Higher Order Multipole Transition Effects in the Coulomb Dissociation Reactions of Halo Nuclei

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Scheme of Presentation

1. Introduction

- *What is Nucleon Halo?*
- *What are Coulomb Breakup Reactions?*
- *What is the Need of Studying the Higher Order Multipole Transition Effects Separately?*

2. Eikonal Approximation Approach

3. Results of Our Calculations

4. Conclusions and Future Prospectus

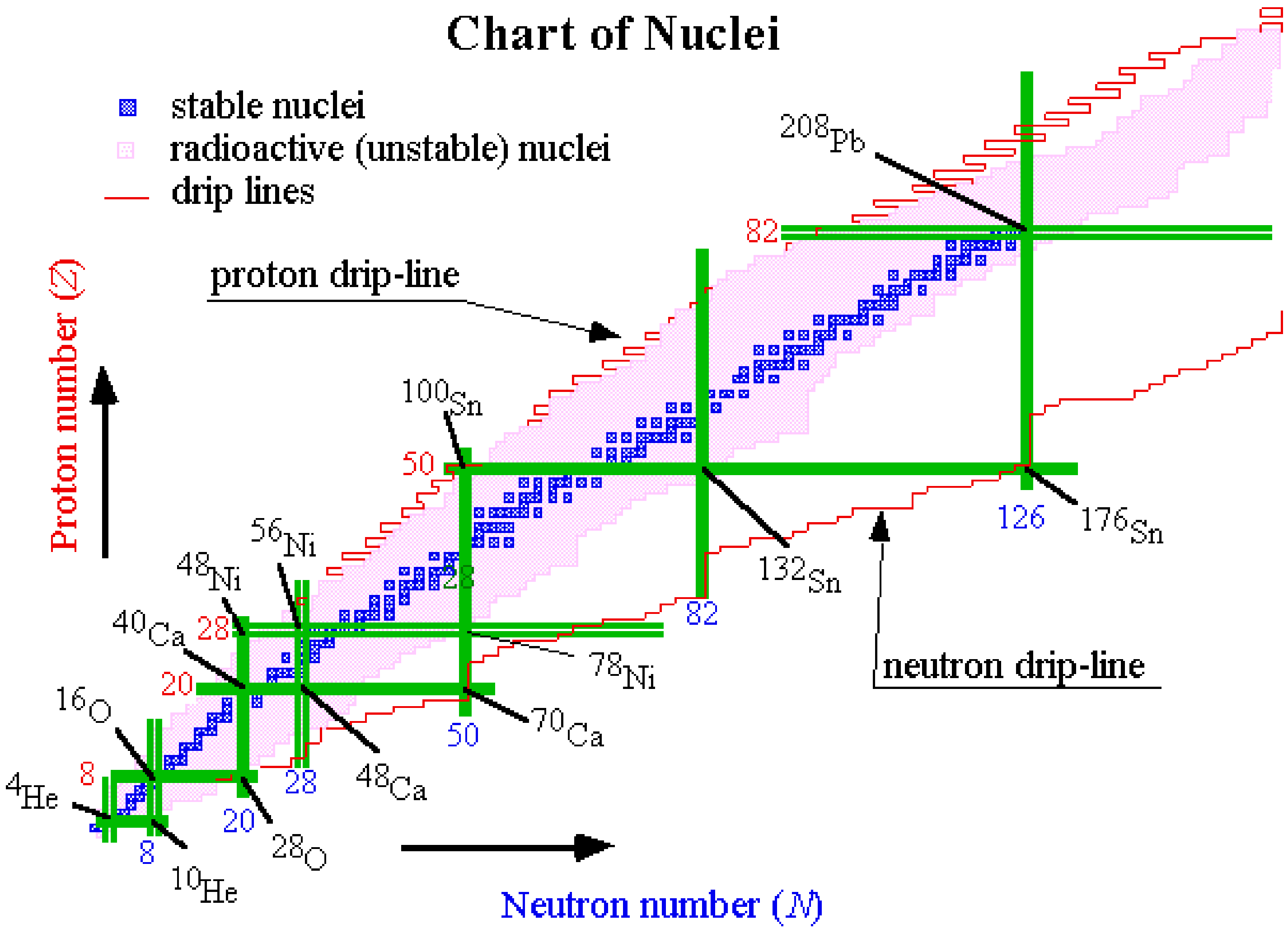
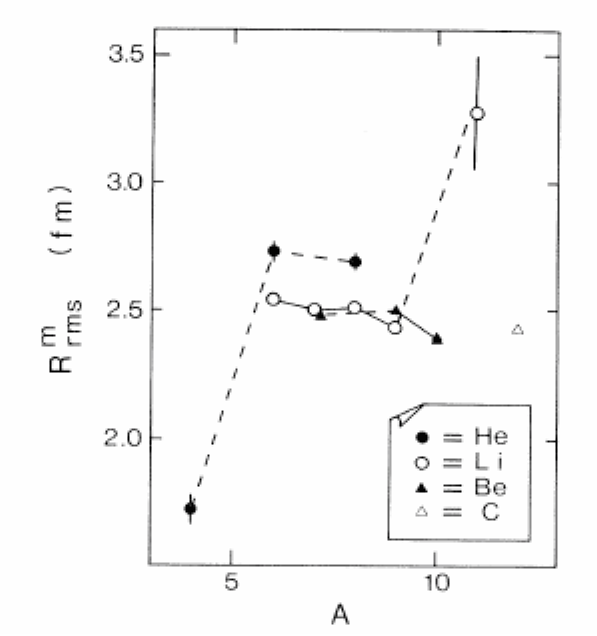
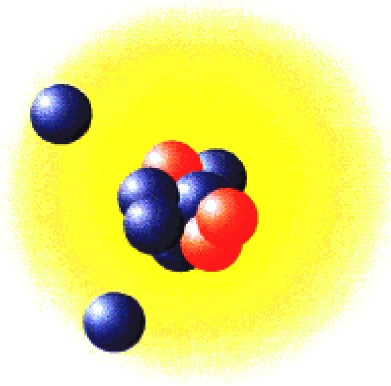


Fig. 1 Nuclear Landscape

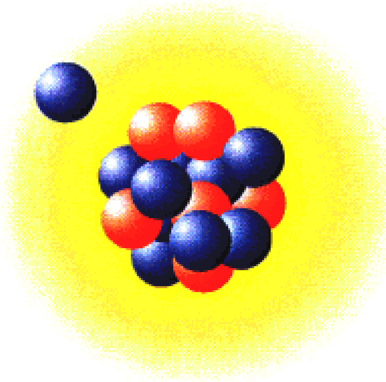
• An abrupt rise in the rms matter radius of ^{11}Li determined from the measurement of interaction cross section for various Li-isotopes had been observed by Tanihata et al[1985] which was attributed to large deformation and/or long tail in the matter distribution of ^{11}Li.



•This novel structure feature has been found in a number of light, extremely neutron rich nuclei.



^{11}Li
Halo Nucleus



^{19}C
Halo Nucleus

- The combination of the low neutron separation energy and the short range of nuclear forces allow the neutron (or cluster of neutrons) to tunnel into the space surrounding the nuclear core so that neutrons are present with appreciable probability at distances much more than the normal nuclear radius.

- Small binding energy, large matter radius, long tail in density distribution and the narrow component in the longitudinal momentum distribution of the dissociated fragment are some characteristics features of halo nuclei.

- In fast peripheral heavy-ion collisions, the breakup of projectile into two fragments is an important reaction channel.
- The force causing dissociation is obviously coulomb or nuclear depending on the size of the target and the impact parameter.
- If the size of target is large and the impact parameter is larger than the sum of the radii of target and projectile then the nuclear forces do not come into play and the projectile gets excited due to coulomb forces and it may breakup in to constituent clusters. This process is referred to as coulomb or electromagnetic breakup.

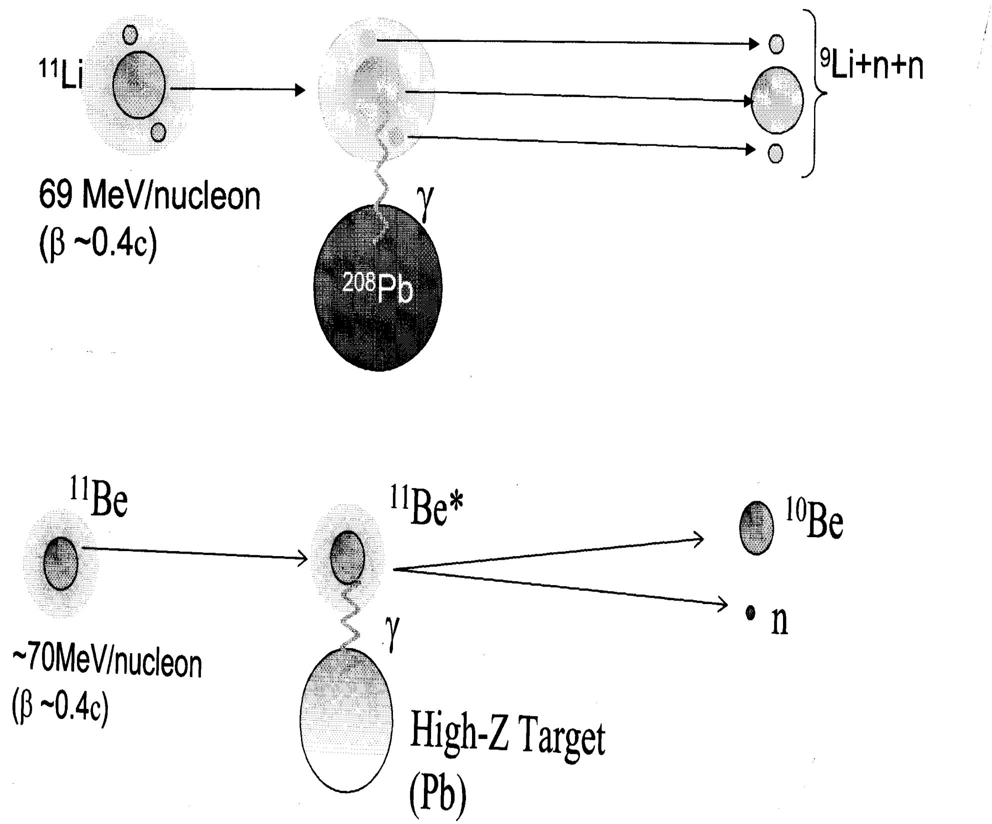


Fig. 3 Coulomb Breakup of ^{11}Li and ^{11}Be

- Recently the breakup of nuclei under the time varying electromagnetic field of heavy targets has attracted a significant interest in conjugation with nuclear astrophysics and nuclear structure studies.

- Various problems of nuclear astrophysics are directly related to the radiative capture reactions at low energies. So far, these reactions can not be performed in the laboratory because of the unavailability of the stellar environment.

- Thus an alternative approach, proposed by G. Baur et al, consists in using the coulomb breakup reaction as a source of information regarding the corresponding radiative capture reaction through the detailed balance theorem, is used as an effective tool.

b + c $\rightarrow$ a + γ (radiative capture reaction)

γ + a $\rightarrow$ b + c (coulomb breakup reaction)

The cross sections of corresponding reactions are related by the detailed balance theorem as

$$\sigma(b+c \rightarrow a+\gamma) = \frac{(2j_a+1)2}{(2j_b+1)(2j_c+1)} \frac{k_\gamma^2}{k^2} \sigma(a+\gamma \rightarrow b+c)$$

σ(a + γ $\rightarrow$ b + c) is the coulomb break up cross section
σ(b + c $\rightarrow$ a + γ) is the radiative capture cross section

(1) Ground state Wave function

(2) Spectroscopic factors

(3) Angular momentum

(4) Spin parity of ground state

(5) Binding energy of projectile

(6) Confirmation of halo structure

- However, different multipole transitions contribute differently in the radiative capture and the coulomb breakup reactions. As a result, in order to obtain reliable astrophysical information from coulomb breakup reactions the effects of higher order multipole transitions, in particular E2 and E1-E2 interference, has to be reported.

Theoretical Formalism

At high energy the eikonal approximation approach is the most convenient one to describe the coulomb breakup process and in this approach the transition amplitude for any electric multipolarity is given as

$$f_c(\vec{Q},\vec{q}) = i\frac{Z_t\alpha}{\beta\gamma}kR^2\sum_{lm} i^m\sqrt{2l+1}\left(\frac{\omega}{c}\right)^l G_{Elm}\left(\frac{c}{v}\right)\phi_m(Q)\,M(Elm) \qquad 1$$

The matrix element appearing in eq. (1) contain structural information regarding projectile's ground state and in the long wavelength approximation is given by

$$M(Elm) = \sum_{j=1,2} Z_j e\int \phi_f^*(\vec{r})\, r_j^l\, Y_{lm}(\hat{n}_j)\,\phi_i(\vec{r})d^3\vec{r} \qquad 2$$

and the use of simple shell model wave function for the ground state of the projectile and plane wave for the final state continuum modifies it to the following form

$$M(Elm) = \sqrt{4\pi}\, Z_l^{eff} \sqrt{2l+1}\sqrt{2L+1} \sum_{\lambda \upsilon} i^{-\lambda} \frac{1}{\sqrt{2\lambda+1}} Y_{\lambda\upsilon}(\hat{q}) \langle Ll00|\lambda 0\rangle \langle LlMm|\lambda\upsilon\rangle$$

$$\times \int_0^\infty r^2 dr\, r^l j_\lambda(qr) R_L(r), \qquad 3$$

Now, the differential cross section for coulomb excitation is related to the transition amplitude through the relation by

$$d^4\sigma = \frac{1}{\sqrt{2L+1}} \sum_M \left| f_c(\vec{Q},\vec{q}) \right|^2 \frac{Q\, dQ\, d\vec{q}}{(2\pi)^2 k^2} \qquad 4$$

Substitution of Eqs.(2) and (3) into Eq. (1) and resulting relation into Eq.(4) along with some mathematical exercise leads to

$$\frac{d\sigma}{d\vec{q}} = \frac{Z_t^2\alpha^2}{2\pi} \sum_{\substack{M,\ell_1,\ell_2,m_1,m_2,\\ \lambda_1,\lambda_2,\nu_1,\nu_2}} \imath^{m_1-\lambda_1}(-\imath)^{m_2-\lambda_2}\hat{L}\hat{\ell}_1^2\hat{\ell}_2^2\hat{\lambda}_1^{-1}\hat{\lambda}_2^{-1}(\frac{\omega}{c})^{\ell_1+\ell_2-2}$$
$$Z_{\ell_1}^{eff} Z_{\ell_2}^{eff} G_{E\ell_1 m_1} G^*_{E\ell_2 m_2} f_{m_1 m_2} I_{L\ell_1\lambda_1} I_{L\ell_2\lambda_2} Y_{\lambda_1\nu_1} Y^*_{\lambda_2\nu_2}$$
$$\langle L\ell_1 00|\lambda_1 0\rangle\langle L\ell_2 00|\lambda_2 0\rangle\langle L\ell_1 M m_1|\lambda_1\nu_1\rangle\langle L\ell_2 M m_2|\lambda_2\nu_2\rangle \qquad 5$$

In order to obtain the explicit expression for the longitudinal momentum distribution corresponding to pure dipole, quadrupole and dipole-quadrupole Interference term, we integrate Eq(5) over azimuthal angle and make use of properties of spherical harmonics and of C.G. Co-efficients, and obtain

$$\frac{d\sigma}{q^2 dq sin\theta d\theta} = \frac{Z_t^2\alpha^2}{\sqrt{4\pi}} \sum_{\substack{\ell_1,\ell_2,m,\\ \lambda_1,\lambda_2,S}} (-1)^{2L+S+\ell_1+m+\lambda_2}(-1)^{\frac{(\lambda_2-\lambda_1+\ell_1-\ell_2)}{2}}\, \hat{\ell}_1^2\hat{\ell}_2\hat{\lambda}_2\hat{S}(\frac{\omega}{c})^{\ell_1+\ell_2-2}$$

$$Z_{\ell_1}^{eff} Z_{\ell_2}^{eff} G_{E\ell_1 m_1} G^*_{E\ell_2 m_2} \overline{K}_m\, I_{L\ell_1\lambda_1} I_{L\ell_2\lambda_2} \langle L\ell_1 00|\lambda_1 0\rangle \langle L\ell_2 00|\lambda_2 0\rangle$$

$$\langle\lambda_1\lambda_2 00|S0\rangle \langle\ell_1\ell_2 m - m|S0\rangle\, \overline{Y}_{S0}(q)\, U(S\ell_1\lambda_2 0 : \ell_2\lambda_1) \qquad 6$$

Now by putting L=0, $l_1 = l_2 = \lambda_1 = \lambda_2 = 1$ and taking summation over $m_1 = m_2 =$ m = -1, 0, 1 and S=0 , 2 we get

$$\frac{d\sigma_{E_1}}{q^2 dq sin\theta d\theta} = \frac{4Z_t^2(Z_2^{eff})^2\alpha^2}{3\gamma^2\beta^2}\xi^2(I_{011})^2((K_1^2 - K_o^2)((1+2P_2) - (1-P_2)\gamma^2)$$

$$+\frac{2}{\xi}K_o K_1(1-P_2)\gamma^2) \qquad 7$$

Similarly for quadrupole and dipole-quadrupole interference

$$\frac{d\sigma_{E_2}}{q^2 dq sin\theta d\theta} = \frac{Z_t^2 (Z_2^{eff})^2 \alpha^2}{105\gamma^2\beta^4}\xi^2 (I_{022})^2 (\frac{\omega}{c})^2$$
$$(\frac{4}{\xi^2}K_1^2(7 - 10P_2 + 3P_4) + (K_1^2 - K_o^2)(28 + 20P_2 + 57P_4)$$
$$+(7 + 5P_2 - 12P_4)\gamma^2(2 - \beta^2)^2(\frac{2}{\xi}K_o K_1 - (K_1^2 K_o^2))) \qquad 8$$

$$\frac{d\sigma_{E_1 E_2}}{q^2 dq sin\theta d\theta} = \frac{4Z_t^2 Z_1^{eff} Z_2^{eff}\alpha^2}{5\gamma^2\beta^3}\xi^2 I_{011} I_{022}(\frac{\omega}{c})$$
$$((K_1^2 - K_o^2)(2P_1 + 3P_3) + (\frac{2}{\xi}K_o K_1 - (K_1^2 K_o^2))(P_1 - P_3)\gamma^2 \qquad 9$$

Now the expressions for the longitudinal momentum distribution of the outgoing Core fragments may be obtained by integrating Eqs.(7), (8) and (9) over all transverse momenta q_r

$$\frac{d\sigma_{E_1}}{dq_z} = \int_{|q_z|}^{\infty} \frac{4Z_t^2(Z_2^{eff})^2\alpha^2}{3\gamma^2\beta^2}\xi^2(I_{011})^2 \\ ((K_1^2 - K_o^2)((1+2P_2) - (1-P_2)\gamma^2) + \frac{2}{\xi}K_oK_1(1-P_2)\gamma^2)qdq \quad 10$$

$$\frac{d\sigma_{E_2}}{dq_z} = \int_{|q_z|}^{\infty} \frac{Z_t^2(Z_2^{eff})^2\alpha^2}{105\gamma^2\beta^4}\xi^2(I_{022})^2(\frac{\omega}{c})^2 \\ (\frac{4}{\xi^2}K_1^2(7-10P_2+3P_4) + (K_1^2 - K_o^2)(28+20P_2+57P_4) \\ +(7+5P_2-12P_4)\gamma^2(2-\beta^2)^2(\frac{2}{\xi}K_oK_1 - (K_1^2K_o^2)))qdq \quad 11$$

$$\frac{d\sigma_{E_1E_2}}{dq_z} = \int_{|q_z|}^{\infty} \frac{4Z_t^2 Z_1^{eff} Z_2^{eff} \alpha^2}{5\gamma^2\beta^3} \xi^2 I_{011} I_{022}(\frac{\omega}{c})$$

$$((K_1^2 - K_o^2)(2P_1 + 3P_3) + (\frac{2}{\xi}K_o K_1 - (K_1^2 K_o^2))(P_1 - P_3)\gamma^2$$

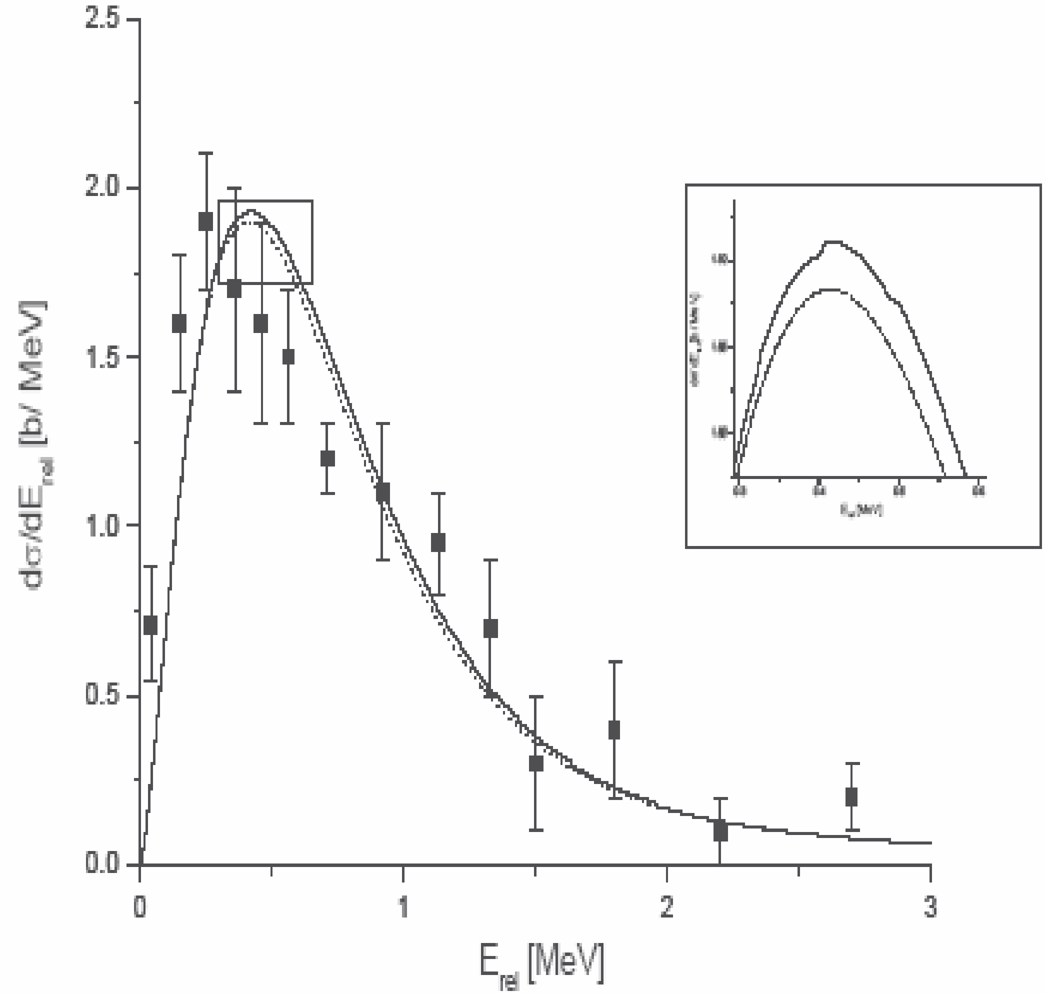
$$(2 - \beta^2))qdq$$

12

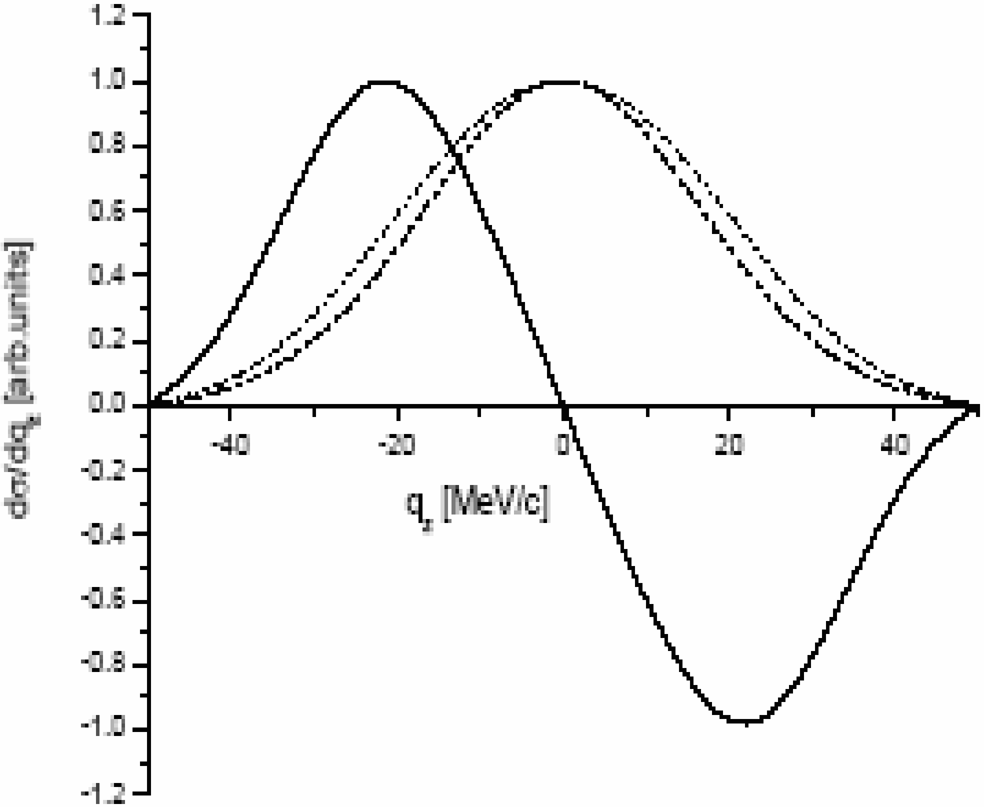
Our Results

Table II. *Integrated coulomb dissociation cross section on Pb target.*

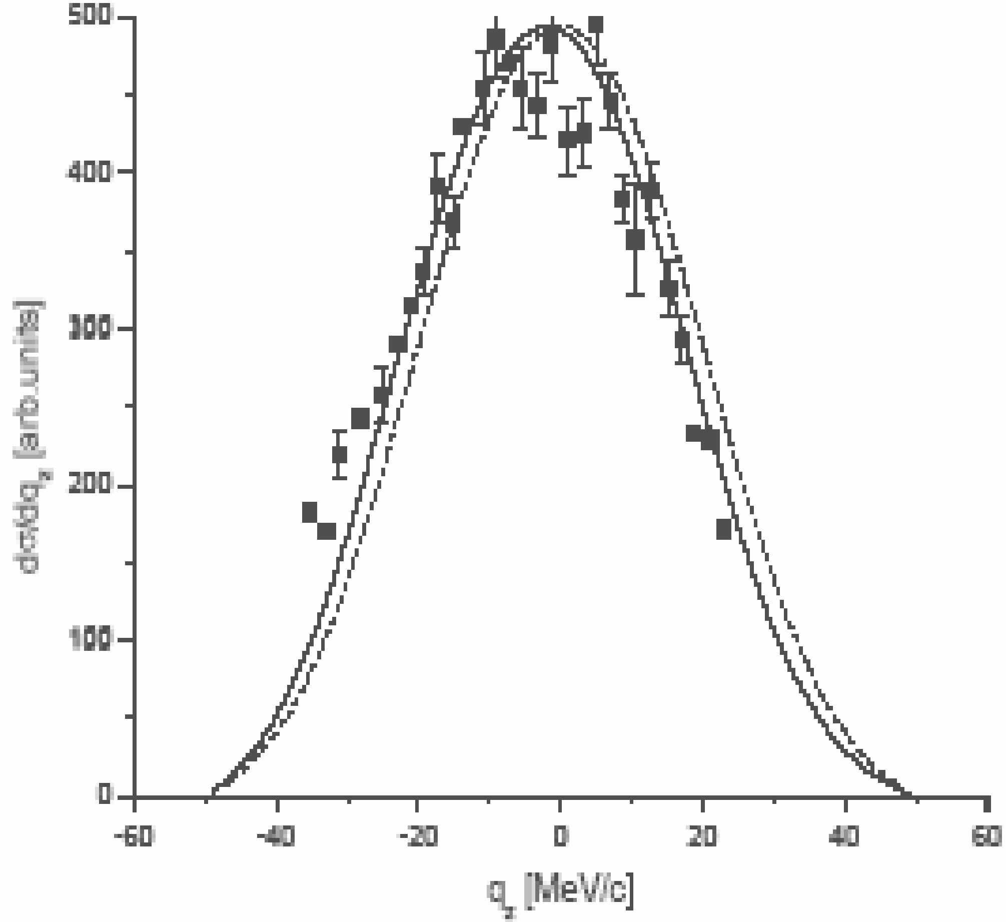
Sr. No.	Projectile	Z_i^{eff}		S_n(MeV)	E_{beam} (AMeV)	Cross section (mb)			
		E_1	E_2			σ_{E1}	σ_{E2}	σ_{CD}	σ_{Exp}
1.	^{11}Be	0.36	0.033	0.504	72	1983	59	2042	1800±400[8]
2.	^{14}B	0.35	0.025	0.970	86	679	7.4	686.7	
3.	^{15}C	0.4	0.026	1.218	550	254	2.2	256.2	360±10[19]
4.	^{19}C	0.31	0.016	0160	77	3157	26.0	3183.0	
5.	^{19}C	0.31	0.016	0.240	77	2640	24.0	2664.0	
6.	^{19}C	0.31	0.016	0.530	77	1249	12.0	1261.0	1100±400[20]



2.5
2.0
1.5
1.0
0.5
0.0
0
1
2
3
dσ/dE_rel [b/ MeV]
E_rel [MeV]



1.2
1.0
0.8
0.6
0.4
0.2
0.0
-0.2
-0.4
-0.6
-0.8
-1.0
-1.2
-40
-20
0
20
40
q_z [MeV/c]
$d\sigma/dq_z$ [arb.units]



500
400
300
200
100
0
-60
-40
-20
0
20
40
60
dσ/dq_z [arb.units]
q_z [MeV/c]

Conclusions

- A Small but finite contribution of quadrupole transition in the integrated coulomb breakup cross section has been found while that of E1-E2 interference is nil.
- The inclusion of E1-E2 introduces a small asymmetry in the longitudinal momentum distribution of the outgoing core fragment and improves the agreement between the data and predictions
- The measurement of the asymmetry in the LMD may be used to extract the contribution of E1-E2 interference in the process of coulomb breakup.

Future Prospectus

- Complete theory of Coulomb breakup incorporating all higher order dynamical effects is still lacking.

- Development of core plus multi nucleon reaction theory is strongly desired.

- In case of neutron rich nuclei a magic number N = 16 was found due to level inversion of $1d_{5/2}$ and $2s_{1/2}$. But in the case of proton rich nuclei, this is not confirmed yet.

THANKS