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MEASUREMENT OF THE MOMENTUM TRANSFER DEPENDENCE OF QUASIELASTIC (e,e'p) SCATTERING AT LARGE MOMENTUM TRANSFER AND LARGE MISSING ENERGY

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Measurement of the Momentum Transfer Dependence of Quasielastic (e,e′p) Scattering at Large Momentum Transfer and Large Missing Energy

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ABSTRACT

We propose to measure the momentum transfer dependence of large missing energy strength in the quasielastic (e,e′p) reaction. Recent experimental data support the point of view that at large momentum transfers quasielastic (e,e′p) scattering from protons with initial momenta below the Fermi momentum and with missing energies below about 80 MeV are calculable in a Glauber framework, with a standard off-shell prescription for the electron-nucleon scattering and conventional initial-state wave functions. At missing energies above 80 MeV rescattering of the proton via inelastic channels, e.g. by pion production, will be significant. This experiment will measure the missing energy strength up to removal energies of 300 MeV, addressing the following questions:

- Can we understand the quasielastic (e,e′p) reaction at large momentum transfers AND large missing energies in a conventional framework?
- If so, what is the average removal energy for a proton in a nucleus?

The momentum transfer dependence and the A dependence of the quasielastic (e,e′p) reaction will be measured for four targets, ^{2}H, ^{4}He, ^{12}C, and ^{58}Ni, for momentum transfers between 1.9 and 8.7 (GeV/c)^2. For momentum transfers below 6.2 (GeV/c)^2 we only propose kinematics to measure that part of the missing energy region which is not covered by approved proposals PR91-007 and PR91-013. The collaboration includes the principals of these proposals. The experiment will use the coincidence spectrometer pair in Hall C to detect the scattered electron and the knocked-out proton.

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I. Physics Motivation

1.1 Quasielastic (e,e′p) Scattering from Nuclei

In inclusive (e,e′) quasielastic scattering experimental results at large momentum transfer support the point of view that the harder a nucleon is hit, the better the electron scattering process approximates a single-particle picture.[1]

It was first pointed out by Jacob and Maris that coincidence experiments in the quasielastic region provide much more detailed information on the single-particle aspects of nuclear structure.[2] Indeed, experimental studies of the quasielastic (e,e′p) reaction at low Q^2 (≤ 0.5 (GeV/c)^2) have proved to be very useful in gaining information on the structure of nuclei. They provided direct evidence for the shell structure of nuclei not only near the Fermi level, but also far below this level.[3] Later, due to improved energy resolution, bound-state wave functions and spectroscopic factors for transitions to specific states of the residual nucleus could be obtained.[4,5] These single-particle properties have been quite extensively investigated with the (e,e′p) reaction.[6-8]

One of the surprising observations was the violation of the spectroscopic sum rule. This sum rule states that the measured spectroscopic strength corrected for Final-State Interaction effects and integrated over recoil momentum and missing energy should correspond to the total number of protons in the nucleus. The lack of strength observed has been a challenge for theoretical nuclear physics. Recently possible explanations for this effect have been given. Strong correlations among the nucleons in the nucleus shift strength up to very large missing energies. Thus, it was outside the experimentally accessible domain in energy and momentum of the experiments.[9-11]

Increasing the momentum transfer of the scattering will provide new information relevant to this problem. Firstly, the range in experimentally accessible missing energies will be greatly increased because of the higher incident electron energy. Secondly, Final-State Interaction effects should become easier to calculate as the final-state proton-nucleon interaction is becoming essentially constant. Thirdly, as the proton is hit harder the wavelength becomes smaller compared to the proton size and the approximation of a single-particle scattering becomes better, as observed in quasielastic (e,e′) scattering.

The first measurements of quasielastic (e,e′p) scattering at momentum transfers larger than 1 (GeV/c)^2 have been performed by the NE18 collaboration at SLAC.[12] NE18 measured (e,e′p) scattering from nuclei in the momentum transfer range of $1.0 \leq Q^2 \leq 6.8$ (GeV/c)^2. The experiment used the Nuclear Physics Injector to provide electron beams with energies of 2.0-5.1 GeV. The 1.6 GeV/c spectrometer was used to detect the scattered electrons and the 8 GeV/c spectrometer to detect the recoiling protons. Nuclear targets used were ^{1}H, ^{2}H, ^{12}C, ^{56}Fe, and ^{197}Au.

The ^{2}H(e,e′p) data confirm the quasielastic nature of the (e,e′p) reaction. The extracted momentum distributions are well described by a calculation using the Bonn potential. The lack of experimental strength found at large missing energies after deradiating the data supports the radiative correction procedure used.

For the ^{12}C(e,e′p) reaction the specific p-shell behaviour at low missing energy, and s-shell behaviour at larger missing energy is observed. The momentum distributions are well described by Woods-Saxon bound-state wave functions with parameters determined from previous Saclay measurements[6] at significantly lower momentum transfer. The deradiated missing energy spectra seem to indicate that single-nucleon strength is dominant at large values of the momentum transfer.

The missing energy resolution was not sufficient to separate different shells in the ^{56}Fe(e,e′p) and ^{197}Au(e,e′p) reactions, and only the integrated strength can be compared to results of previous measurements.

The integrated coincidence strength, corrected for Final-State Interaction effects by performing Glauber calculations, agrees reasonably well with the expected spectroscopic strength, i.e. the number of protons in the target nucleus.

Thus, the conclusion from the NE18 results seems to be that the quasielastic (e,e′p) reaction is satisfactorily described by incorporating Final-State Interaction effects by performing Glauber calculations. A natural extension of this work would be to extend the NE18 measurements to larger missing energies, to see whether also this region can be understood in this framework. Probing our understanding of this larger missing energy region with the (e,e′p) reaction is interesting for two reasons. Firstly, large missing energy strength might have an appreciable effect on the average removal energy of a bound proton; secondly the rescattering contributions might be more complex in this region. We will address these two issues in more detail in the next sections.

1.2 Large Missing Energy Strength

In this section we describe the expectations for strength in the large missing energy region assuming the Plane-Wave Impulse Approximation holds for the quasielastic (e,e′p) reaction.

Recently, the Rome group[13−17] calculated the spectral function S(E,**p**) for a variety of nuclei. We will show here some of their results for the ^{3}He nucleus, where the calculations are thought to be most realistic. The spectral function represents the joint probability to find a nucleon with binding energy E and momentum **p** in the nucleus or, equivalently, the probability that the (A-1) residual system is left with excitation energy E^*_{A-1} after a nucleon with momentum $\mathbf{p}$ has been removed. They decompose the spectral function in a ground-state and a break-up channel:

$$S(E,\mathbf{p}) = S(E,\mathbf{p})_{gr} + S(E,\mathbf{p})_{ex}(1-\delta_{E,E_{min}}). \tag{1.1}$$

The break-up channel momentum distribution $n_{ex}(\mathbf{p})$ can now be defined as:

$$n_{ex}(\mathbf{p}) = \int_{E_{min}}^{\infty} S(E,\mathbf{p})_{ex}(1-\delta_{E,E_{min}})dE. \tag{1.2}$$

The spectral function integrated over the removal energy is shown for ^{3}He in figure 1.1.

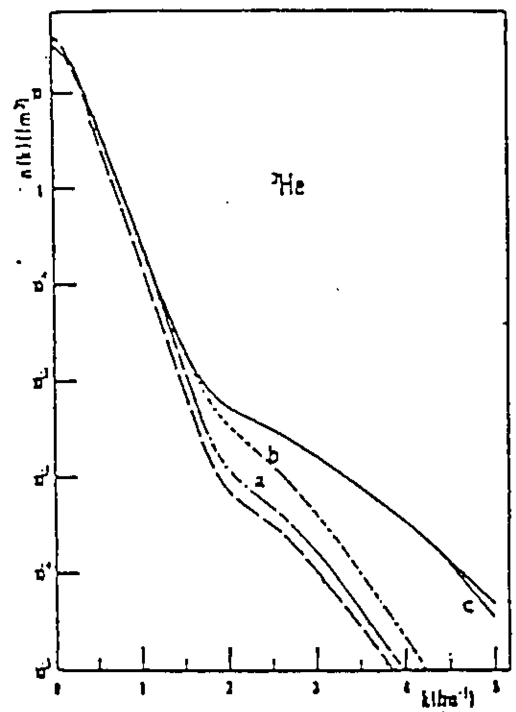

Figure 1.1. The integrated spectral function for ^{3}He. The dashed curve represents n_{gr} and the curves labeled a, b and c represent the sum of n_{gr} and the three-body channel spectral function integrated from E_{min} up to 12, 50 and 300 MeV, respectively. The full curve is $n_{gr} + n_{ex}$.

The following important observations can be made:

- For momenta $p > 2$ fm^{-1} the momentum distribution is dominated by the break-up channel configurations in the nuclear ground-state wave function, i.e. by ground-state correlations.
- The small (3 %) wave function components with removal energy above 50 MeV have a large effect on the density at high momenta.
- High momentum components are strictly linked to high missing energies.

The relationship between high-momentum components and continuum strength has been observed in measurements of ^{3}He(e,e'p) and ^{4}He(e,e'p) at Saclay. The missing energy spectra (Fig. 1.2) for these reactions are at large missing momenta dominated by a broad structure populating the continuum out to large missing energies. As the missing momentum increases, the broad structure seems to move to higher missing energy, as is expected for the interaction with a correlated nucleon pair. The arrows in the figure indicate the position expected from disintegration of a two-nucleon pair at rest. The width then reflects the center-of-mass motion of the pair.

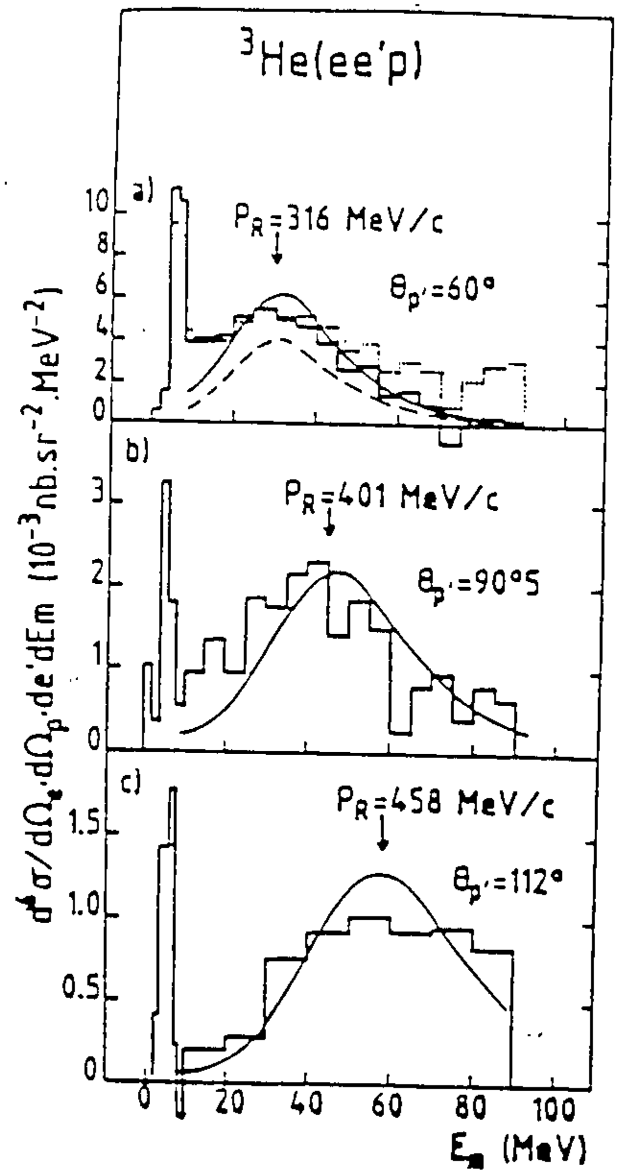

Figure 1.2. The missing energy spectra obtained in the ^{3}He(e,e'p) reaction at Saclay.

Benhar et al.[18] have obtained an accurate approximation to the spectral function for nuclear matter using the realistic Urbana V_{14} + three-nucleon interaction.[19] Their method is based upon the use of a ground-state variational wave function, using orthogonalized correlated basis states for the intermediate (A-1) states. Also here it is seen that correlations cause large deviations from the mean-field picture. In addition, the probability to find nucleons with high momentum and large binding energies is significant, increasing the average removal energy compared to previous calculations to about 70 MeV.[20] This large value of the average removal energy and high-momentum components has significant consequences in describing the nuclear dependence observed in deep-inelastic scattering (EMC effect). The present theoretical belief is that a large part of the observed EMC effect can be explained by nucleon contributions alone.

In summary, one expects large missing energy strength in PWIA as being due to knockout of a strongly correlated proton. Assuming one has a valid prescription for the electromagnetic interaction with an off-shell nucleon,[21] the average binding energy of a proton inside a nucleus can be derived from a measurement of the full spectral function or light-cone momentum distribution.[22]

1.3 Rescattering Contributions at Large Missing Energy

The nucleon struck by the virtual photon interacts strongly with the rest of the nucleus as it exits. In rescattering it can lose energy and change direction. As the nucleon loses energy in the rescattering process, the event will appear with higher missing energy, and potentially contribute to the quasi-elastic strength measured at large missing energy. Thus, before drawing any conclusion about the large missing energy strength measured, one has to study the possible influence of other reaction mechanism effects ending up at large missing energies.

This question of additional reaction mechanism contributions ending up at large missing energy is an intriguing question in itself. High momentum (p,2p) data from Brookhaven[23] have been interpreted as evidence for color transparency effects. However, interpretation of these data is complicated by the presence of the strong interaction to produce the hard scattering. In a comparable momentum transfer range the NE18 experiment does not see a similar rise of the measured (e,e′p) yield. A possible explanation for this result might be related to the fact that the in the (p,2p) experiment only the scattered proton was measured, and the quasifree character of the reaction was selected by kinematics. Thus, no cut was applied to the missing energy range probed.

Recently, several authors have concluded that at sufficiently large momentum transfer Final-State Interaction effects require consideration of Gribov corrections to a Glauber calculation. At high energies they expect that excited states of the nucleon produced in the scattering process propagate long enough through the nuclear medium to rescatter diffractively.[24–26] Therefore, at high energies a simple Glauber calculation to estimate rescattering effects will not be sufficient, and one has to include all diffraction excitation transitions, or Gribov's inelastic shadowing.[24]

Since the NE18 results are described satisfactorily by incorporating Final-State Interaction effects via Glauber calculations, we initially describe rescattering contributions appearing at large missing energies using a simple cascade model. We have modelled the (e,e′p) reaction as a two-step process: the virtual photon couples to either a proton or a neutron, followed by the possibility of a rescattering process with other nucleons in the nucleus. In both steps the production of pions is incorporated.

Contributions from the pion production process will occur only above the missing energy required to produce the rest mass of the pion. Thus, a signature of a pion production contribution would be a rise of the experimental cross section above this threshold. The pion can be a knocked-out pionic component or be produced on a nucleon by the applied external field, either directly or through a resonance. Another possible source of pion production is the rescattering process $N + N \rightarrow N + N + \pi$. Nozawa, Blankleider, and Lee have developed a dynamical model of pion photoproduction on the nucleon.[27] They include Born terms and the Δ-excitation in the electron-pion coupling. The off-energy shell πN final-state interaction is parametrized and fitted to phase-shift data. It is relatively straightforward to include this model in multiple scattering formulations including more nucleons. Nozawa and Lee have extended this model to include the electroproduction of pions on the nucleon.[28]

To estimate the possibility of pion production in the rescattering mechanism, a cascade model is used. In this calculation experimental NN single pion and double pion production cross sections have been used,[29,30] and extrapolated to higher momenta. Below momenta of 2 GeV/c the single-pion production process, and in particular the Δ-production, dominates the inelastic NN interaction. We have included also the effect of the higher-lying resonances in the cascade model, and intend to include double-pion production.

II. The Experiment

The proposed experiment will measure the (e,e′p) cross section at large missing energies as a function of A and Q^2 at the highest Q^2 attainable at CEBAF. For momentum transfers below 6.2 $(GeV/c)^2$ we only propose kinematics to measure that part of the spectral function up to 300 MeV in missing energy which is not covered by approved proposals PR91-013 and PR91-007.[31,32] These proposals will measure the nuclear transparency for a missing energy range below pion threshold as a function of A and Q^2. At the highest Q^2 one hopes to see effects of color transparency, the effect of the diminishing of Final-State Interactions if the scattering occurs on a small object.

We propose to extend the Q^2 range to 8.7 $(GeV/c)^2$, the maximum Q^2 possible in Hall C. Possible effects of Gribov's inelastic shadowing are predicted at these high Q^2.[26]

Note that proposals PR91-013 and PR91-007 intend to use very similar target nuclei. PR91-013 intends to use ^{12}C, ^{28}Si, ^{58}Ni, and ^{208}Pb. PR91-007 uses ^{4}He, ^{12}C, ^{56}Fe, and ^{197}Au. Both proposals intend to perform ^{1}H(e,e′p) calibration experiments. Here we intend to use the target nuclei ^{2}H, ^{4}He, ^{12}C and either ^{56}Fe or ^{58}Ni. The use of ^{2}H as a second calibration target to check radiative corrections contributions has proved to be very valuable for the analysis of the NE18 data. Note that in proposals PR91-013 and PR91-007 the lowest count rates are obtained for the heaviest target nuclei ^{197}Au or ^{208}Pb, which we do not intend to use.

It is important to probe the large missing energy strength for both the few-body nucleus ^{4}He and the heavier target nuclei ^{12}C and ^{56}Fe, in order to disentangle uncertainties in the off-shell electron-nucleus cross section from momentum transfer dependent rescattering effects showing up at large missing energies (the probability for rescattering from a Glauber calculation amounts to 44 % for the ^{12}C nucleus and to 64 % for the ^{56}Fe nucleus).

The SOS and HMS spectrometers will be used to detect the scattered electron and the knocked-out proton.

III. Count Rate and Running Time Estimates

3.1 Kinematics

The full kinematics are given in Table 3.1. In the low missing energy region the kinematics are chosen to be close to the top of the quasi-elastic peak. Note that at the lowest momentum transfer the HMS will be used for electron detection, and the SOS for proton detection. At each Q^2 we will measure an angular distribution (perpendicular kinematics) and carry out measurements of the spectral function S(E,**p**) over a large missing energy range and a large missing momentum range. Though only count rate estimates will be given for the missing energy region up to 200 MeV, the kinematics cover up to 300 MeV in missing energy. The missing momentum range covered extends up to 600 MeV/c. At the lowest Q^2 several settings of the recoil proton angle are necessary to span the complete scattered proton distribution.

Table 3.1. Kinematics for the proposed (e,e′p) experiments. The last two columns indicate the proposed proton spectrometer settings of proposals PR91-013 and PR91-007, and the proposed additional settings of this proposal.

Q^2	E	E′	$\theta_{e'}$	p′	θ_q	θ_p	
$(GeV/c)^2$	GeV	GeV	deg	GeV/c	deg	deg	deg
1.9	4.0	3.00	22.8	1.70	43.3	43,46,49,52	+ 39,56
3.8	3.8	1.80	43.5	2.78	26.4	26,29,32	+ 23,35
5.9	4.0	0.87	81.1	3.96	12.5	13,15	+ 18
7.3	5.25	1.35	61.0	4.74	14.4		+ 14,17
8.7	6.0	1.35	62.5	5.51	12.6		+ 12,14

The phase space acceptances are such that at the larger values of Q^2, only two kinematical settings are sufficient, given the large momentum acceptances of the SOS and HMS spectrometers.

3.2 Count Rate Estimates

We have assumed the following spectrometer acceptances: for SOS ± 20 % in momentum and a solid angle of 9 msr, for HMS ± 10 % in momentum and a solid angle of 6.4 msr. As SOS can see only 4 cm transverse length of the extended target (for a spectrometer angle of 90 degrees), a target thickness of 200 mg/cm^2 has been used in the estimates for a ^{4}He target nucleus (assuming a high-pressure cryogenic gas target at a temperature of 20 K and a pressure of 20 atm). For the measurements on ^{1}H and ^{2}H we assume liquid targets of 15 cm length, but will reduce the beam currents to 20 μA only, corresponding to a safe limit of 100 W of power dissipated in the target. Thus, the beam entrance and exit foils will be located outside the acceptance of the spectrometers. The count rates estimated assume a 6 percent radiation length ^{12}C and a 12 percent radiation length ^{58}Ni target. Note that in some of the kinematics proposed in PR91-007 far thinner targets will be used. In those cases we will use these thick targets only for additional kinematics covering the large missing energy range. The coincidence count rate N_C is calculated from the five-fold differential cross section, the beam current, the target thickness, and the angular and momentum acceptances. The coincidence cross section for the discrete transition is given in PWIA by:

$$\frac{d^5\sigma}{dEd\Omega_e d\Omega_x} = \int_{\Delta E_m} \frac{d^6\sigma}{dE_e dT_x d\Omega_e d\Omega_x} \frac{\partial T_x}{\partial E_m} dE_m = \frac{E_x|\mathbf{p_x}|}{1 - \frac{E_x}{E_{A-1}} \frac{\mathbf{p_{A-1}} \cdot \mathbf{p_x}}{\mathbf{p_x^2}}} \sigma_{ep} \rho(|\mathbf{p_m}|). \quad (3.2)$$

Here $\rho(|\mathbf{p_m}|)$ is the single-particle momentum distribution and for σ_{ep} we used the off-shell electron-proton cross section description σ^1_{cc} by De Forest[21].

We have written a Monte Carlo code to estimate the expected count rates for different E_m and p_m slices. We use numerical input spectral functions, taken from fits to previous data, corrected for Final-State Interaction effects. Final-State Interaction effects are estimated by using a global absorption probability, estimated from Glauber calculations. For the missing energy region above 100 MeV of ^{58}Ni we use as input a G-matrix calculation of a nuclear matter spectral function by Ji,[33] adapted for ^{58}Ni.[34] In this calculation the strong correlation between high momentum and high missing energy is taken into account.

Coincidence rates are given in Table 3.2, assuming an average current of 100 μA. To reduce the random rates we intend to operate at a lower average current (10 μA), and at reduced target thicknesses at Q^2 of 1.9 (GeV/c)^2. Coincidence rates are given for two missing energy regions, 0-100 MeV and 100-200 MeV, respectively. Table 3.2 also shows the (e,e') and (e,p) singles rates. We assume that the negatively charged pions will be rejected by the electron trigger, using a combination of the Cherenkov and the Shower Counter in the detectors. This worked satisfactorily for rejecting pions in the NE18 experiment. The electron singles rate is determined by adding both the inclusive quasielastic contribution and the Fermi-smeared deep-inelastic contribution. The hadron singles rate is determined from parameterization of previous measurements with incident Bremsstrahlung photons of energy 5-19 GeV. This parameterization gave good agreement with measured hadron singles rates in NE18. The real-to-random ratio has been determined by assuming a resolving time of 2 ns.

Table 3.2. Single-arm counting rates, coincidence rate and the real-to accidental coincidence ratio R/A for the proposed kinematics. All rates are given for a 12 % radiation length ^{58}Ni target. Coinicidence rates are given for the central proton spectrometer setting. A coincidence resolving time of 2 ns and a duty factor of 100 % have been assumed in the calculation of R/A. Coincidence rates are given for two missing energy regions, 0-100 MeV (I) and 100-200 MeV (II), respectively. Time requested is the sum for all target nuclei, including possible ^{1}H calibrations.

Q^2	(e,e′)	(e,h)	N_C(I)	N_C(II)	R/A	Time
$(GeV/c)^2$	[Hz]	[Hz]	[hr^{-1}]	[hr^{-1}]		[hr]
1.9	11K	26K	300K	60K	178	16
3.8	440	2.6K	15K	4K	2280	30
5.9	15	2.6K	1500	400	6710	44
7.3	20	1.1K	500	180	4350	76
8.7	11	410	200	80	8680	96

3.3 Beam Time Request

We request 90 hours of beamtime to cover the large missing energy region, in connection to the approved experiments 91-013 and 91-007, for the target nuclei ^{2}H, ^{4}He, ^{12}C, and ^{58}Ni. Note that several kinematics settings are required here, such that a large amount of overhead is included in the requested beam time. In addition we request 172 hours of beamtime to extend these experiments to larger momentum transfer. Assuming that these measurements will be performed in conjunction with experiments 91-007 and 91-013, no setup and checkout time is required. The total beam time required is 262 hours or 11 days (see Table 3.3).

Table 3.3. Beam time request.

	Time [hours]
Data Acquisition: additional to PR91-007 and PR91-013	90
Data Acquisition: extension to larger Q^2	172
TOTAL	262

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