Role of nuclear and electromagnetic interactions in coherent dissociation of 3A GeV/c relativistic ^{7}Li to ^{3}H + ^{4}He

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CONTENTS:

1.Introduction. Physical motivation of this study.

GeV energy region.

Coulomb and nuclear diffractional interactions.

Classical investigations of the elastic scattering of particles and nuclei are well known.

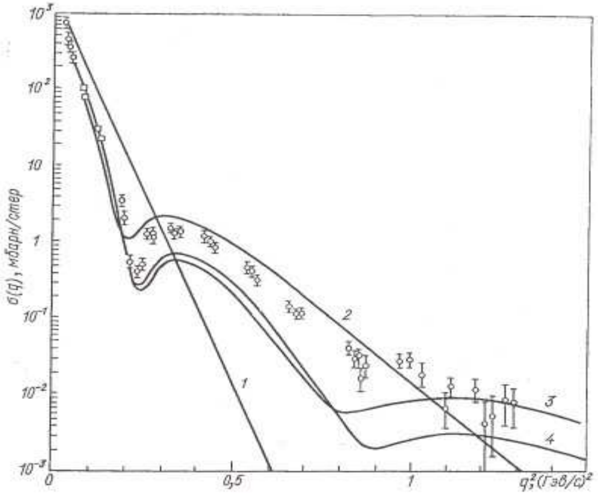


Рис.4. Зависимость дифференциального сечения упругого рассеяния протонов с энергией 1000 *Мэв* на ядре He^4 от квадрата переданного импульса q^2 [24]:

1 соответствует учету только однократного рассеяния (импульсное приближение); 2 —учету однократного и двухкратного рассеяния и т. д.

It is of interest to study the different class nucleus-nucleus collisions leading to the desintegration of projectile.(Pomeranchuk and Feinberg,1953) Nowdays this field of hight energy physics is deeply involved in the research program of BECQUEREL Project,2008, http://becquerel.jinr.ru/.

These processes are favourable to separate the Coulomb mechanism and nuclear one suppressed at small momentum transfers Q (where Coulomb interaction is important) tue to orthogonality of the initial and final internal states of incident nucleus .

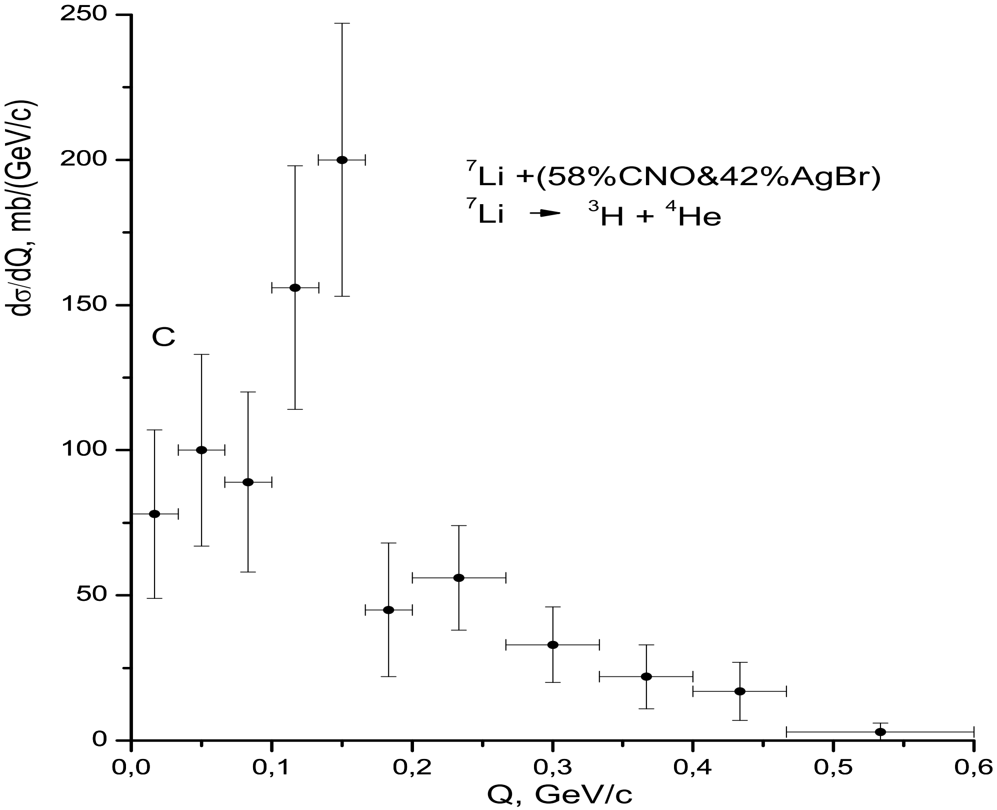
The different diffractional pattern is expected in comparison with elastic scattering one.

The simplist process is a coherent tow-body breakup of projectile.
To avoid a tedious treatment of final nuclear breakup states
as a first step it is preferable to take the simple probe projectiles:
the deuteron (n,p)
or the lightest 1p-shell nuclei having the dominating
two-cluster structure:
$^6Li\ (\alpha, d)$, $^7Li\ (\alpha, t)$,$^7Be\ (\alpha,^3He)$
Measurements of dσ/dQ are not available now for the two-body
coherent breakup for these projictiles including deuteron.

2. Experiment and results.

Nuclear photoemulsion BR-2 has been irradiated in the 3A GeV/c
^7Li beam by
the JINA nuclotron.
The nuclear contents of emulsion:
H–$2.97 \cdot 10^{22}$cm^{-3}, CNO–$2.85 \cdot 10^{22}$cm^{-3}, Br–$1.03 \cdot 10^{22}$cm^{-3},
Ag–$1.03 \cdot 10^{22}$cm^{-3}.
Singly and doubly charged particles were easily distinguished visually by
the ionization density.
Masses of fragments were determined by the multiple Coulomb scattering method
descibed in M.I. Adamovich *et al.*, J. Phys. G **30**, 1479 (2004),
D.A. Artemenkov, thesis, JINA, (2008).

The 3730 inelastic interactions of ^7Li were observed and only 85 events of the coherent desintegration of ^{7}Li to ^{3}H+^{4}He were separated.
The total length of beam tracks for these 85 events is 548.37 m that corresponds to the mean free path 6.5±0.7 m for the reaction considered.
The total cross section averaging over all photoemulsion nuclei is σ=85/(5.4837$\cdot$10^{4}см$\cdot$4.91$\cdot$10^{22}см$^{-3}$)=31±4 mb.
The experimental cross section dσ/dQ is shown in Fig.1
The accuracy of measurement of Q is about 10 MeV/c.



250
200
150
100
50
0
dσ/dQ, mb/(GeV/c)
C
7Li +(58%CNO&42%AgBr)
7Li → 3H + 4He
0,0
0,1
0,2
0,3
0,4
0,5
0,6
Q, GeV/c

Ingredients used to treat the experimental data:

1.The current two-cluster model of ^{7}Li for the bound and continuum states
developed by the NPI MSU theoretical group (Neudatchin, Smirnov, Kukulin).

2.The Bertulani-Baur theory (Coulomb breakup of relativistic ^{7}Li to ^{3}H+^{4}He) .

3.Akhieser-Sitenko-Glauber diffractional theory developed in application to two-cluster nuclei by the NPI (Kiev) theoretical group (Evlanov et al.)(Nuclear diffractional breakup of relativistic ^{7}Li to ^{3}H+^{4}He)

(^{3}H,^{4}He)-INTERACTION POTENTIAL

$$V(r) = -V_0(1 + exp[(r - R)/a])^{-1}, \quad V_{so}(r) \ = -V_1 \mathbf{ls} \frac{d}{r\,dr} V(r),$$

$$V_c(r) = \begin{cases} \frac{Z_1 Z_2 e^2}{2R}(3 - \frac{r^2}{R^2}), & r \leq R \\ \frac{Z_1 Z_2 e^2}{r}, & r > R. \end{cases}$$

This cluster model gives the successful description of the ^{7}Li properties, scattering phases and the two-body photodesintegration data (Dubovichenko, Burkova et al.)
with parameters

$$V_{00}\text{=98.5 MeV},\ \ \Delta V\text{=11.5 MeV},\ \ R\text{=1.8 fm},\ \ a\text{=0.7 fm},$$

$$V_0 = V_{00} + \Delta V(-1)^{l+1},\ \ V_1 = 0.015(3+(-1)^{l+1})\ \text{fm}^2.$$

Allowed states: $3P_{3/2}(-2.36\,\text{MeV})$, $3P_{1/2}(-1.59)$.
Forbidden states: $0S_{1/2}(-57.4)$, $2S_{1/2}(-15.9)$, $1P_{3/2}(-34.4)$, $1P_{1/2}(-32.3)$, $2D_{5/2}(-13.7)$, $2D_{3/2}(-11.1)$.

E1-TRANSITIONS: $3P_{3/2} \to S_{1/2}, D_{3/2}, D_{5/2}$.

$$\frac{d\sigma_c}{dQ} = \frac{32}{9}\left(\frac{Ze^2}{\hbar v}\right)^2 c_d Q R^2 \int_0^\infty \frac{\xi^2}{(\xi^2+(QR)^2)^2}(I_2^2(k)+\frac{1}{2}I^2_{0,1/2}(k))(f_1^2+\frac{1}{\gamma^2}f_0^2)k^2 dk.$$

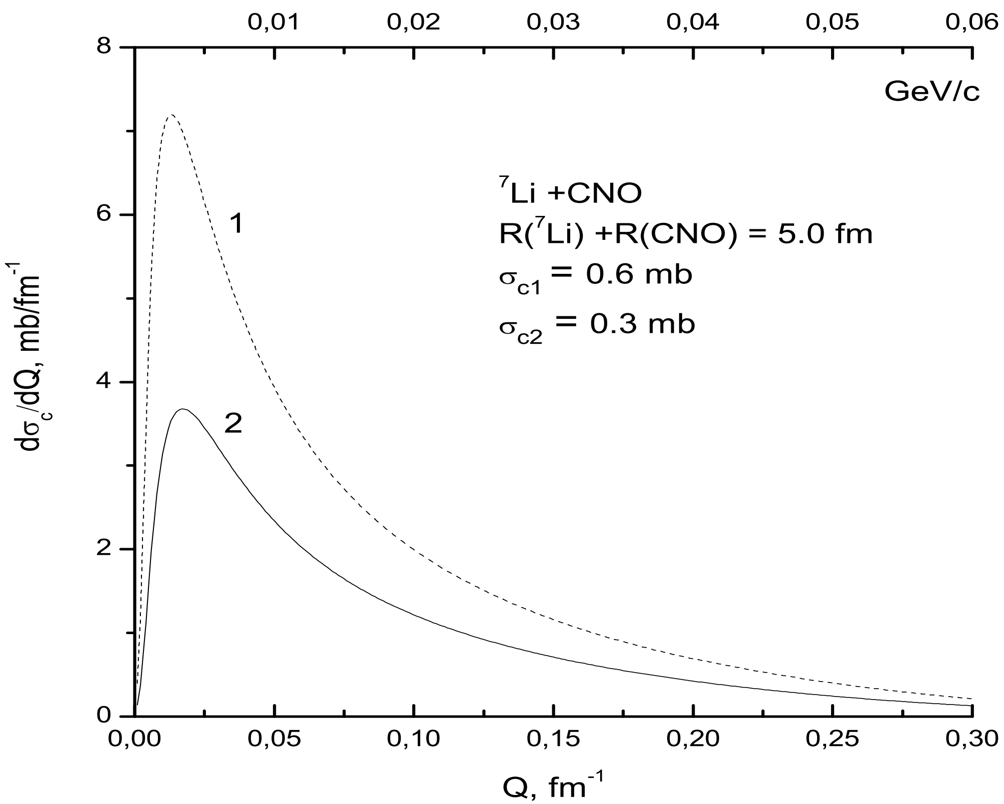
$$f_n = \xi J_n(QR)K_{n+1}(\xi) - QRJ_{n+1}(QR)K_n(\xi),\; I_{l,j}(k) = \int_0^\infty R_{l,j}(k,r)R_i(r)r^3 dr,$$

J_n, K_n- the Bessel functions,

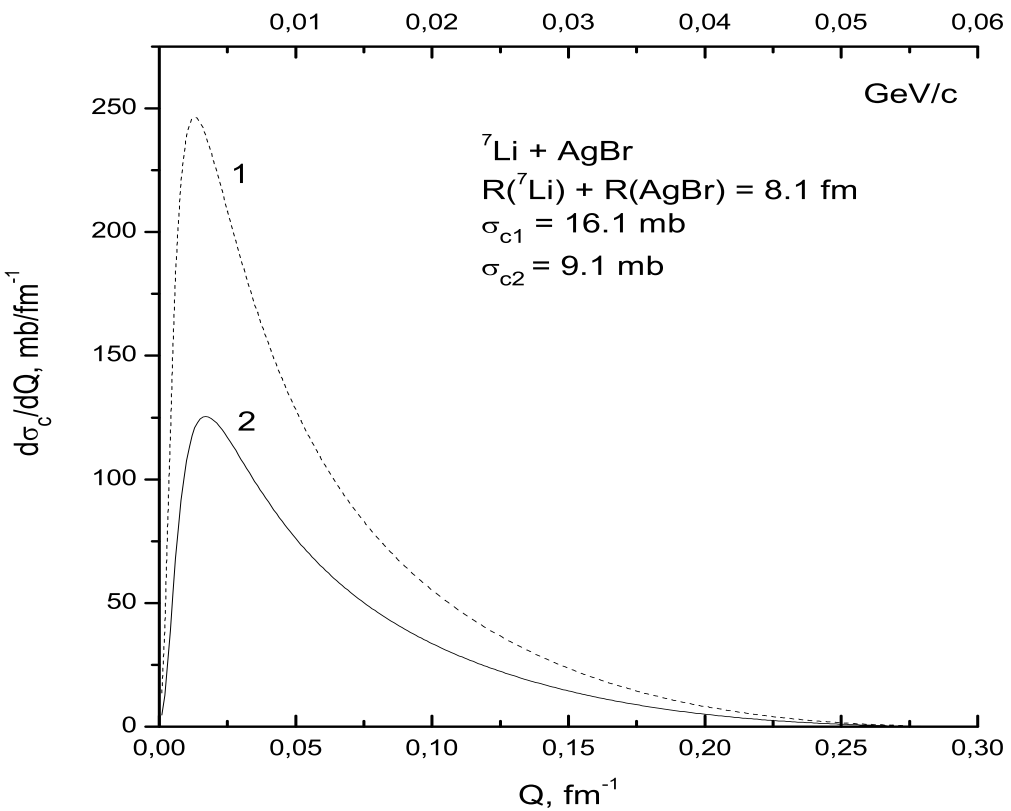
R$_i, R_{lj}-$ the radial wave functions of clusters in ground and continuum state

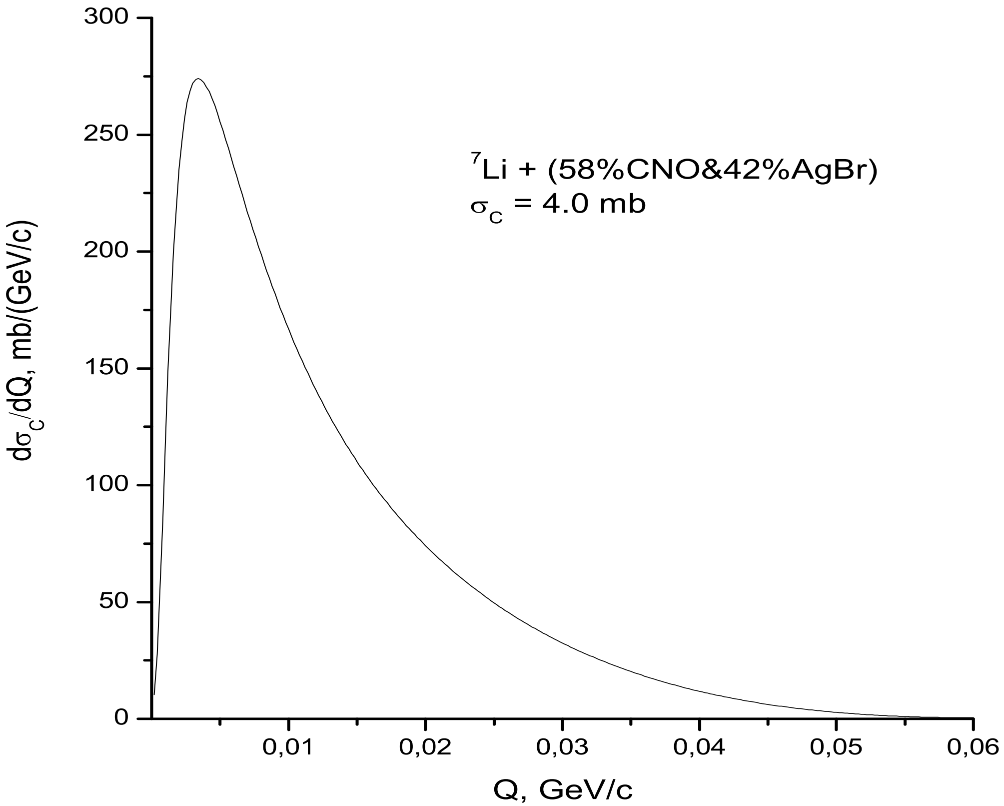
$\gamma = (1-(v/c)^2)^{-1/2}$, $\xi = (\omega R)/(\gamma v)$, $\omega = E_b + (\hbar k)^2/(2\mu_{\alpha t})$.

$c_d = (Z_1\beta_1 - Z_2\beta_2)^2$, $\bar{R} = 5.0\,\mathrm{fm}, \bar{Z} = 7(CNO)$; $\bar{R} = 8.1\,\mathrm{fm}, \bar{Z} = 41(AgBr)$.

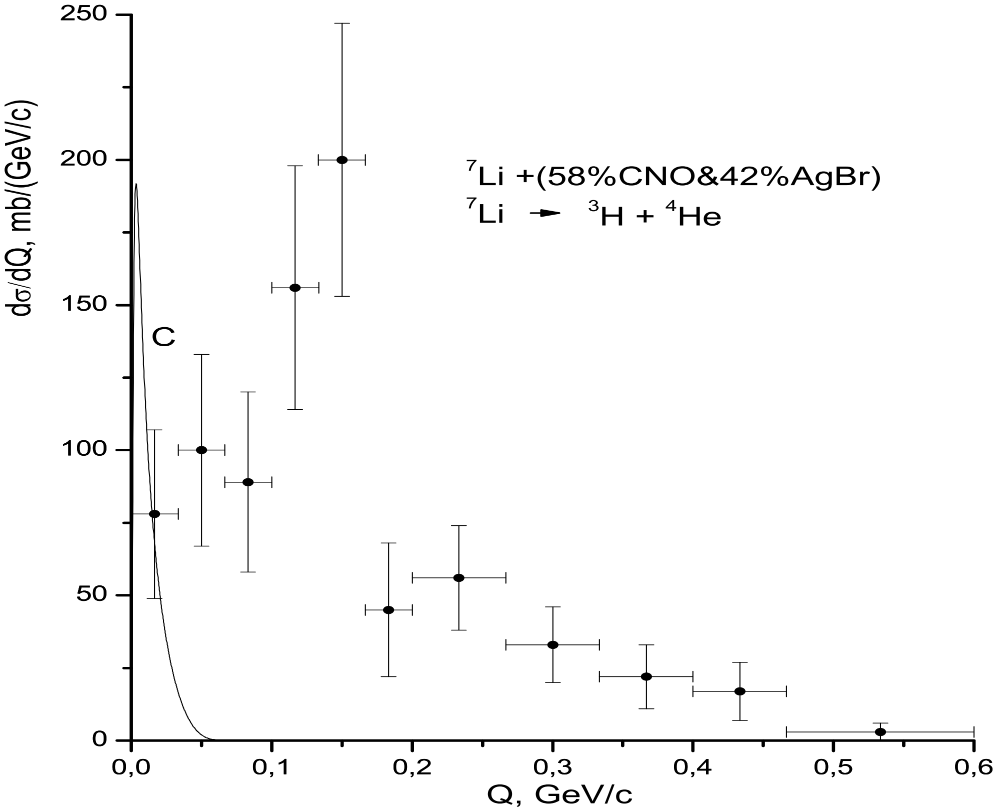


0,01
0,02
0,03
0,04
0,05
0,06
GeV/c
8
6
4
2
0
^{7}Li +CNO
R(^{7}Li) +R(CNO) = 5.0 fm
σ_{c1} = 0.6 mb
σ_{c2} = 0.3 mb
1
2
$d\sigma_c/dQ$, mb/fm^{-1}
0,00
0,05
0,10
0,15
0,20
0,25
0,30
Q, fm^{-1}


0,01
0,02
0,03
0,04
0,05
0,06
GeV/c
250
200
150
100
50
0
1
2
⁷Li + AgBr
R(⁷Li) + R(AgBr) = 8.1 fm
σc1 = 16.1 mb
σc2 = 9.1 mb
dσc/dQ, mb/fm-1
0,00
0,05
0,10
0,15
0,20
0,25
0,30
Q, fm-1



^{7}Li + (58%CNO&42%AgBr)
σ_C = 4.0 mb
$d\sigma_C/dQ$, mb/(GeV/c)
Q, GeV/c
0
50
100
150
200
250
300
0,01
0,02
0,03
0,04
0,05
0,06



250
200
150
100
50
0
dσ/dQ, mb/(GeV/c)
^{7}Li +(58%CNO&42%AgBr)
^{7}Li → ^{3}H + ^{4}He
C
0,0
0,1
0,2
0,3
0,4
0,5
0,6
Q, GeV/c

THE DIFFRACTIONAL BREAKUP OF DEUTERON (Akhieser, Sitenko 1955):

$$A_{\mathbf{Q},\mathbf{k}} = \iint \varphi_{\mathbf{k}}(\mathbf{r})^* \psi_{\mathbf{Q}}(\boldsymbol{\rho})^* \Omega_n \Omega_p \, \psi_0(\boldsymbol{\rho}) \varphi_0(\mathbf{r}) d\boldsymbol{\rho} \, d\mathbf{r}$$

$$= - \iint \varphi_{\mathbf{k}}(\mathbf{r})^* \psi_{\mathbf{Q}}(\boldsymbol{\rho})^* (\omega_n + \omega_p - \omega_n \, \omega_p) \psi_0(\boldsymbol{\rho}) \varphi_0(\mathbf{r}) d\boldsymbol{\rho} \, d\mathbf{r}$$

$$A_{\mathbf{Q},\mathbf{k}} = -\frac{2\pi R}{L^{7/2}} \frac{J_1(QR)}{Q} \Big\{ F(\frac{\mathbf{Q}}{2}, \mathbf{k}) + F(-\frac{\mathbf{Q}}{2}, \mathbf{k}) \Big\}$$
$$+ \frac{R^2}{L^{7/2}} \int \frac{J_1(|\frac{\mathbf{Q}}{2} + \mathbf{Q}'|R)}{|\frac{\mathbf{Q}}{2} + \mathbf{Q}'|} \frac{J_1(|\frac{\mathbf{Q}}{2} - \mathbf{Q}'|R)}{|\frac{\mathbf{Q}}{2} - \mathbf{Q}'|} F(\mathbf{Q}', \mathbf{k}) d\mathbf{Q}',$$

где

$$F(\mathbf{q}, \mathbf{k}) = \int exp(i\mathbf{q}\mathbf{r}) \varphi_{\mathbf{k}}(\mathbf{r})^* \varphi_0(\mathbf{r}) d\,\mathbf{r}, \quad d\sigma = |A_{\mathbf{Q},\mathbf{k}}|^2 L^2 \frac{L^2 d\mathbf{Q}}{(2\pi)^2} \frac{L^3 d\mathbf{k}}{(2\pi)^3}.$$

For the black nucleus model with a sharp border:

$$\omega(b) = 1 - \Omega(b) \qquad \text{(Akhieser, Sitenko 1955,1957).}$$

В теории многократного рассеяния:

$$\omega(b) = 1 - exp(i\chi(b)) \qquad \text{(Glauber 1955), where}$$

$$exp(i\chi(b)) = <\psi_{A_1}(\{\mathbf{s}_j\})\psi_{A_2}(\{\mathbf{s}_i\})| \times \prod_{j=1}^{A_1}\prod_{i=1}^{A_2}[1 - \Gamma_{ji}(\mathbf{b} - \mathbf{s}_j - \mathbf{s}_i)]$$
$$\times \psi_{A_1}(\{\mathbf{s}_j\})\psi_{A_2}(\{\mathbf{s}_i\}) >, \text{ where}$$

$$\Gamma_{ji}(\mathbf{b}) = \frac{1}{2\pi i k_{ji}}\int exp(-i\mathbf{q}\mathbf{b}) f_{ji}(q) d\,q$$

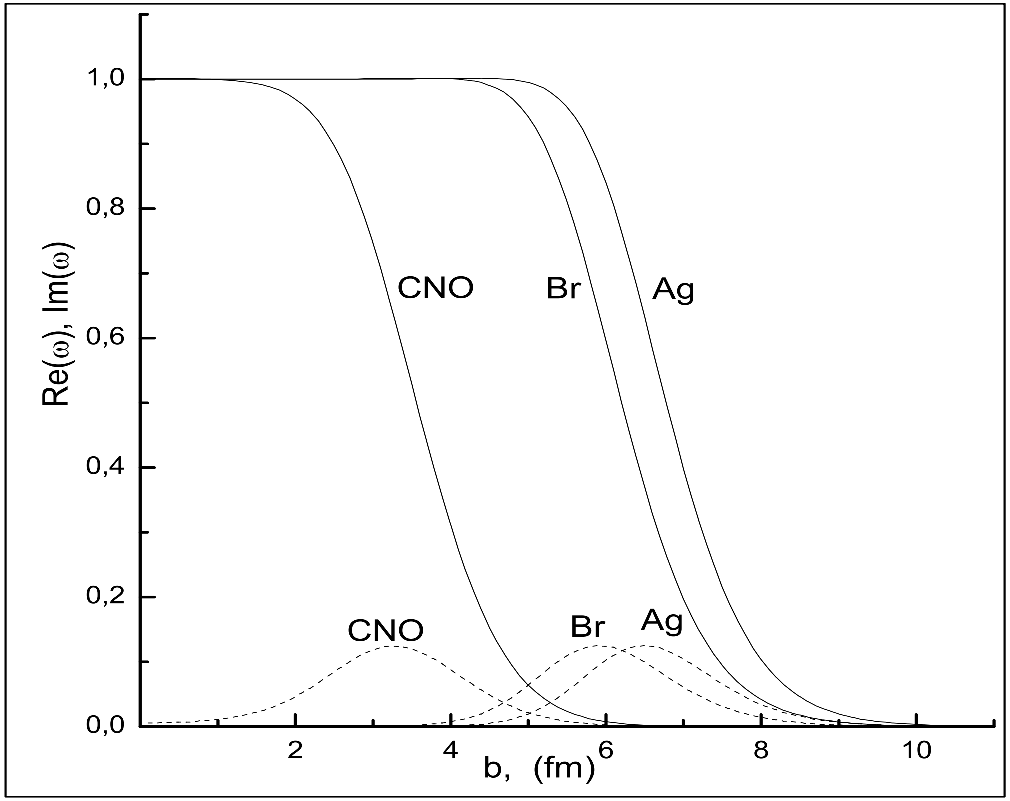
In the optical limit:

$$i\chi(b) = - <\psi_{A_1}\psi_{A_2}| \sum_{j=1}^{A_1}\sum_{i=1}^{A_2}\Gamma_{ji}(\mathbf{b} - \mathbf{s}_j - \mathbf{s}_i)|\psi_{A_1}\psi_{A_2}> .$$

V. Franco, A. Tekou:

$$i\chi(b) = -\frac{A_1 A_2 \sigma_N}{8\pi^2}(1-i\rho)\int exp(-i\mathbf{qb}-a_N q^2/2)K(q)S_{A_1}(q)S_{A_2}(q)d^2q,$$

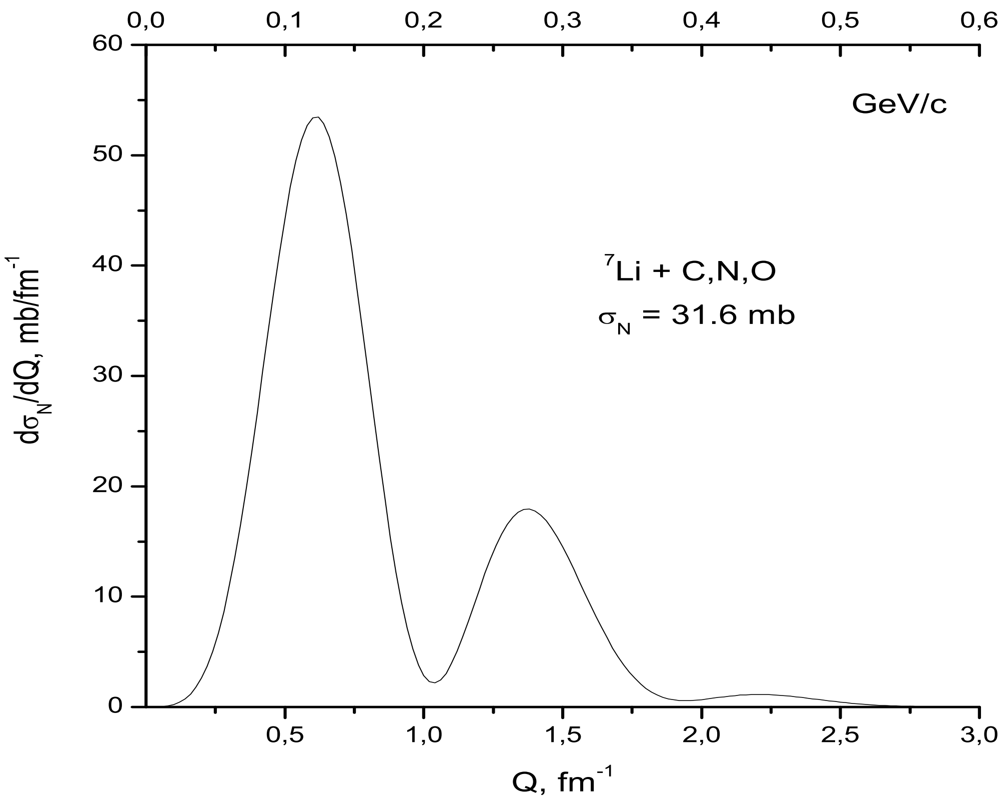
$\bar{r}_t$=1.70, $\bar{r}_\alpha$=1.67, $\bar{r}_{CNO}$=2.54, $\bar{r}_{Br}$=5.1 , $\bar{r}_{Ag}$=5.62 (fm).
σ_N=43.0 mb, ρ=-0.35, a_N=0.242 fm^2.


1,0
0,8
0,6
0,4
0,2
0,0
Re(ω), Im(ω)
CNO
Br
Ag
CNO
Br
Ag
2
4
6
8
10
b, (fm)

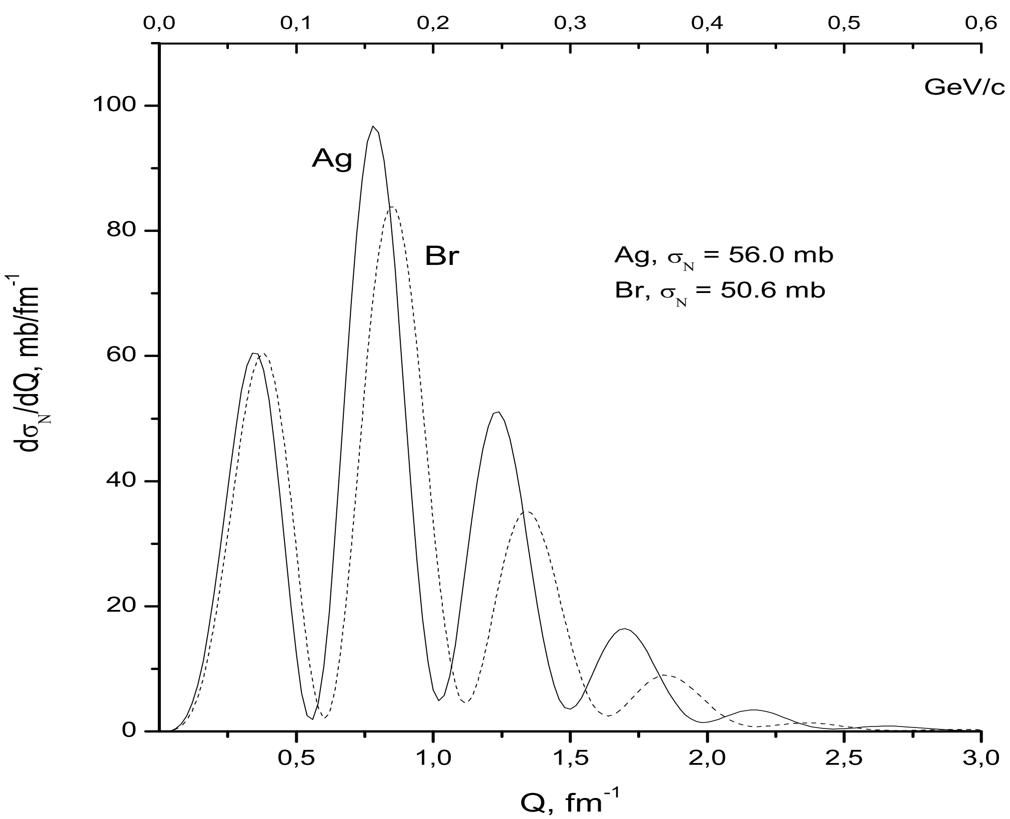
$$\frac{d\sigma_N}{dQ} = A\Big(1 + I_0(Q) - \frac{3}{2}\sum_{lj,L}(I_L^{lj}(\beta_1 Q) + (-1)^L I_L^{lj}(\beta_2 Q))^2 (10l0|L0)^2 \times \begin{Bmatrix} j & l & 1/2 \\ 1 & 3/2 & L \end{Bmatrix}^2\Big)$$

$$\frac{A}{4\pi Q} = \left|\int_0^\infty \omega(b) J_0(Qb) b db\right|^2,\ I_0(q) = \int_0^\infty j_0(qr) R_i^2 r^2 dr,$$

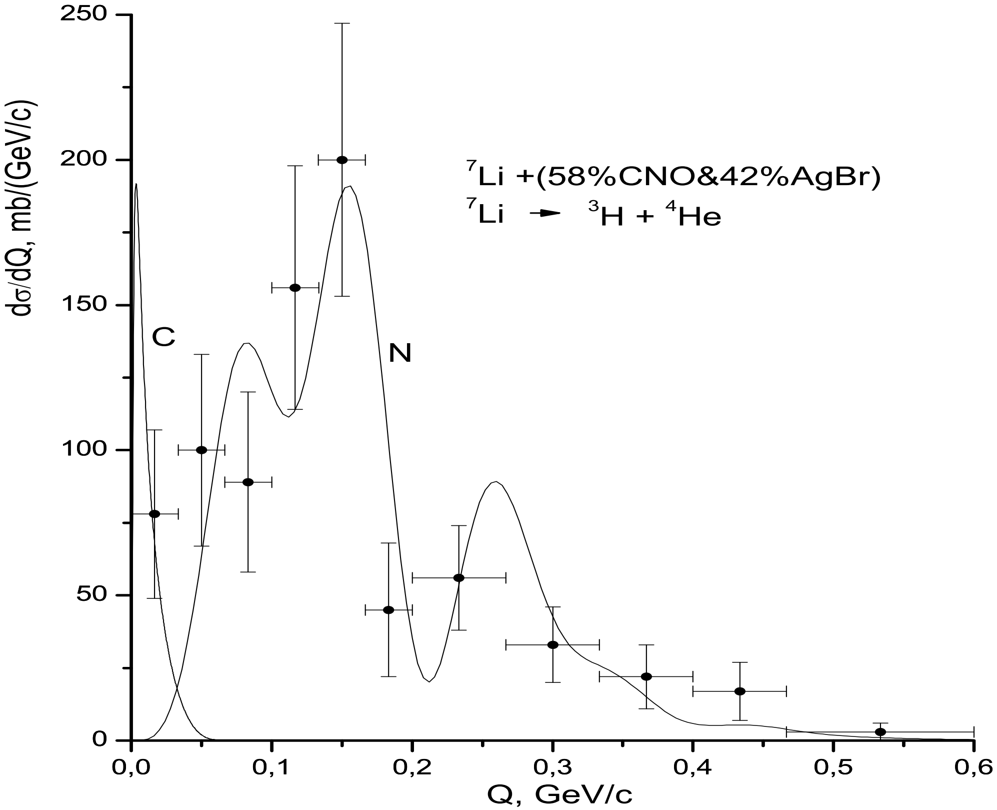
$$I_L^{lj}(q) = \int_0^\infty j_L(qr) R_{lj} R_i r^2 dr$$



0,0
0,1
0,2
0,3
0,4
0,5
0,6
GeV/c
60
50
40
30
20
10
0
$d\sigma_N/dQ$, mb/fm^{-1}
^{7}Li + C,N,O
σ_N = 31.6 mb
0,5
1,0
1,5
2,0
2,5
3,0
Q, fm^{-1}



0,0
0,1
0,2
0,3
0,4
0,5
0,6
GeV/c
100
80
60
40
20
0
Ag
Br
Ag, σ_N = 56.0 mb
Br, σ_N = 50.6 mb
$d\sigma_N/dQ$, mb/fm^{-1}
0,5
1,0
1,5
2,0
2,5
3,0
Q, fm^{-1}



^{7}Li +(58%CNO&42%AgBr)
^{7}Li → ^{3}H + ^{4}He
C
N
dσ/dQ, mb/(GeV/c)
Q, GeV/c
0
50
100
150
200
250
0,0
0,1
0,2
0,3
0,4
0,5
0,6

sults (column 6) by between 0 and 4 %. On the other hand, when these cross sections are calculated using $\chi_1(b)$, the results (column 2) differ from these exact results by between 1 and 18 %. Thus, by means of the very simple modification of the usual optical phase shift function we obtain significantly improved results.

If we compare the cross sections presented in columns 5 and 6 with the data shown in column 7, we note that the results are in good qualitative agreement, but that there is room for improvement. We also note that the large discrepancy between theory and experiment for the ^{12}C-^{12}C cross section[2,14] is reduced considerably by use of a harmonic oscillator wave function and by use of the new first-order optical phase shift function $\bar{\chi}_1(b)$.

V. ELASTIC SCATTERING ANGULAR DISTRIBUTIONS

In Fig. 1 we show the differential cross section $d\sigma/d|t|$ as a function of t, the squared four-momentum transfer, for α-α elastic scattering at an incident energy of 2.1 GeV/nucleon. The solid curve is the exact Glauber result. The dashed curve is obtained using the new first-order optical phase shift function $\bar{\chi}_1(b)$ in Eq. (9). The dotted curve is obtained with the usual first-order optical phase shift function $\chi_1(b)$ in Eq. (12). We note that

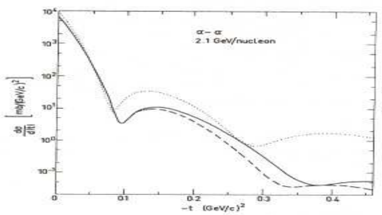


FIG. 1. Differential cross sections for ^4He-^4He elastic scattering at an incident energy of 2.1 GeV/nucleon as a function of t, the squared four-momentum transfer. The solid curve is the exact Glauber multiple scattering result. The dashed curve is obtained using the new first order optical phase shift function $\bar{\chi}_1(b)$. The dotted curve is obtained using the usual first order optical phase shift function $\chi_1(b)$.

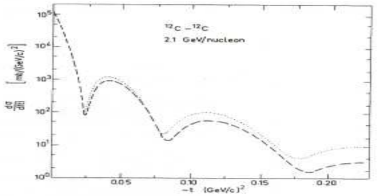
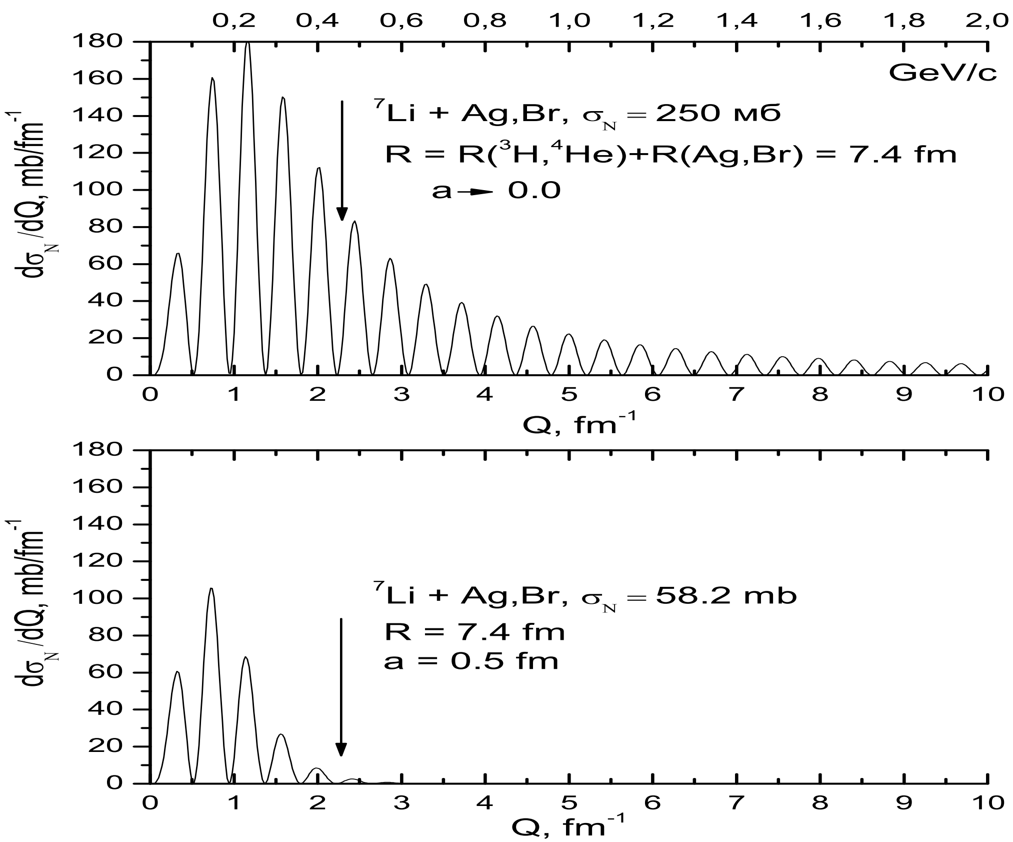


FIG. 2. Differential cross sections for ^{12}C-^{12}C elastic scattering at an incident energy of 2.1 GeV/nucleon as a function of t. The dashed (dotted) curve is obtained using the new (usual) first order optical phase shift function.

up through the second maximum $[-t\sim 0.14\ (\mathrm{Gev}/c)^2]$ the results obtained with the new optical phase shift function $\bar{\chi}_1(b)$ are very close to the exact Glauber results, whereas the results obtained with the usual optical phase shift function $\chi_1(b)$ differ from the exact Glauber results by as much as a factor of 5. At large momentum transfers (not shown) the cross section obtained with $\chi_1(b)$ *increases*, whereas the exact cross section and that obtained with $\bar{\chi}_1(b)$ continue to decrease. The cross section obtained with $\chi_1(b)$ attains an *absolute* minimum of ~0.1 mb/(GeV/c)^2 at $-t\approx 1.2\ (\mathrm{GeV}/c)^2$. Beyond this value of t the cross section rises and, after a very shallow relative minimum of ~0.4 mb/(GeV/c)^2 at $-t\approx 1.8\ (\mathrm{GeV}/c)^2$, it rises *monotonically*.

In Fig. 2 we show the differential cross section for ^{12}C-^{12}C elastic scattering at 2.1 GeV/nucleon. The dashed curve is obtained using the new first-order optical phase shift function $\bar{\chi}_1(b)$ in Eq. (9). The dotted curve is obtained with the usual first-order optical phase shift function $\chi_1(b)$ in Eq. (12). Harmonic oscillator wave functions were used. As expected, the center-of-mass effects are smaller for this heavier system than they were for α-α scattering. Nevertheless, one still observes differences of a factor of ~2 near the first minimum $[-t\approx 0.026\ (\mathrm{GeV}/c)^2]$, and beyond the second minimum $[-t\gtrsim 0.085\ (\mathrm{GeV}/c)^2]$, and a factor of ~3 beyond the third minimum $[-t\gtrsim 0.18\ (\mathrm{GeV}/c)^2]$. The difference increases markedly at larger momentum transfers (not shown). At very large momentum transfers the cross section obtained with the usual optical phase shift function χ_1 increases.


0,2 0,4 0,6 0,8 1,0 1,2 1,4 1,6 1,8 2,0
GeV/c
^{7}Li + Ag,Br, $\sigma_N = 250$ мб
R = R(^{3}H,^{4}He)+R(Ag,Br) = 7.4 fm
a → 0.0
$d\sigma_N/dQ$, mb/fm^{-1}
Q, fm^{-1}
^{7}Li + Ag,Br, $\sigma_N = 58.2$ mb
R = 7.4 fm
a = 0.5 fm
$d\sigma_N/dQ$, mb/fm^{-1}
Q, fm^{-1}

CONCLUSIONS:

Coherent dissociation of relativistic nuclei ^{7}Li at the momentum of 3A GeV/c to ^{3}H + ^{4}He was studied by the photoemulsion technique.

Results on the total (31$\pm$ 4 mb) and differential vs the momentum transfer Q cross sections are presented.

The shape of this cross section differs from usual shapes of elastic scattering cross sections.

The observed Q-dependence of cross section is interpreted within the cluster model and the Akhieser-Sitenko-Glauber approach mainly as the superposition of two individual nuclear diffractional patterns from light (C,N,O) and heavy (Br, Ag) nuclei.

The contributions to cross section due to the electromagnetic (the Bertulani-Baur theory) and nuclear interactions are well separated in the variable Q. Calculated values are correspondingly 4 mb (Q$\leq$ 50 MeV/c) and 40.7 mb (Q$\leq$ 400 MeV/c).

Counter technique experiments on pure targets to observe the predicted cross section oscillations are desirable.