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(e,e'X) EXPERIMENTS AT NIKHEF-K

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(e,e'X) EXPERIMENTS AT NIKHEF-K

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Abstract: The present status of the instrumentation for (e,e'X) coincidence experiments and photopion production is reviewed. With the availability of high resolution in missing energy (<200 keV) and sub nanosecond coincidence timing with two magnetic spectrometers a new generation of proton knockout experiments will be feasible. A series of approved experiments now underway will be discussed. We show some first results and discuss future developments in experimentation.

1. INTRODUCTION

The aim of this paper is twofold. The first objective is to give a brief survey of the instrumentation for electromagnetic coincidence experiments (e,e'X) that have been recently put into full operation at NIKHEF-K. In addition our large solid angle hadron spectrometer of the QDQ type enables a study of charged pion-production processes in nuclei, induced by virtual photons.

We will discuss the largely improved resolution of the missing energy variable E_m in e.g. proton knockout reactions. The resolution δE_m can be routinely pushed below 200 keV at incoming energies around 400 MeV by the application of the generalized dispersion-matching technique. In combination with the optimized interspectrometer coincidence time resolution of 800 ps a new series of high resolution (e,e'p) reaction studies can now be endeavoured to complement and extend the pioneering work of Mougey *et al.* at Saclay.

The second aim is to discuss a sample of the ongoing experiments at NIKHEF-K. In the study of single-particle properties of nuclei both the (e,e'p) reaction and single-nucleon pickup and stripping reactions (d,^{3}He), (d,p) have made principal contributions. We will discuss the proposed (e,e'p) reactions with a synthesizing view towards the hadron induced reactions.

The physics we are going to report on, has been made possible through the combined effort of a multitude of people. Principal contributions have been made by C. de Vries$^{1)}$, P.C. Dunn, C.W. de Jager, P.H.M. Keizer, R. Maas and H. de Vries.

2. INSTRUMENTATION FOR COINCIDENCE REACTIONS

In fig. 1 is shown the general layout of the new spectrometer setup and the focal plane multiwire proportional chamber detection systems that are in operation now at NIKHEF-K. The setup comprises a high resolution ($\delta p/p \simeq 10^{-4}$) QDD type spectrometer mainly for scattered electron detection, and a large solid angle ($\Delta\Omega \simeq 18$ msr) fair-resolution ($\simeq 3.10^{-4}$ $\delta p/p$) QDQ type spectrometer. Both spectrometers have a 10% momentum band; the QDD (QDQ) can bend a maximum momentum of 600 MeV/c (750 MeV/c).

In our efforts to open new avenues for hadron detection experiments we have concentrated on the following parameters of the instrumentation:

a. The resolution of the missing energy variable E_m, defined for the two-body final state reaction

$$1 + T \rightarrow 2 + 3 + M$$

as $E_m = e(1) + M_T - e(2) - e(3)$ where $e(j)$ is the total energy of particle (j) and the recoil energy of the daughter nucleus has been neglected.

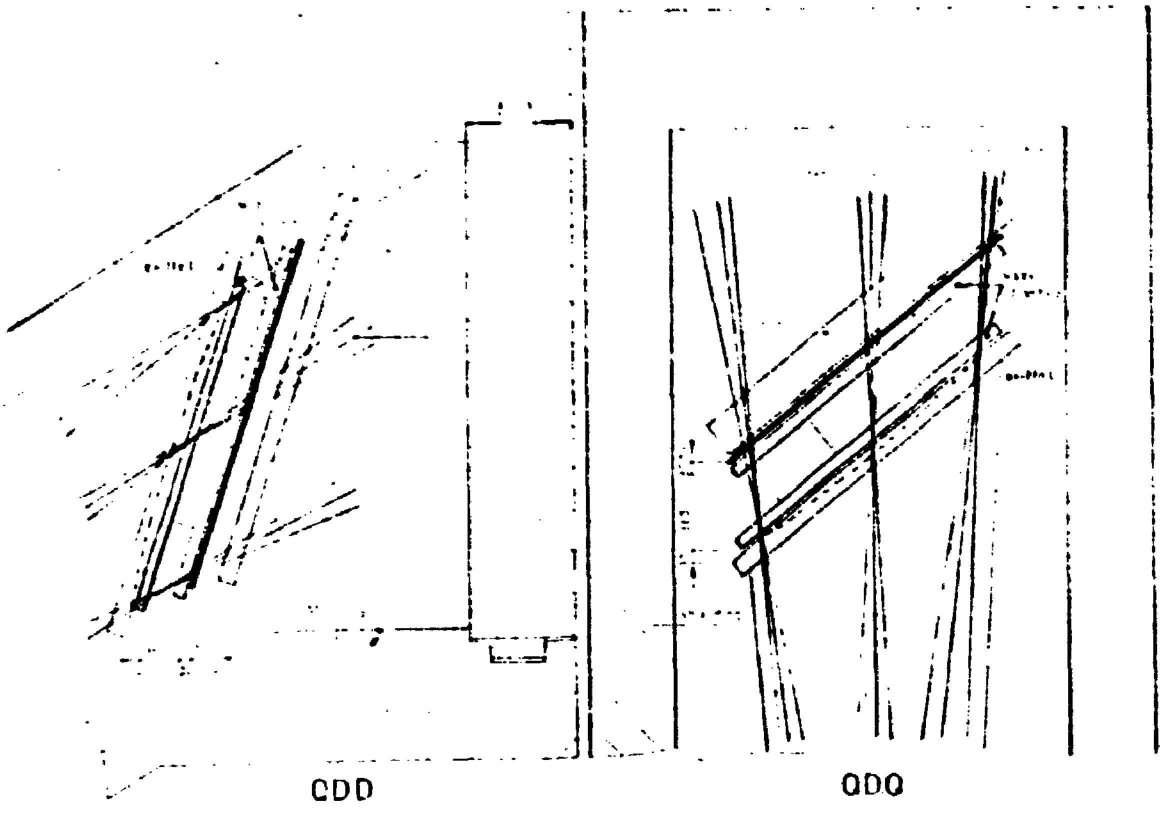
It has been shown by Lapikás and de Witt Huberts[2] (see also the Appendix) that the single-arm dispersion matching technique can be generalized for coincidence reactions detection with two or more spectrometers. With this technique the important contribution of the primary beam energy spread can be nullified to first order in magnet optics. The missing mass resolution δE_m then receives contributions from various sources as shown in Table I.

Table I Typical contributions to missing energy resolution δE_m

Momentum (MeV/c)	Resolution (10^{-4})	Contribution (keV)
$p_1 = 400$	< 1 (intrinsic)	< 40
$p_2 = 300$	< 3 (QDD)	< 90
$p_3 = 400$ ($T_3 = 85$ MeV)	< 5 (QDQ)	< 85
second order effects		< 80
target ^{12}C (30 mg/cm^2)		80
	Total δE_m	< 170

b. Coincidence time resolution

Improvement of interspectrometer coincidence time resolution t_c down to the (600-800)ps limit given by typical scintillator-PM photoelectron statistics requires very accurate flight time corrections. Full particle orbit reconstruction with the wire chamber detection systems and the availability of high-precision (measured) magnetic transport matrix elements up to a third order is a prerequisite.



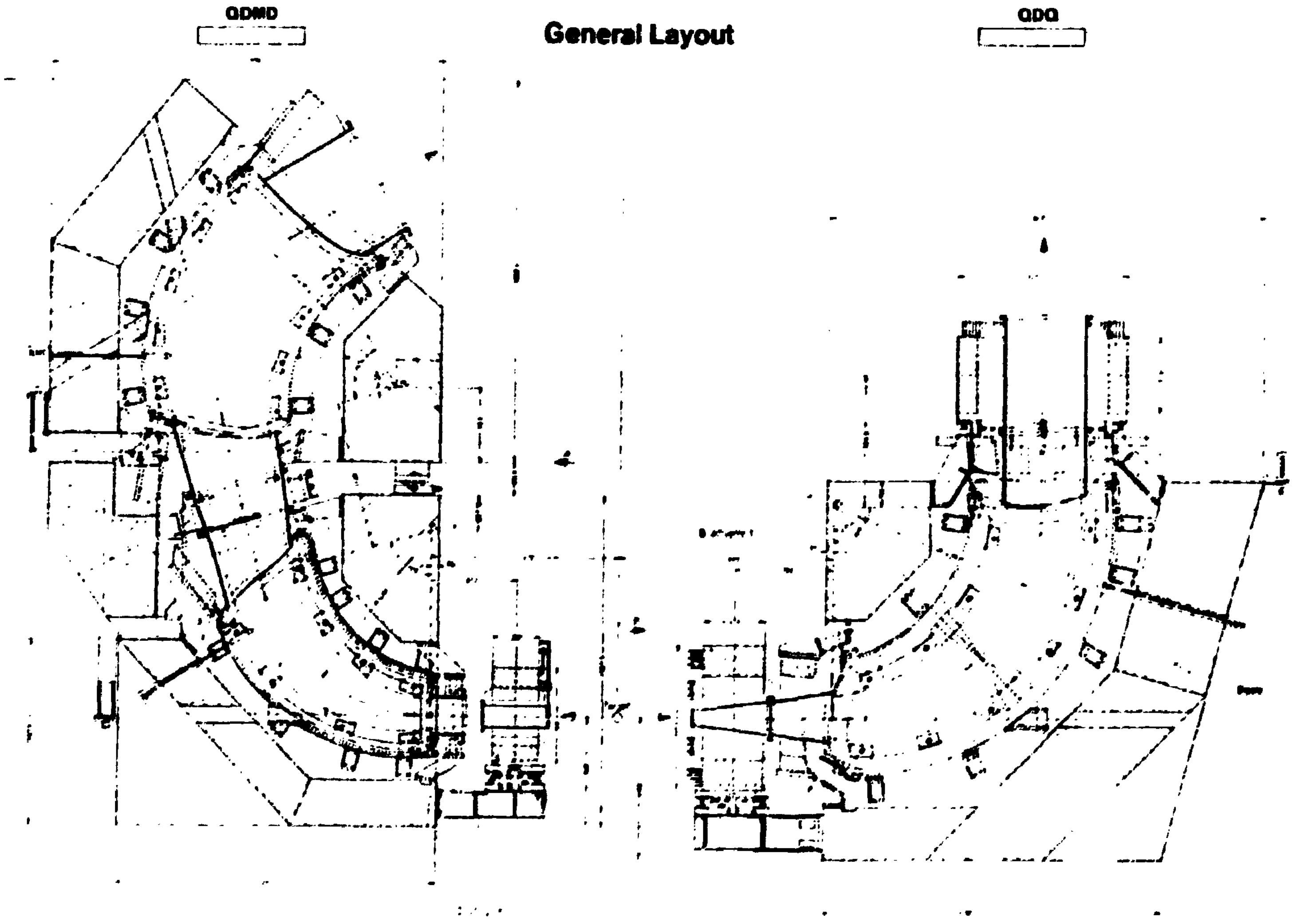

General Layout

Fig. 1 Two spectrometer (QDD and QDQ) setup with focal plane detection systems (schematic).

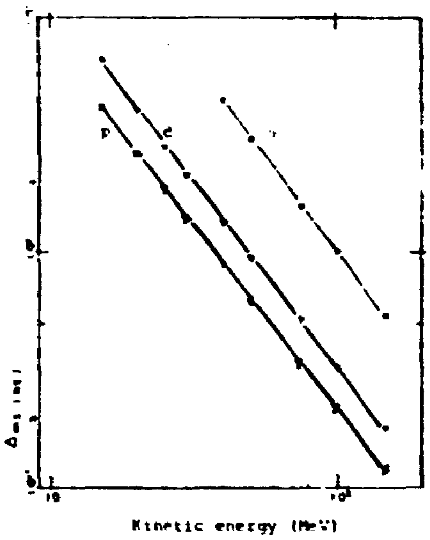


Fig. 2 Flight time spread for various hadron as function of m.s.

Orbit reconstruction accuracy is affected by multiple scattering processes to the extent illustrated in fig. 3 for various kinds of hadrons.

c. The detection of charged pions induced by photons on nuclei requires a strong suppression of the contaminant electron and position background. P.C. Dunn has designed and put into operation a flexible hadron trigger system in the focal plane of the QDQ spectrometer. An aerogel detector (index of refraction $n = 1.05$) with large photon collection efficiency ($\bar{n} = 17$ photo-electron) and with a homogeneous response all along the 1 meter long focal plane ensures an $\approx 3.10^4$ suppression factor for electrons when used in an anticoincidence trigger scheme.

Having described the design goals we now discuss the present status of the coincidence instrumentation, illustrated by a series of figures. The major part of the tune-up has been performed in the kinematically complete reaction (e,e'p) with a CH_2 target ($d \sim 10$ mg/cm^2) and with full solid angles (5.6 and 17 msr) in the two spectrometers. In fig. 4a, b is shown the effect of two-arm dispersion matching. Beam of 280 MeV with an energy spread of 750 keV on target with the optimal choice of spectrometer matrix elements a missing energy resolution $\delta E_m \approx 175$ keV has been obtained, close to the expected value 140 keV. A typical value that can be routinely achieved on heavier nuclei is 200 keV. The broad trapezoidal distribution in fig. 5a is the non flighttime corrected timing spectrum. A value of ≤ 800 ps FWHM with the full correction algorithm has been achieved for proton kinetic energy $T = 90$ MeV. At smaller energies a slight time-resolution deterioration to 1 ns occurs.

The enormous improvement of δE_m compared to the old-day standard of $\sim 1 - 1.5$ MeV in (e,e'p) reactions combined with the optimized time resolution yields a coincidence quality factor $R = df/t_c/\delta E_m \sim 20$ where df is the duty factor (a few percent for MEA accelerator), an order of magnitude larger than hitherto available. The $\delta E_m \sim$ of 150 keV for the (e,e'p) reaction undershoots the best values obtained in (p,2p) reactions[3] and compares favourably with the hitherto superior energy resolution of pickup and stripping reactions[4,5]. Finally in fig. 6 is illustrated the coincidence detection efficiency of the apparatus.

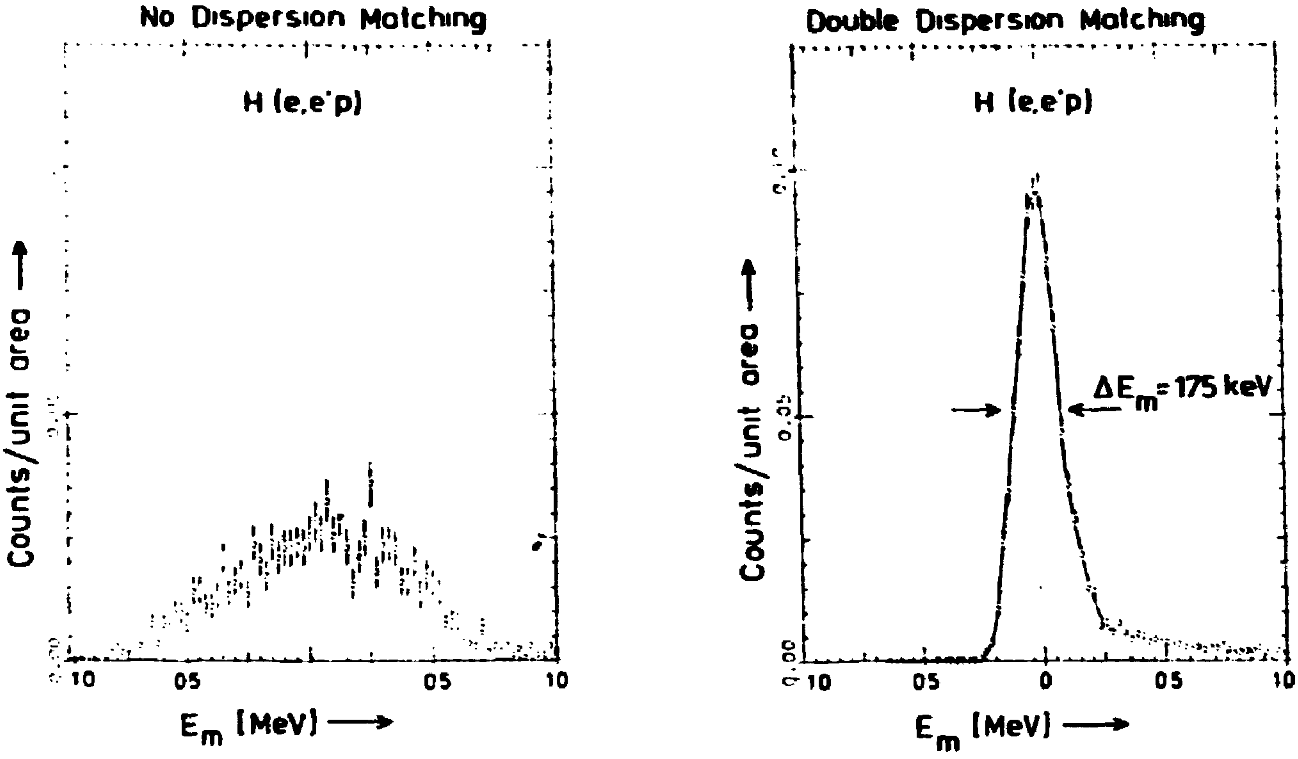


Fig. 4a,b. Effect of two-arm dispersion matching on E_m (CH_2 target)

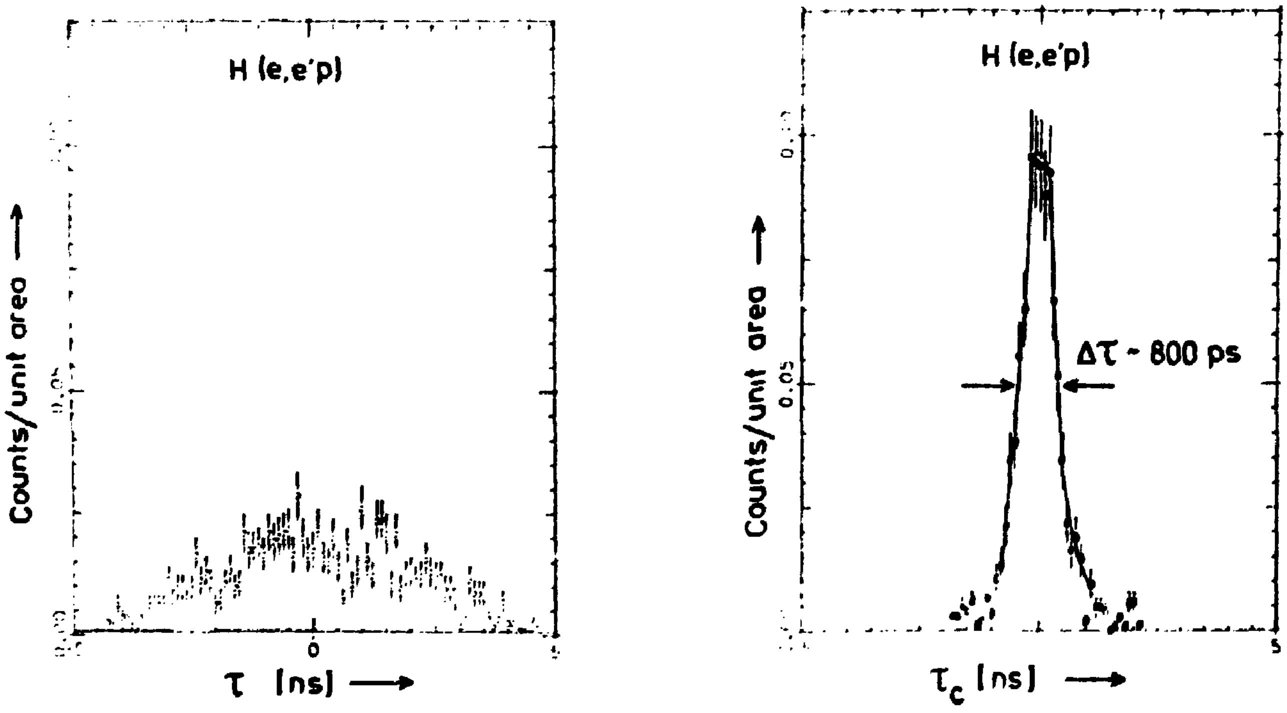


Fig. 5a,b. Effect of flight time corrections on coincidence resolution

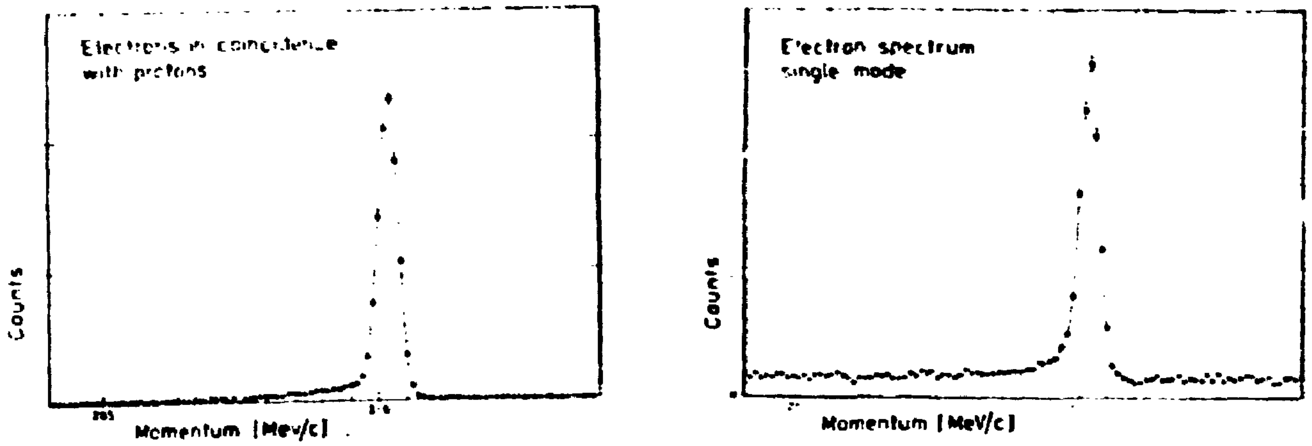


Fig. 6 Illustration of coincidence detection-efficiency

Electrons scattered from protons in CH_2 are observed in the QDD spectrometer on a smooth radiation tail background from C. In the coincident spectrum only the proton peak is observed. From a comparison of the two spectra we find a coincidence efficiency $\varepsilon_c = 99 \pm 2\%$.

3. SURVEY OF ONGOING COINCIDENCE MEASUREMENTS

3a. The reactions $^3He(e,e'p)d$ and $^3He(e,e'd)p$

A study of the proton spectral function $S(E_m,p)$ has been proposed as an extention of the recent Saclay-work of E. Jans *et al.*[6]. It has become clear from this work that corrections to the strict plane wave impulse approximation (PWIA) become increasingly important when the recoil proton momentum p is increased beyond ∿ 250 MeV/c. Recently significant progress has been made[7] in the theoretical treatment of some reaction mechanism aspects, including exchange currents and off-shell effects[8].

The basic physics motivation of the experiment is to study high momentum components (out to 500 MeV/c) in ^3He. Detecting the outgoing deuterons of the two-body breakup reaction implies an important reduction of the random coincidence rate. Our apparatus allows a simultaneous measurement of p and d final state channels. With appropriate kinematics (fig. 7a) the same recoil momentum range can be measured. We recall that a recent single-arm (high-q, low ω) inelastic (e,e') experiment has found enhanced high-p components in ^3He in disagreement with the (e,e'p) result (fig. 7b).

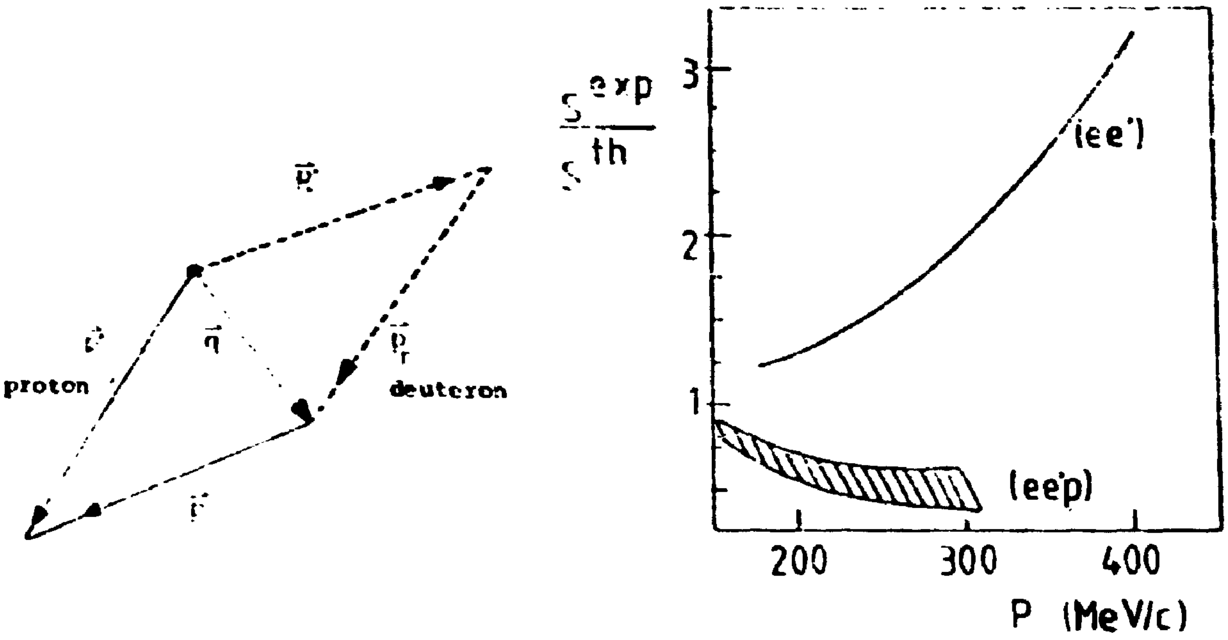


Fig. 7a,b. a) Kinematics for symmetric p and d detection.
b. Ratio of experimental and theoretical spectral function S.

3b. High-resolution spectroscopy with the (e,e'p) reactions

With the availability of missing energy resolution (< 200 keV) comparable to the best (p,2p) and single-nucleon pickup reactions (p,d) and (d,^{3}He), a synthesizing approach to these two kinds of reactions becomes feasible. In general the enormous advantage of strongly reduced distortion in the (e,e'p) reaction will allow to assess the importance of multistep processes in the hadron reactions. This is especially important when knockout from normally unoccupied states, with a small occupation probability, is considered. On the other hand the analyzing power of pickup reactions with polarized beams ($\vec{d}$,^{3}He)$^{5)}$, ($\vec{d}$,t)$^{9)}$ offer the unique possibility of j-assignments. We believe that a combined analysis of the two types of reactions will lead to a more profound understanding of nuclear hole states.

As a first example we show in fig. 8 recent data from NIKHEF-K on the ^{12}C(e,e'p)^{11}B reaction, obtained with 253 MeV electron beam energy. The missing energy resolution obtained is 200 keV, enabling a detailed study of discrete final states in ^{11}B. At the recoil momentum value of 100 MeV/c of this spectrum there are only a few states distinctly excited: the $3/2^-$ ground state, and two additional states $1/2^-$ (2.12 MeV) and $3/2^-$ (5.02 MeV). In the comparison with the (p,2p) spectrum$^{3)}$ and (d,^{3}He)$^{10)}$ shown in fig. 9, some fascinating questions arise. The $3/2^-$ state at E_x = 5.02 MeV is excited in both (e,e'p) and hadron induced reactions whereas in (e,e'p) the $5/2^-$ (4.44 MeV) state is not. Neither do we see any appreciable strength around ∿ 6.75 MeV, where $7/2^-$ ($1f_{7/2}$ hole?) and $1/2^+$ ($2s_{1/2}$ hole?) states are located.

Are multistep processes besetting the hadronic reactions in these cases? One may hope that with additional (e,e'p) data and a theoretically refined analysis these questions will be clarified.

As a next example consider the missing energy spectrum of the reaction ${}^{51}V(e,e'p){}^{50}Ti$ shown in fig. 10a at two values of recoil momentum. We assume that the target may be described as a $(1f_{7/3})^3$ proton configuration outside a ${}^{48}Ca$ core. Then four $l = 3$ transitions to the $(1f_{7/2})^2$ multiplet $(0^+, 2^+, 4^+, 6^+)$ at (0.156, 2.68 and 3.20 MeV) may be populated as indeed is observed. In addition two $(2s_{1/2}$ - hole) states with $J^\pi = 3^-, 4^-, 5^-$ at (5.4, 5.9, 6.45, 7.65 MeV), may be populated. With increasing value of recoil momentum one observes that the $l = 0$ transfers decrease relative to the $l = 2, 3$ transfers, as expected. There is remarkable qualitative agreement with the spectrum of the $(d,{}^3He)$ reaction at 34.4 MeV incoming energy[11]) as is illustrated in fig. 10b. Also for excitation energies in ${}^{50}Ti$ larger than 7 MeV the knockout strength increases with p_m indicating that relatively large l transfers are involved. We foresee that a detailed study at smaller values of p_m mar reveal the importance of 2p-admixtures in the low-lying states of ${}^{50}Ti$. Another aspect that can be investigated is related to the question of missing sumrule strength of spectroscopic factors C^2S when the appropriate radial wave function for the bound state is used. Magnetic elastic electron scattering of high multipolarity has yielded such wave functions very precisely[12]). High resolution study of the excitation spectrum out to 15 MeV, in combination with new hadron experiments now underway[13]), will be instrumental in clarifying the crucial question of the spreading of hole strength that is presumably induced by short range correlations in nuclei.

As a final example we discuss the reaction ${}^{90}Zr(e,e'p){}^{89}Y$. In fig. 11a is shown the (e,e'p) spectrum at three values of recoil momentum. In fig. 11b is given the result of a polarized pickup experiment ${}^{90}Zr(\vec{d},{}^3He){}^{89}Y$ with $E_d = 52$ MeV[5]) at an angle where the $l = 3$ angular distribution is expected to have a maximum. In the (e,e'p) reaction $l = 3$ knockout is expected to peak at $p_m \sim 150$ MeV/c. The low-lying states, $1/2^-$ (gs), $9/2^+$ (0.91 MeV), $5/2^-$ (1.75 MeV) are populated in the two reactions in a roughly similar fashion, keeping in mind the different angular momentum selectivity involved.

However, at excitation energies > 4 MeV extreme dissimilarities become apparent. Whereas the $(\vec{d},{}^3He)$ reaction shows a giant resonance (GR) like bump (dotted area) superimposed on a continuum background of unknown origin the (e,e'p) shows none of these features. The (e,e'p) spectrum has distinct peaks at $\sim$ 4.5, 8 and 9.2 MeV with a p_m dependence similar to the state at 1.75 MeV that has been unambiguously identified in the $(\vec{d},{}^3He)$ experiment as a $1f_{5/2}$-hole state exhausting most of the C^2S sumrule value. It is a surprising fact that these peaks have no counterparts in the hadron reaction. Is it possible that, due to reaction mechanism complications, the distinct peaks through mixing with the continuum have evolved into the GR bump?

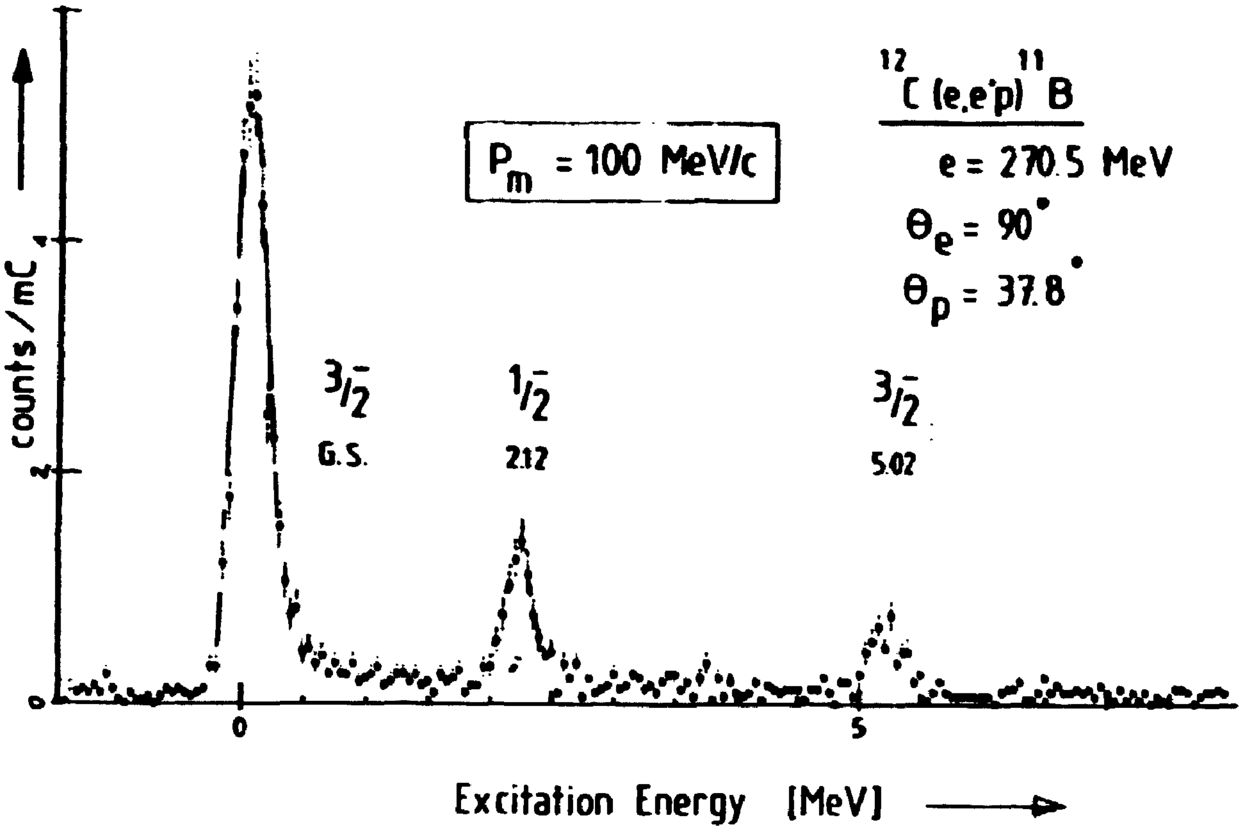


Fig. 8 Missing energy spectrum of the ^{12}C(e,e'p)^{11}B reaction

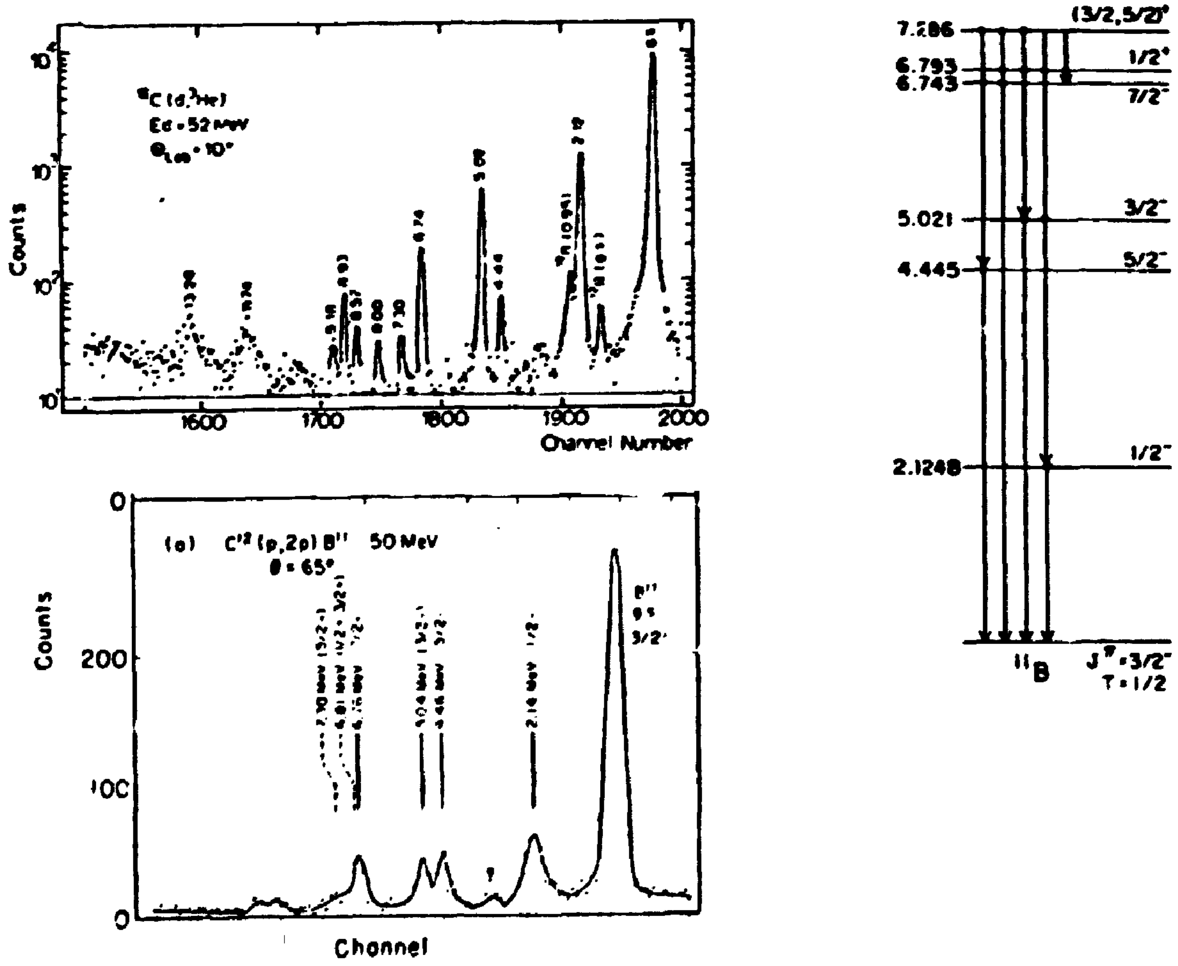


Fig. 9 Pickup (d,^{3}He) (figure adapted from Ref. 10) and knockout (p,2p) reactions leading to excited states in ^{11}B (left). Excitation spectrum of ^{11}B (right).

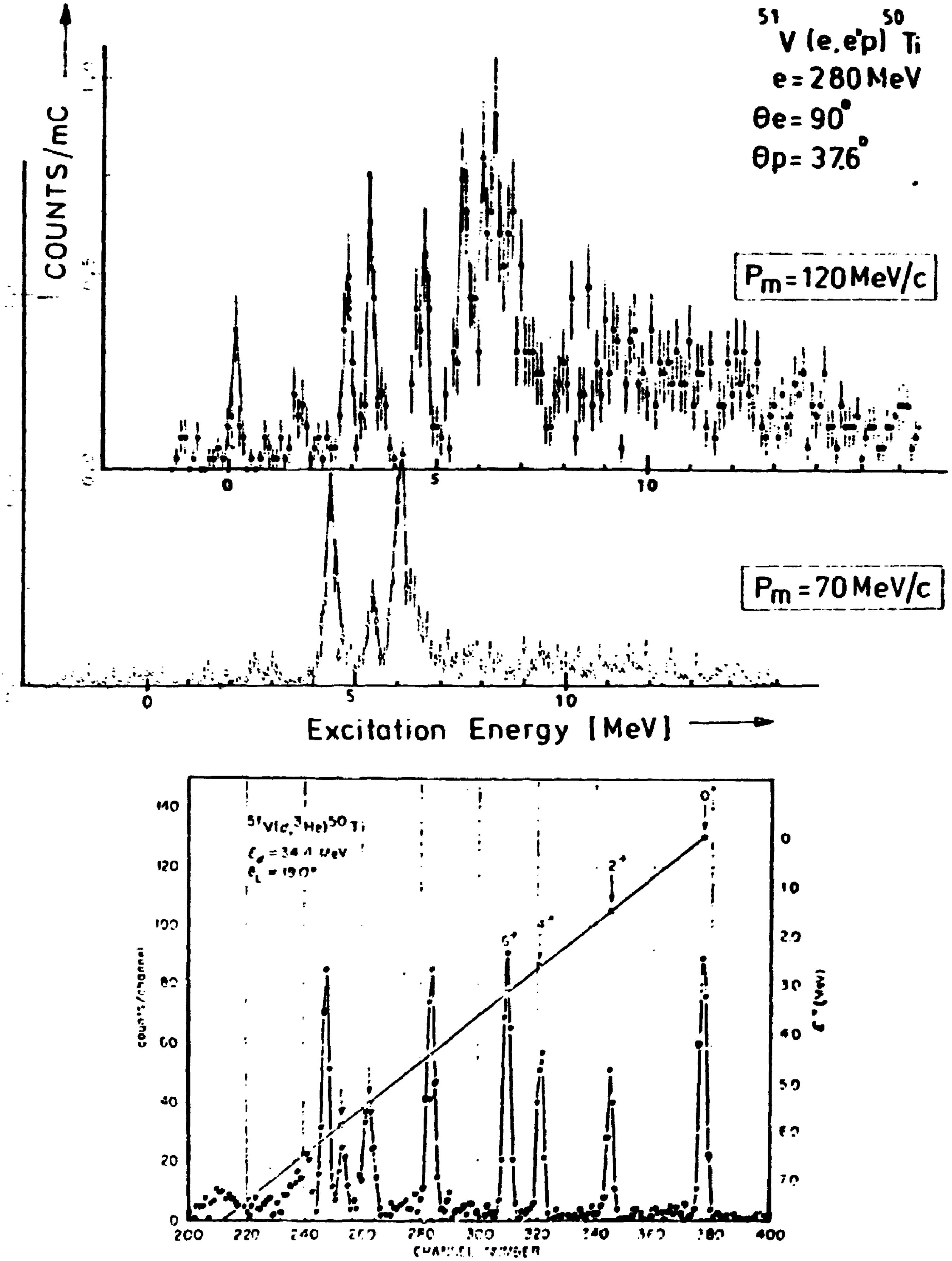


Fig. 10a,b. a) Missing energy spectrum of ^{51}V(e,e'p)^{50}Ti reaction. b) Pickup reaction ^{51}V(d,^{3}He)^{50}Ti results (Ref. 11)

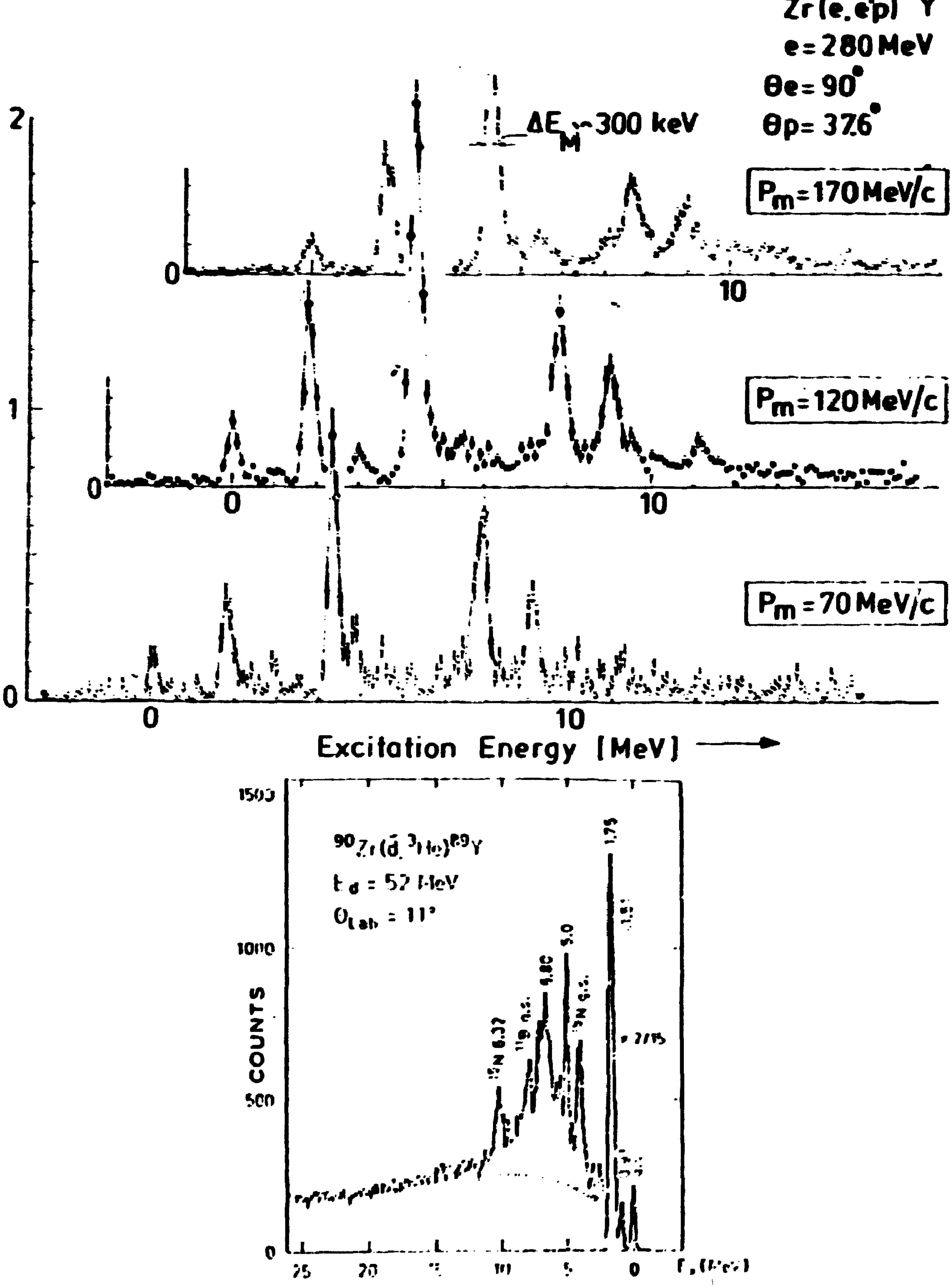


Fig. 11a,b. a) E_m spectrum of the reaction ^{90}Zr(e,e'p)^{89}Y.
b) Polarized pickup spectrum of ^{90}Zr(d,^{3}He)^{89}Y reaction (Ref.5).

This structure has been interpreted through the vector-polarization measurements as a superposition of $1f_{7/2}$ hole states, exhausting most of the sumrule strength.

Clearly there are some interesting problems to be solved in this region of the periodic table.

CONCLUSIONS

We have indicated how to exploit the new instrumental possibilities of the NIKHEF-K two-spectrometer setup for high resolution proton knockout spectroscopy. We note that each of the (e,e'p) spectra shown have been obtained in typically (2-3) hours of beam time with only a small amount of accidental coincidences.

For a viable exploitation of these experiments it will be necessary to develop theoretically in more detail the final state interaction aspects of the (e,e'p) reaction. Work in this direction is developing[14)] but detailed application to the (e,e'p) data has just barely begun.

By a synthesizing approach with the single nucleon transfer reactions, exploiting the typical virtues of the electromagnetic and hadronic probes, we believe that significant progress in the understanding of nuclear (deep) hole states will be possible in the near future.

APPENDIX

A dispersion matching method for coincidence reactions

We want to show that the standard single-arm dispersion matching technique may be generalized for coincidence reactions of the type $(1 + M \rightarrow 2 + 3 + M^*)$. We shall treat the case where (1) = (2) = electron and (3) = nonrelativistic proton. Particles 2 and 3 are detected by spectrometers with first order dispersion $\langle x|\delta\rangle_j$ and central momentum $p_j^{(0)}$ $(j = 2,3)$.

Consider a dispersed beam with $D_B = x_1/\delta_1$ where x_1 denotes vertical displacement on the target and δ_1 is the corresponding deviation from the central beam momentum p_1. For an event (A) occurring at $x_1 = 0$ and with ejected particle momenta p_2, p_3 the missing energy E_m is given by

$$E_m = p_1 - p_2 - p_3^2/2M_3 \tag{1}$$

where $M, M^* >> p_1, p_2$ is assumed. For another event (B) with $x_1 \neq 0$ and momenta $p_j(1+\delta_j)$, we find

$$E_m = p_1(1+x_1/D_B) - p_2(1+\delta_j) - p_3^2(1+\delta_3)^2/2M_3 \tag{2}$$

The requirement that (A) and (B) lead to the same final state E_m yields to first order

$$p_1 x_1/D_B - \delta_2 p_2 - \delta_3 p_3^2/M_3 = 0 \tag{3}$$

Now assume that event (A) is detected at focal plane coordinates x_2 and x_3. Then event (B) will be found at the shifted values $x_j + \delta x_j$ where the shifts $\delta x_j = \langle x|x\rangle_j\, x_1 + \langle x|\delta\rangle_j\, \delta_j p_j/p_j^{(0)}$ correspond to momentum shifts

$$\delta_j^* = \delta x_j/\langle x|\delta\rangle_j = -x_1/D_j + \delta_j p_j/p_j^{(0)} \; . \qquad (4)$$

In order to find the same missing energy value for events (A) and (B) these shifts δ_j^* have to cancel in the missing energy expression. This requires

$$\delta_2^*\, p_2^{(0)} + \delta_3^*\, p_3^{(0)}\, p_3/M_3 = 0 \qquad (5)$$

which becomes in first order after substitution of (4)

$$-x_1(p_2^{(0)}/D_2 + p_3^{(0)2}/D_3M_3) + (\delta_2 p_2 + \delta_3 p_3^2/M_3) = 0 \; . \qquad (6)$$

Using (3) we find that (6) can be fulfilled for every x_1, i.e. for the full dispered beam, if

$$D_B = p_1/(p_2^{(0)}/D_2 + (p_3^{(0)})^2/M_3D_3) \qquad (7)$$

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