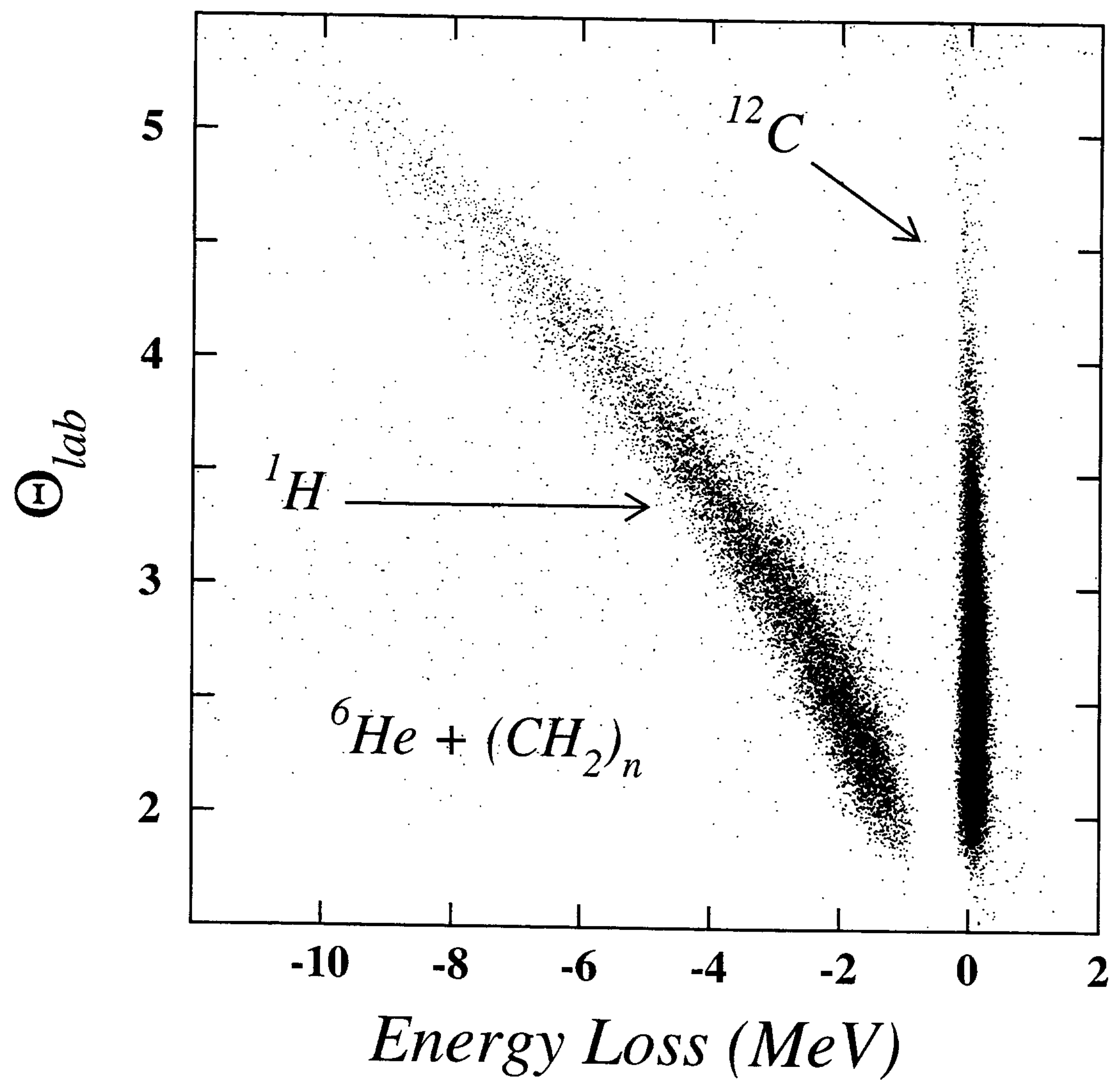
[1] F. Petrovich *et al.*, Ann. Rev. Nucl. Part. Sci. **36** (1986) 29.
[2] G.R. Satchler and W.G. Love, Phys. Rep. **55** (1979) 183.
[3] I. Pecina *et al.*, Phys. Rev. C **52** (1995) 191.
[4] J.J. Kolata *et al.*, Phys. Rev. Lett. **69** (1992) 2631.
[5] M. Lewitowicz *et al.*, Nucl. Phys. **A562** (1993) 301.
[6] M. Zahar *et al.*, Phys. Rev. C **49** (1994) 1540.
[7] A. Joubert *et al.*, Particle Accelerator Conference IEEE Vol. 1 (1991) 594.
[8] J.S. Al-Khalili, I.J. Thompson and J.A. Tostevin, Nucl. Phys. **A 581** (1995) 331.
[9] M.V. Zhukov *et al.*, Phys. Rep. **231** (1993) 153.
[10] J.S. Al-Khalili and J.A. Tostevin, Phys. Rev. C **49** (1994) 386.
[11] J.S. Al-Khalili, Nucl. Phys. **A 581** (1995) 315.
[12] I.J. Thompson *et al.*, Nucl. Phys. **A 588** (1995) 59c.
[13] B. Tatischeff and I. Brisaud, Nucl. Phys. **A 155** (1970) 89.
[14] L.G. Arnold *et al.*, Phys. Rev. C **23** (1981) 1949.
[15] E.D. Cooper *et al.*, Phys. Rev. C **47** (1993) 297.
[16] H. Sagawa, Phys. Lett. B 286 (1992) 7.
[17] M. El-Azab Farid and G.R. Satchler Nucl. Phys. A438 (1985) 525.
[18] M.E. Brandan and G.R. Satchler Nucl. Phys. A487 (1988) 477.
[19] Dao T. Khoa, G.R. Satchler and W. von Oertzen, Phys. Lett. B 358 (1995)14.
[20] K. Yabana, Y. Ogawa and Y. Suzuki, Phys. Rev. C **45** (1992) 2909; K. Yabana, Y. Ogawa and Y. Suzuki, Nucl. Phys. **A539** (1992) 295.
[21] M.C. Mermaz, Phys. Rev. C **47**, 2214 (1993).

FIGURES

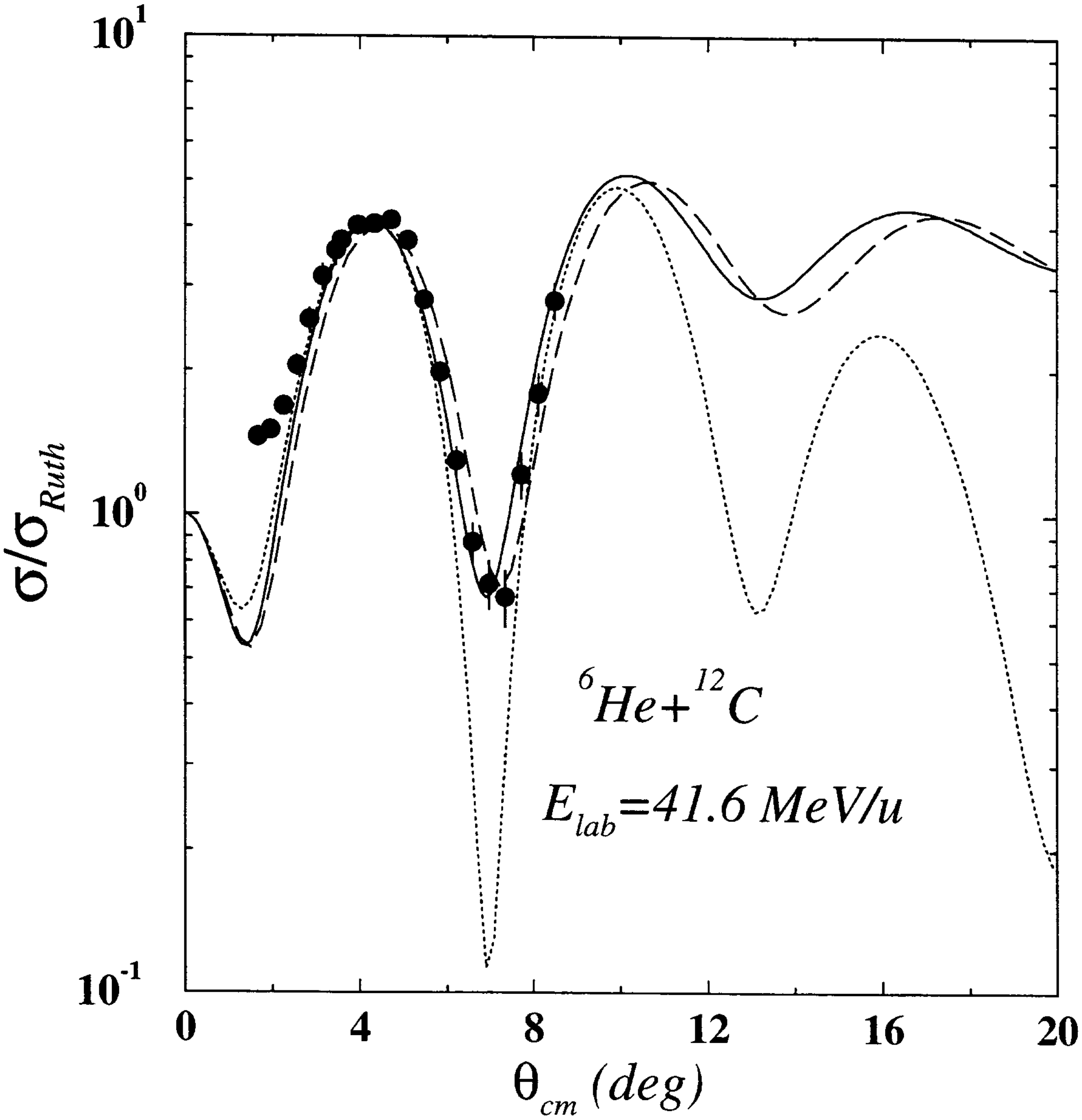
FIG. 1. Two-dimensional plot of the scattering angle in the focal plane of the SPEG spectrometer as a function of the energy loss (see text).

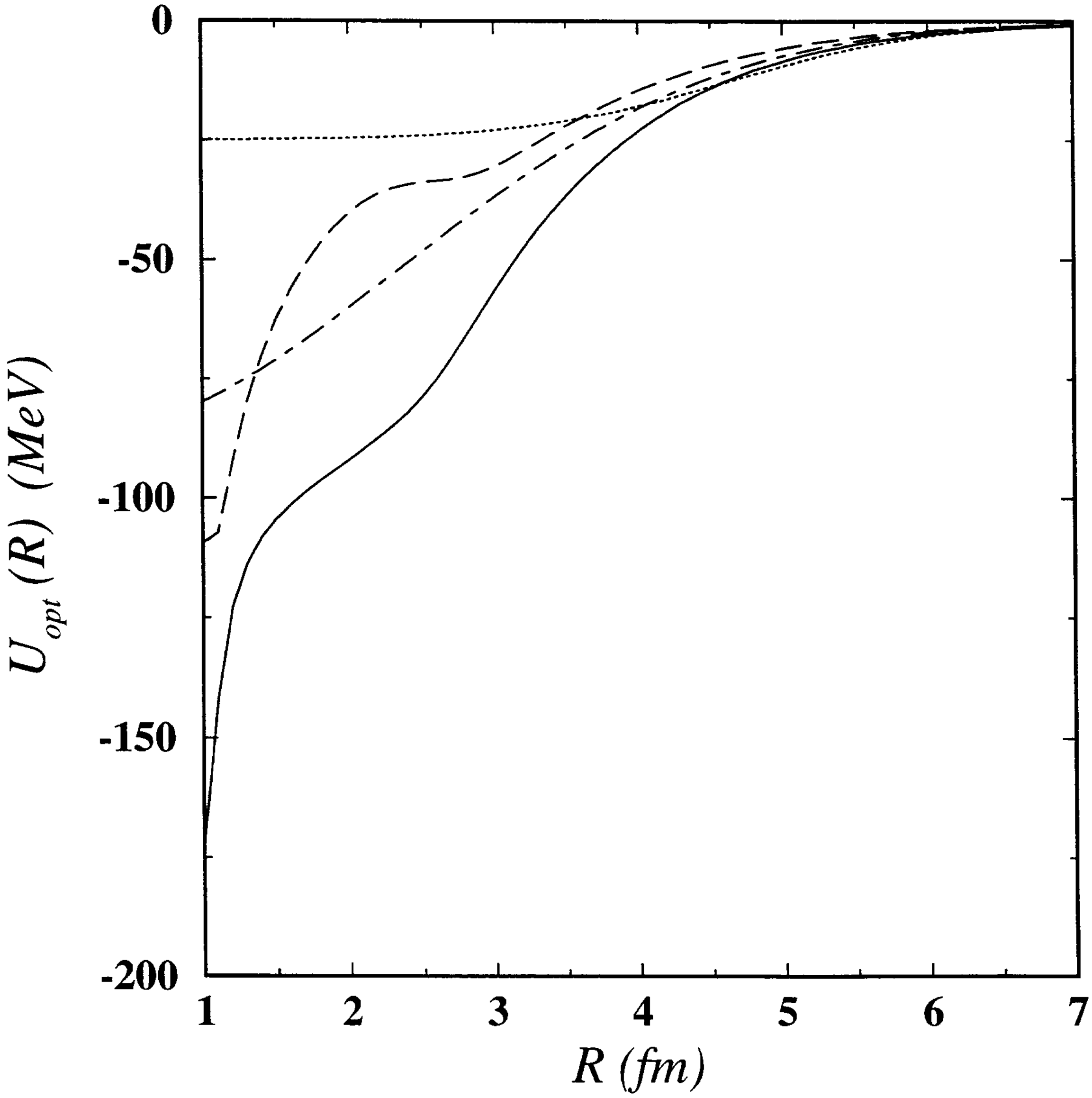
FIG. 2. Elastic scattering angular distribution for $^{6}He+^{12}C$ at 41.6 MeV/nucleon. The solid curve is calculated from the parameter-free four-body eikonal model with a Faddeev wave function for ^{6}He. The dashed curve is calculated from a three-body eikonal model using a di-neutron wave function. The dotted curve was obtained using a density-dependent double folding model.

FIG. 3. Calculated real (solid) and imaginary (dashed) parts of the Glauber optical potential for the $^{6}He+^{12}C$ system obtained from the four-body eikonal model. The dot-dashed curve is the real potential obtained from a DDM3Y calculation and the dotted curve is an imaginary Woods-Saxon with parameters from ref. [18]. The dot-dashed and dotted curves make up the interaction used to produce the dotted cross section in Fig.(2).



^{12}C
^{1}H
$^{6}He + (CH_2)_n$
Θ_{lab}
5
4
3
2
-10
-8
-6
-4
-2
0
2
Energy Loss (MeV)


10^1
10^0
10^{-1}
σ/σ_{Ruth}
0
4
8
12
16
20
θ_{cm} (deg)
$^6He+^{12}C$
E_{lab}=41.6 MeV/u


0
-50
-100
-150
-200
1
2
3
4
5
6
7
R (fm)
U_opt (R) (MeV)