CEBAF PROPOSAL COVER SHEET

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Newport News, VA 23606

and received on or before OCTOBER 31, 1989

TITLE: Study of the (e,e'd) reaction on ^{3,4}He

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THIS PROPOSAL IS BASED ON A PREVIOUSLY SUBMITTED LETTER OF INTENT

/ / YES
/X/ NO

IF YES, TITLE OF PREVIOUSLY SUBMITTED LETTER OF INTENT

ATTACH A SEPARATE PAGE LISTING ALL COLLABORATION MEMBERS AND THEIR INSTITUTIONS

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roposal Received 10·31·89

og Number Assigned PR-89-029

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contact: Blok

Study of the (e,e'd) reaction on ^{3,4}He

THE HALL A COLLABORATION

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Kent State University, University of Maryland, Massachusetts Institute of Technology
University of New Hampshire, National Institute of Science and Technology
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Abstract: The (e,e'd) reaction offers an efficient way to study two-nucleon correlations in nuclei. At low momentum transfer ($q^2 \leq 5$ fm^{-2}) a ^{4}He(e,e'd) experiment was carried out at NIKHEF-K showing a considerably slower fall-off with q^2 compared to the free electron- deuteron cross section. We plan to extend these measurements and similar ones on ^{3}He to much higher q^2 at CEBAF in order to study the nuclear response at high momentum transfer. Employing a cryogenic liquid He target (150 mg/cm^2) it will be possible to cover a fairly large range in q^2: 6 - 50 fm^{-2}. Longitudinal-transverse separations and measurements of the recoil- momentum dependence are planned as well.

1. Introduction

Single-nucleon characteristics of nuclei such as single-particle wave functions and spectroscopic factors, have been studied in great detail by stripping and pickup reactions and recently also by the (e,e'p) reaction. However, very little is known about two or more nucleon correlations. Yet information on such correlations is of prime importance for the understanding of e.g., high-momentum components in nuclear wave functions and such processes as α-decay and π-absorption.

Some information on correlations has come from two or more nucleon transfer reactions and knockout reactions. In many cases the results of such investigations are inconsistent, however. Most probably this is due to the complicated reaction mechanism, which encompasses multi-step processes, optical-model potentials of composite particles, three-body final states (in knockout reactions), etc.

Knockout reactions induced by high-energy electrons have some distinct advantages in this respect. The interaction driving the knockout is known and weak, the incoming and outgoing electron waves can be calculated (almost) exactly and in the final state the projectile (the electron) is a spectator and does not rescatter. These points make electrons the preferable probe in knockout reactions for nuclear structure investigations.

A full investigation of two-nucleon correlations requires (e,e'2N) triple coincidence experiments. Unfortunately, even with high duty-factor beams such experiments, especially in the case of the (e,e'pn) reaction, are not easily performed and the obtainable energy resolution is at best a few MeV. Another way to probe p-n correlations is to use the (e,e'd) reaction. By projecting these correlations onto a deuteron in the final state some details are lost since effectively an integral is taken over certain correlations. On the other hand the final state in the (e,e'd) reaction can be used as an isospin filter. Moreover the (e,e'd) reaction can be performed with a resolution similar to that of (e,e'p) reactions and the analysis is facilitated by the fact that there is only one strongly interacting particle in the final state.

It is of great interest to study the (e,e'd) reaction on few nucleon systems, i.e. on ^{3}He and ^{4}He. First of all ^{4}He is a dense tightly bound nuclear system, where the effects of correlations will be relatively large. When the experimental energy resolution is good enough, the ^{2}H final state, which has S=1, T=0, can be separated from the breakup continuum, which just above threshold is mainly of S=0, T=1 character. Secondly microscopic calculations for the A=3 and A=4 systems are available, resp. are becoming feasible, which is of importance if one wants to describe the (e,e'd) reaction in detail (see section 2).

In this letter of intent we will discuss the possibilities of such He(e,e'd) experiments for Hall A at CEBAF. First a brief review is given of existing (e,e'd) data on light nuclei (section 2). Thereafter the kinematics to be used in a future CEBAF experiment and the expected count rates are presented.

If the (e,e'd) process is described analogously to (e,e'p) as quasi-elastic scattering, the cross section can (approximately) be written as:

$$\sigma^{exp} = K\, \sigma_{ed}(q)\, \rho^{D}(\mathbf{p_m},\mathbf{p_d}),$$

where σ_{ed} is the free (off-shell) electron-deuteron cross section and ρ^D is the (distorted) momentum distribution of the deuteron in the nucleus. A crucial condition for a quasi-elastic scattering mechanism is that the cross section should follow the free electron-deuteron cross section. This has been investigated for the ^{6}Li(e,e'd)^{4}He reaction [1] by keeping p_m constant and varying q. As is shown in fig. 1 the measured cross section very nicely followed $K\sigma_{ed}(q)$. Thus the nuclear structure $^6\mathrm{Li}\rightarrow\alpha$+d (shape of the momentum distribution, α-d cluster probability) could be investigated and compared to the results of α-p-n three-body and cluster-model calculations.

A similar set of data has been collected on ^{3}He [2]. The q-dependence of the ^{3}He(e,e'd) cross sections, measured at p_m=60 MeV/c, can satisfactory be described in the momentum transfer interval studied: 350<q<450 MeV/c by a microscopic calculation by Laget including FSI and MEC (see fig.2). Also the deuteron momentum distribution has been measured: from 0 to 200 MeV/c at a fixed value of q=380 MeV/c. The data can within 25% be described by the full calculation of Laget. The diagram that represents coupling of the virtual photon to a correlated pn-pair is important to get a good description of the data.

Measurements of the ^{4}He(e,e'd) reaction have also been performed at NIKHEF-K [3]. The q-dependence of the measured cross sections, shown in fig. 3, can not be described by the free electron-deuteron cross section (preliminary results obtained at MIT/Bates for ^{12}C(e,e'd) indicate a similar, even larger, discrepancy at q^2 = 19.5 fm^{-2} [4]). At first glance this is not too surprising as the proton and neutron are expected to be closer together in ^{4}He than in a free deuteron. The influence of this effect can be seen in a microscopic description of the (e,e'p) reaction, in which the reaction is not described as resulting from the interaction of the electron with a pre-formed deuteron cluster, but instead with separate protons (and neutrons) in the nucleus. Leaving out two-step processes like (e,e'p)(p,d) and considering only a charge interaction, the reaction in DWIA is described by the following T-matrix element:

$$T = <\phi_d(\rho)\,\chi_d(\mathbf{R})\,\phi_{A-2}\mid F_p(q)\,e^{i\mathbf{q}\cdot\mathbf{r}_p}\mid\phi_A>,$$

where the ϕ's are (internal) wave functions of the indicated nuclei and χ_d is the d-(A-2) relative wave function as given, for instance, by an optical-model wave function. In this expression $F_p(q)$ represents the proton form factor. Note that only the direct term is included, exchange terms have been left out as they are small in normal kinematics. An A $\rightarrow$ A-2 expansion is made, which yields an overlap function $\phi(\mathbf{r}_1,\mathbf{r}_2)$. Going over to relative and center of mass coordinates of the p-n pair, the overlap function is written as

$$< A\text{-}2\mid A> = \Sigma_{S,T,\lambda,\Lambda}\,[\,\phi_{np}{}^{\lambda,S,T}(\rho)\,\psi_\Lambda(\mathbf{R})\,]_{J^\pi,T},$$

where we have assumed A and A-2 to have spin/parity and isospin 0^+, 0 and J^π, T, respectively.

quantum numbers λ and Λ, while S and T are its spin/isospin quantum numbers. Writing $\mathbf{r}_p = \mathbf{R} + \rho/2$ one finds that T contains the factors

$$F(q) \equiv \langle \phi_d \,|\, F_p(q)\, e^{iq.\rho/2} \,|\, \phi_{np} \rangle \qquad \text{and} \qquad \langle \chi_d(\mathbf{R}) \,|\, e^{iq.\mathbf{R}} \,|\, \psi(\mathbf{R}) \rangle.$$

In complete analogy to the (e,e'p) case the latter is seen to yield a (distorted) momentum distribution with $\psi(\mathbf{R})$ being the bound-state wave function.

The factor F(q) contains only the internal p-n variable, and its value depends on ϕ_{np}, i.e. on the relative wave function of the p-n pair in the parent nucleus. Some simple cases are:

(a) $\phi_{np} = \phi_d$ (extreme cluster model).

In this case $F(q) = F_d(q)$, the form factor for scattering of an electron from a free deuteron, and the cross section for the (e,e'd) reaction will follow $\sigma_{ed}(q)$. This is a good approximation in the case of ^6Li, which can be described fairly well as an α–d system [1].

(b) $\phi_{np} = \phi_{'d'}$.

Here 'd' means that the quantum numbers S and T are the same as for the deuteron, but the radial wave function, e.g. its extension, may be different. This probably applies to the $^4He(e,e'd)^2H$ reaction [3]. Because of the size of ^4He (rms = 1.68 fm) in comparison to that of a free deuteron (rms = 2.11 fm), an expansion of ^4He into 'd' x ^2H gives a radial extent of the 'd' that is much smaller compared to a free deuteron. Simple estimates based on volume arguments only, yield a reduction of the radial size of at least a factor of two. However, a calculation due to Morita [5] using a realistic variational ^4He wave function, which includes various types of correlations, yields in the q-range in which the NIKHEF experiment was performed a slope that is only slightly different from that of $\sigma_{ed}(q)$, as seen in fig.3. The origin of the discrepancy with the experimental data is not clear. It may be that the calculations underestimate the high q-components in the p-n relative wave function, or that two-body currents play a role. Also (e,e'p)(p,d) contributions have to be considered. Similar results were also obtained for the $^4He(e,e'd)$ pn channel [3].

3. The CEBAF experiment

Given the aforementioned low-q^2 results it is important to extend the existing He(e,e'd) data to a larger q-range. The interest can be seen from fig. 4, where the deuteron form factor $A(q^2)$ is shown and also the 'transition form factor' for ^4He

$$F_{d\text{-}pn}{}^2 = |\langle d \,|\, e^{iq.\rho/2} \,|\, pn \rangle|^2,$$

which in a microscopic description determines the q-dependence. The form factor $F_{d\text{-}pn}{}^2$ starts at low q^2 below $A(q^2)$ and it has a flatter slope due to the reduced size of the p-n pair in ^4He compared to the free deuteron. At higher q^2 the curves are about the same, and $F_{d\text{-}pn}{}^2$ goes through a minimum (the expected similar minimum of $F_C{}^2$ for the deuteron is filled in by $F_Q{}^2$). It will be very interesting to measure the q dependence of the cross section up to the highest possible q^2, as we are then probing the internal structure of a deuteron (p-n pair) embedded in a nucleus.

The kinematics chosen for the experiment are listed in table 1. A momentum-transfer range of 0.5 - 1.5 GeV is covered corresponding to a q^2-range of 6 - 50 fm^{-2}. In order to study both the energy allowing us to perform a longitudinal-transverse (LT) separation.

The (e,e'd) count rates shown in table 1 are based on the present design criteria of the Hall A spectrometers [6]: $\Delta\Omega$ = 8 msr and $\Delta p/p$ = 0.10. Moreover, it is assumed that a cryogenic He target of 150 mg/cm^2 thickness is available. According to the present ideas [6] such a target should be able to withstand up to 200 μA electron current. Hence, we assume a luminosity of 3 10^{37} cm^{-2}s^{-1}.

For the ^{4}He(e,e'd) cross sections we have used the calculated momentum distribution of Schiavilla [7] (fig. 5) scaled down by appropriate factors in order to include the effect of the final-state interaction. This value of the distorted momentum distribution was multiplied by 10*$K\sigma_{ed}(q)$, where the factor of 10 accounts for the huge discrepancy between the data and $\sigma_{ed}(q)$ displayed in fig. 3.

It has also been investigated whether the single rates can still be handled at this luminosity. Using the QFS code due to Lightbody and O'Connell [8] we found electron rates of 3.6 10^4 s^{-1} or less, clearly not imposing any limits on our experiment. The single rate in the hadron spectrometer is presumably dominated by the proton singles. Calculations show that these rates do not exceed the 10^5 s^{-1} level. Since protons can be separated from deuterons using standard E-dE techniques, the number of random coincidences entering the analysis of our (e,e'd) data can be assumed to be very low.

Table 1. Kinematics for ^{4}He(e,e'd) at q = 0.5 - 1.5 GeV/c and p_m = 0 MeV/c.

q [GeV/c]	E [GeV]	θ_e [deg]	E_d^{cm} [MeV]	θ_d [deg]	ε	N_{eed} [hr^{-1}]
0.50	0.50	65.8	32.6	-48.5	0.54	7.9 10^4
0.50	1.00	29.9	32.6	-65.1	0.87	1.1 10^6
1.00	1.00	68.7	122.9	-42.6	0.50	2.5 10^3
1.00	2.00	30.0	122.9	-59.7	0.86	4.2 10^4
1.50	2.00	48.4	254.3	-46.3	0.68	2.9 10^2
1.50	4.00	21.7	254.3	-58.1	0.92	2.7 10^3

Apart from the q^2-dependence of the ^{4}He(e,e'd) cross sections we can also study the dependence on the recoil- or missing-momentum variable. Such a measurement will yield the (distorted) momentum distribution of a p-n pair in ^{4}He, which can be compared to theoretical predictions.

We have chosen to measure the missing-momentum dependence at three values of the momentum transfer in order to allow for an unambigous extraction of the true momentum distribution from the data. By having data sets available at three values of q^2, and hence E_d^{cm}, the assumptions for the electron-deuteron coupling and the final-state interaction entering the analysis of the (e,e'd) data can be checked against each other.

It is proposed to measure these momentum distributions at the same q-values that have been used for the previous kinematics listed in table 1. Moreover, the data should be taken in so-called perpendicular (or (q,ω)-constant) kinematics rather than parallel kinematics. In that way we will obtain two data sets: one with p_m kept constant (table 1) while varying q^2, and one with q^2

The count rates displayed in table 2 have been obtained in the same way as before, this time using the full p_m dependence of the cross section as given in fig. 5. With respect to the single rates it should be realized that the situation is even more favorable now, since the hadron spectrometer moves to more backward angles when p_m increases.

The total beam time required to measure all kinematics listed in tables 1 and 2 with good statistics is about 90 hours, where no overhead for adjusting the beam energy or scattering angles has been included. Since most runs require only relatively small amounts of beam time, it might be considered to go to a somewhat smaller target-thickness (100 instead of 150 mg/cm^2) in order to improve the energy resolution. With the presently assumed thickness of 150 mg/cm^2 the resolution varies from 0.6 - 2.6 MeV. Since break-up of the p-n pair requires 2.2 MeV, a resolution better than 1.5 MeV might be desirable in all cases.

Table 2.1 Kinematics for ^{4}He(e,e'd) at q = 0.5 GeV/c, E = 1.0 GeV and θ_e = 29.9°

p_m [MeV/c]	E_d^{cm} [MeV]	θ_d [deg]	N_{eed} [hr^{-1}]
0.0	32.6	-65.1	1.1 10^6
50.0	32.6	-70.8	8.6 10^5
100.0	32.6	-76.6	5.7 10^5
150.0	32.6	-82.6	2.6 10^5
200.0	32.6	-88.7	1.1 10^5
250.0	32.6	-95.1	4.0 10^4
300.0	32.6	-102.0	1.2 10^4

Table 2.2 Kinematics for ^{4}He(e,e'd) at q = 1.0 GeV/c, E = 2.0 GeV and θ_e = 30.0°

p_m [MeV/c]	E_d^{cm} [MeV]	θ_d [deg]	N_{eed} [hr^{-1}]
0.0	122.9	-59.7	4.2 10^4
50.0	122.9	-62.5	3.4 10^4
100.0	122.9	-65.4	2.3 10^4
150.0	122.9	-68.3	1.1 10^4
200.0	122.9	-71.2	4.7 10^3
250.0	122.9	-74.1	1.7 10^3
300.0	122.9	-77.1	5.8 10^2

Table 2.3 Kinematics for ^{4}He(e,e'd) at q = 1.5 GeV/c, E = 4.0 GeV and θ_e = 21.7°

p_m [MeV/c]	E_d^{cm} [MeV]	θ_d [deg]	N_{eed} [hr^{-1}]
0.0	254.3	-58.1	2.8 10^3
50.0	254.3	-59.9	2.3 10^3
100.0	254.3	-61.9	1.5 10^3
150.0	254.3	-63.8	7.2 10^2
200.0	254.3	-65.7	3.2 10^2
250.0	254.3	-67.7	1.2 10^2
300.0	254.3	-69.6	4.0 10^1

made. This seems especially interesting in view of the different behaviour of the two isotopes i the $q^2 = 2\text{-}5\ fm^{-2}$ region. The total beam time (without overhead) thus amounts to appr. 200 hours

Summarizing we observe that only a small amount of beam time is required to explore th very intriguing behavior of the He(e,e'd) reaction at high q^2. Such investigations may help us i understanding the nature of p-n correlations in nuclei and -more generally- how a nucleus respond to a large momentum transfer.

References

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[4] L. B. Weinstein and W. Bertozzi, Proceedings of the fourth workshop on Perspectives in Nuclear Physics at Intermediate Energies, 8 - 12 May 1989, Trieste, Italy.

[5] H. Morita et al., Prog. Theor. Phys. **78** (1987) 1117; ibidem **79** (1988) 863.

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[7] R. Schiavilla, V. R. Pandharipande and R. B. Wiringa, Nucl. Phys. **A449** (1986) 219.

[8] J. W. Lightbody and J. S. O' Connell, Computers in Physics **1** (1988) 57.

Figure Captions

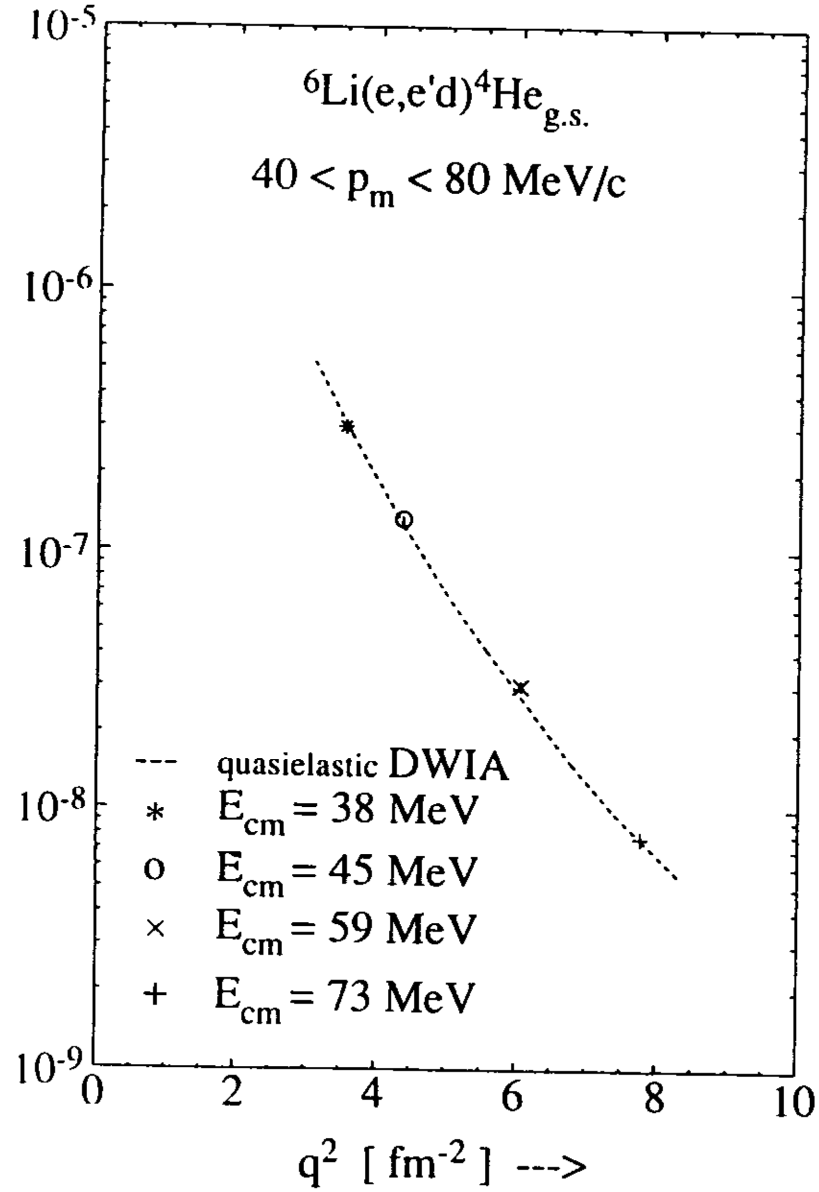
Fig. 1. The cross section for the reaction $^6Li(e,e'd)$ as a function of the momentum transfer compared to the quasi-elastic electron-deuteron cross section.

Fig. 2. The cross section for the reaction $^3He(e,e'd)$ as a function of the momentum transfer, compared to different calculations.

Fig. 3. The cross section for the reaction $^4He(e,e'd)$ as a function of the momentum transfer, compared to the quasi-elastic electron-deuteron cross section.

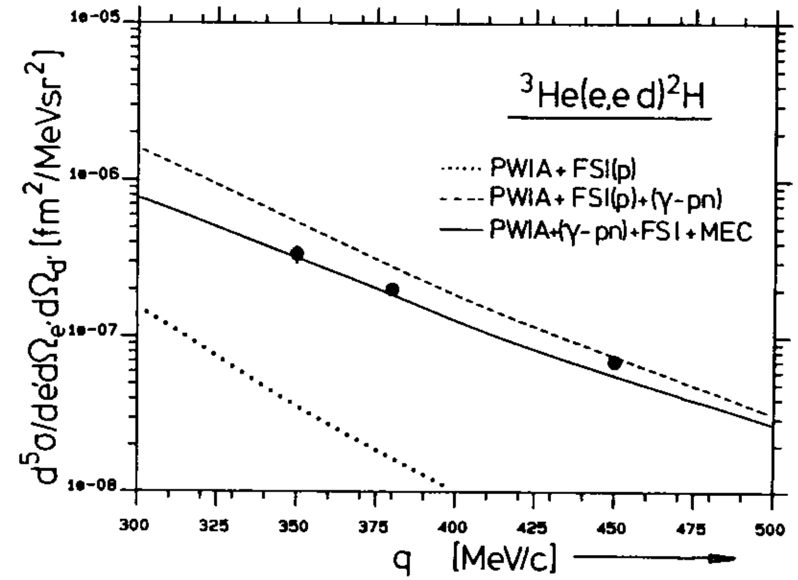
Fig. 4. The elastic electron-deuteron form factor $A(q^2)$ (dashed curve) and the "transition" form factor, defined in the text (dotted curve).

Fig. 5. Measured and calculated deuteron momentum distributions.



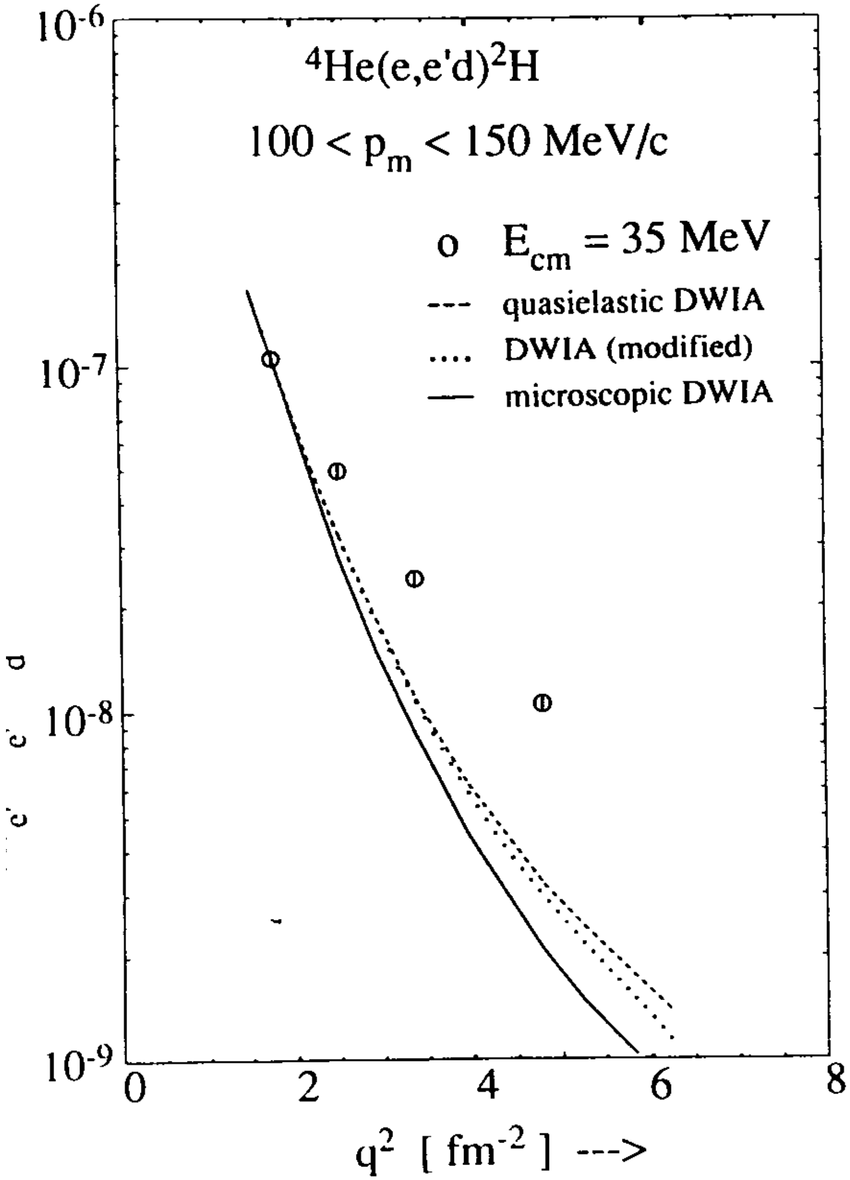
$^6Li(e,e'd)^4He_{g.s.}$
$40 < p_m < 80$ MeV/c
--- quasielastic DWIA
* E_{cm} = 38 MeV
o E_{cm} = 45 MeV
× E_{cm} = 59 MeV
+ E_{cm} = 73 MeV
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0
2
4
6
8
10
q^2 [fm^{-2}] --->

(1)



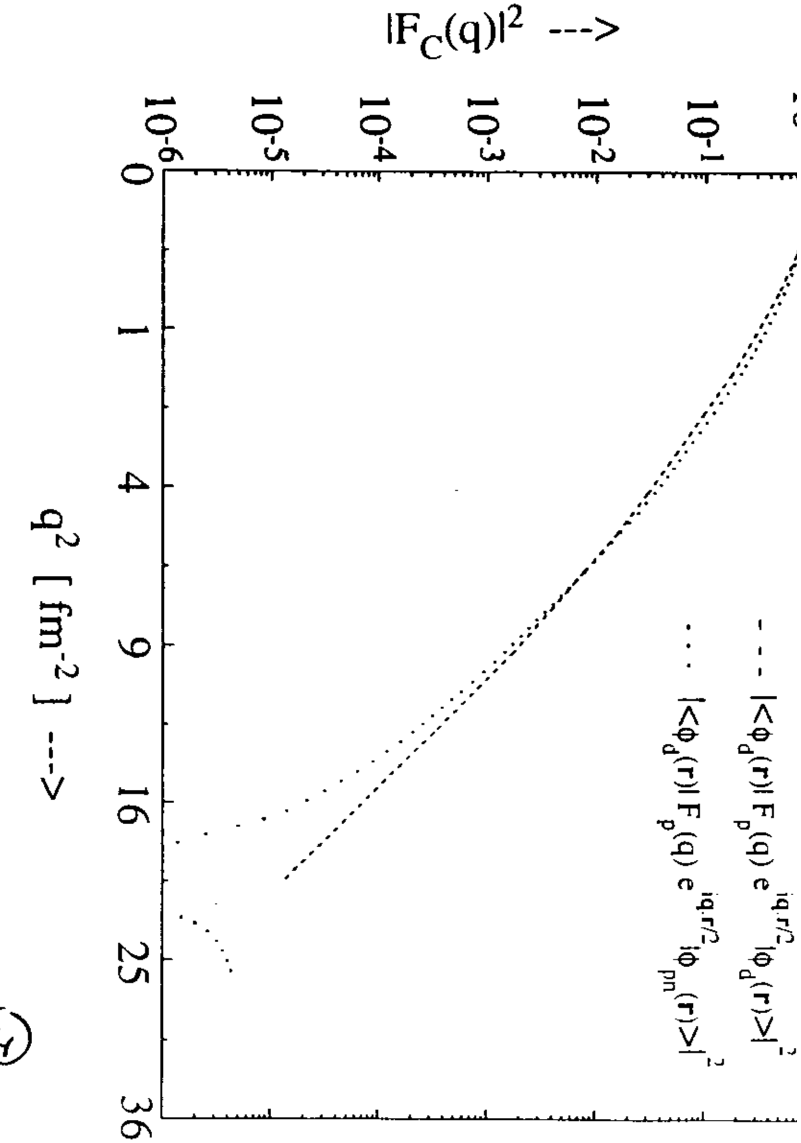
$^3He(e,e d)^2H$
PWIA+ FSI(p)
PWIA+ FSI(p)+(γ-pn)
PWIA+(γ-pn)+FSI+MEC
$d^5\sigma/ded\Omega_e d\Omega_d$ [$fm^2/MeVsr^2$]
1e-05
1e-06
1e-07
1e-08
300
325
350
375
400
425
450
475
500
q [MeV/c]

(2)



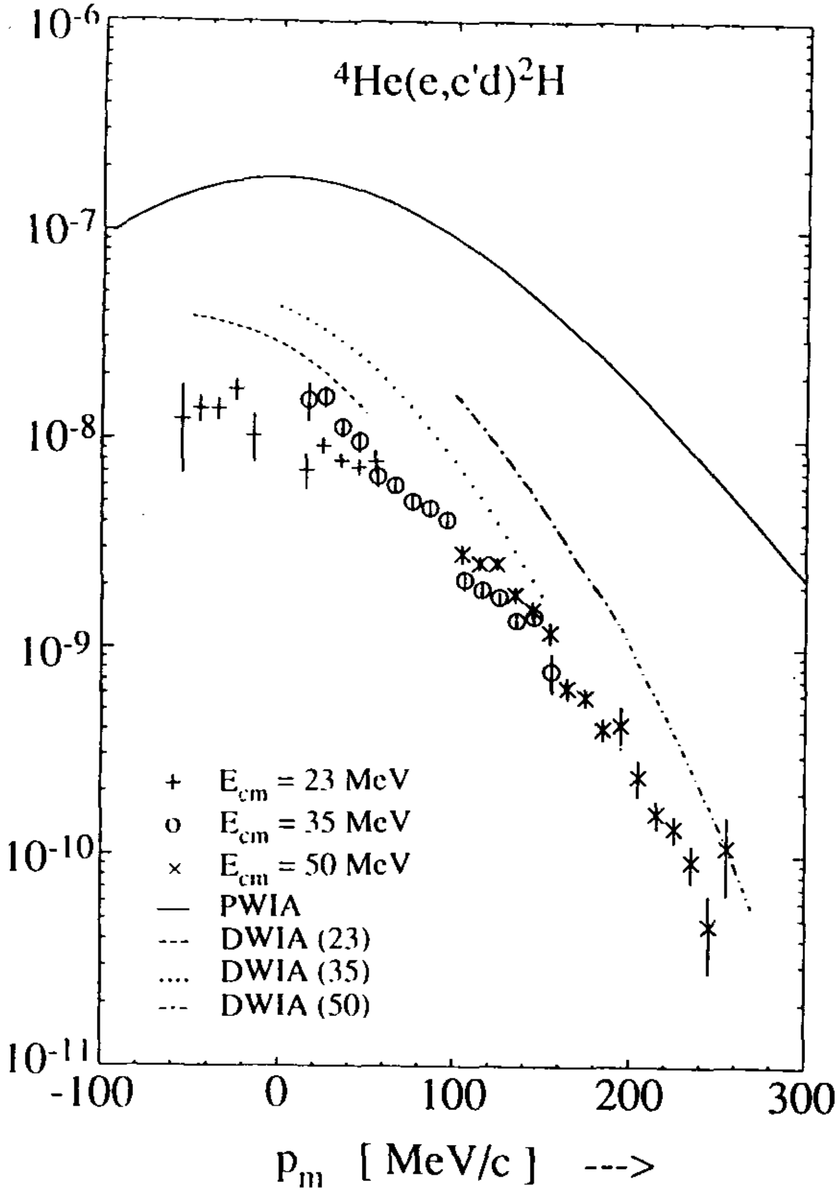
$^4He(e,e'd)^2H$
$100 < p_m < 150$ MeV/c
o $E_{cm} = 35$ MeV
quasielastic DWIA
DWIA (modified)
microscopic DWIA
10^{-6}
10^{-7}
10^{-8}
10^{-9}
0
2
4
6
8
q^2 [fm^{-2}] --->

(3)



$|F_C(q)|^2$ --->
$|\langle\phi_d(\mathbf{r})|\, F_p(q)\, e^{iq.r/2}|\phi_d(\mathbf{r})\rangle|^2$
$|\langle\phi_d(\mathbf{r})|\, F_p(q)\, e^{iq.r/2}|\phi_{pn}(\mathbf{r})\rangle|^2$
10^{-6}
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
0
1
4
9
16
25
36
q^2 [fm^{-2}] --->

(4)



$^4He(e,e'd)^2H$
+ E_{cm} = 23 MeV
o E_{cm} = 35 MeV
× E_{cm} = 50 MeV
— PWIA
--- DWIA (23)
.... DWIA (35)
-·- DWIA (50)
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
-100
0
100
200
300
p_m [MeV/c] --->

5