Exp.-Nr.: A1/1–97

Mainz Microtron MAMI

Collaboration A1: "Virtual Photons"

Proposal for an Experiment

Sept. 15, 1997

Investigation of short-range nucleon-nucleon correlations using the reaction $^{16}O(e,e'pp)^{14}C$ in super-parallel kinematics

Collaborators:

P. Bartsch, D. Baumann, R. Böhm, T. Caprano, S. Derber, M. Ding, A. Ebbes, I. Ewald, J. Friedrich,* J.M. Friedrich, R. Geiges, P. Jennewein, M. Kahrau, M. Korn, K.W. Krygier, A. Liesenfeld, H. Merkel, K. Merle, P. Merle, U. Müller, R. Neuhausen, Th. Pospischil, G. Rosner,* H. Schmieden, A. Wagner, Th. Walcher, M. Weis, S. Wolf

Institut für Kernphysik, Universität Mainz

* Contact persons

Abstract

We propose to measure the two-proton knockout reaction $^{16}O(e,e'pp)^{14}C$ with high angular and energy resolution in super-parallel kinematics (forward proton emitted in the direction of the momentum transfer $\mathbf{q}$, second proton opposite to it). These kinematics are expected to be particularly sensitive to short-range nucleon-nucleon correlations. The experiment aims at resolving two-hole states with respect to ^{16}O up to an excitation energy $E^*(^{14}C) \approx 20\,\text{MeV}$ with a resolution $\delta E^*(^{14}C) \leq 1\,\text{MeV}$. The relative cross sections for populating low excited states in ^{14}C and their momentum distributions will be compared with recent unfactorized model calculations using different realistic NN potentials.

1. Introduction

The phenomenological independent particle model (IPM) of the nucleus assumes that the mutual attraction of the nucleons averages to a mean nuclear field in which pointlike nucleons move. Already Fermi realized that this assumption is too naïve [1]. Without *repulsive* short-range forces between the nucleons any nucleus would just collapse to a size corresponding to the range of the attractive nuclear force (about 2 fm), even when Pauli-blocking is taken into account. In the IPM the nucleons are stationary states extending over the nuclear size (about 5 fm for ^{12}C). This means a nucleon's mean free path is of this order. The strong repulsive nucleon-nucleon interaction in the nuclear many body system needed to explain this quantum-gas like behaviour is related to the repulsive core seen in nucleon-nucleon (NN) scattering. Self-consistent Hartree-Fock calculations making use of the corresponding NN potentials do not describe nuclear properties correctly [2]. With the Bethe-Goldstone equation, on the other hand, the repulsive part of the NN potential can be accounted for [3, 4]. The effect of this repulsion is usually referred to as short-range correlation (SRC).

It has been difficult to obtain a clear experimental signature of SRC in nuclei. Quasi-elastic $(e,e'p)$ measurements gave indirect evidence for the presence of SRC. It was found that the occupation probabilities for the valence shells are considerably smaller than predicted by the independent particle shell model [5]. According to Refs. [6, 7], part of the quasi-hole strength is shifted to high (missing) momenta, well above the Fermi momentum (about 220 MeV/c in Carbon or Oxygen), and high missing energies. At these energies, background processes like pion production and proton-neutron emission following the absorption of a virtual photon on meson exchange currents (MEC) might dominate the $(e,e'p)$ cross section. This makes it hard to interpret the $(e,e'p)$ data at high missing energies in terms of short-range correlations [8, 9]. The $(e,e'p)$ reaction is predicted to be rather insensitive to SRC at low missing energies [7]. Nonetheless, for missing momenta above 500 MeV/c low lying exited states in ^{15}N populated in the reaction $^{16}O(e,e'p)$ displayed a nucleon momentum density one order of magnitude larger than predicted by a mean field calculation [10]. For $(e,e'p)$ reactions on the heavy target nucleus ^{208}Pb the surplus cross section at high missing momenta was attributed to long-range correlations [11].

It is more promising to go beyond $(e,e'p)$ experiments and also observe the second (correlated) nucleon in two-nucleon $(e,e'NN)$ knockout reactions, as first proposed by Gottfried [12]. In order to access small internucleon distances both nucleons should be in a state with large relative momentum. This one-body SRC process competes with two-body processes. Meson exchange currents and the excitation of the Δ resonance with a subsequent decay $\Delta N \to NN$ may also lead to the emission of two high energy nucleons. In order to suppress these background contributions we chose the reaction $(e,e'pp)$ where MEC do not contribute to first (non-relativistic) order. SRC are expected to be most effective for two nucleons in a relative S state, the $^1S_0$ configuration for two protons. There is evidence for the dominance of $^1S_0$ pair emission in (e,e'pp) reactions at low excitation energy [13]. In the $^1S_0$ proton pair configuration however, the dominant M1 transition $pp \rightarrow \Delta^+ p \rightarrow pp$ is strongly suppressed because of total angular momentum and parity conservation. Finally, to facilitate the comparison with theory a light doubly closed shell nucleus should be selected as a target. We chose the nucleus ^{16}O for which two-proton spectral functions were recently published [14]. Only the longitudinal channel was considered in the calculation of the cross section for the reaction $^{16}O(e,e'pp)^{14}C$ in Ref. [14]. However, both long and short-range correlations were treated in a consistent manner. These two-proton spectral functions were used in calculations for the reaction $^{16}O(e,e'pp)^{14}C$ in Ref. [15]. There, the excitation of the Δ resonance was also taken account of in the transverse channel according to Ref. [21]. Distortions of the outgoing protons were taken into account within the framework of the optical model. The optical model parameters were taken from Ref. [22].

We propose to measure the reaction $^{16}O(e,e'pp)^{14}C$ at an energy transfer ω in the so-called “dip” region between the broad peaks in the (e,e') excitation function corresponding to the quasi-elastic (QE) nucleon knockout and the quasi-free excitation of the Δ resonance. This choice is suggested for three reasons. First, SRC are expected to play an important role in this energy transfer region. Calculations including only QE scattering, MEC and pion production underestimate the measured cross sections significantly [16]. Second, the probability of exciting the Δ should be kept small. Finally, the virtual photon must have enough energy to put two highly correlated nucleons onto the mass shell. This is difficult at the low energy side of the QE peak as one would need to sample very small cross sections at the required high momentum transfers. The photon should also posess a large longitudinal polarization as it is the longitudinal nuclear response function that is predicted to exhibit a particularly large sensitivity to ground-state correlations [17, 18].

Two-nucleon emission is expected to exhibit a typical angular pattern [19, 14, 20, 18, 15]. The best choice of angles seems to be the so-called *super-parallel* kinematics. As shown in Ref. [23], the contribution from isobaric currents is largely suppressed under these kinematic conditions because the M_{1+} multipole dominates the excitation of the Δ in the pair and does not (at low missing momentum) contribute to the cross section at $\gamma = 180°$. The experiment can then be used to discriminate between different NN potentials or SRC functions (cf. Ref. [23]). Second, super-parallel kinematics allow a Rosenbluth-type separation of the longitudinal and transverse part of the $(e,e'pp)$ cross section, as first pointed out in Ref. [19].

In this way, the longitudinal part of the $(e, e'pp)$ cross section, the most sensitive to SRC, becomes accessible.

2. Experiment

We propose to perform the $^{16}O(e, e'pp)^{14}C$ experiment in essentially the same kinematics as in a recent feasibility study at *MAMI*. In these short measurements, the reaction products were detected with high angular and energy resolution with three magnetic spectrometers [24]. The electron beam energy was 855 MeV. A beam current around $50\,\mu$A was used, together with a waterfall target [25] of $38\,\mathrm{mg/cm^2}$ thickness. The scattered electrons were observed in spectrometer B at a forward angle $\theta_{e'} = -18°$. The central transferred four-momentum squared was $< Q >^2 = < (\omega, |\mathbf{q}|) >^2 = (215\,\mathrm{MeV}, 316\,\mathrm{MeV/c})^2 = 0.054\,(\mathrm{GeV/c})^2$, the polarization of the virtual photon amounted to $< \varepsilon >= 0.91$. Spectrometer A measured proton #1 emitted in the direction of the three-momentum tranfer $\mathbf{q}$ at $\theta_{\mathrm{q}} = 38.8°$, spectrometer C detected proton #2 emitted opposite to #1 at $\theta_{\mathrm{p_2}} = -141.2°$. Three overlapping kinematical settings were tested under various central missing momenta $< P_{\mathrm{m}} >=<|\ \mathbf{q} - \mathbf{p}_1 - \mathbf{p}_2\ |>= 0$, 70 and 125 MeV/c where $\mathbf{p}_1$ and $\mathbf{p}_2$ denote the measured momenta of protons #1 and #2, respectively. At the same time, the initial *relative* proton-proton momentum sampled by the experiment was kept nearly constant. It was selected to range from 0.4 to 1.2 GeV/c irrespective of the central missing momentum chosen. Finally, special care was taken to uniformly sample the triple coincidence phase space in the excitation energy interval of interest $0\,\mathrm{MeV} \leq E^*(^{14}C) \leq 40\,\mathrm{MeV}$.

The coincidence time resolution between any of the three spectrometers lay between 1 and 2 ns. True triple coincidences were observed above a flat background of random coincidences. Even at a luminosity close to $10^{37}\,\mathrm{nucleons/cm^2/s}$, the true-to-random triple coincidence rate was 1:2, as demonstrated in the online coincidence time spectrum of Fig 1. Above a low uniform background of totally random coincidences one observes three ridges of true double coincidences between any two spectrometers with another particle accidentally measured in the third spectrometer. About half of the counts in the centre peak are due to true triple coincidences.

Fig. 2 shows a spectrum of the reaction $^{16}O(e, e'pp)$ as a function of the excitation energy E^* in the residual nucleus ^{14}C. $E^*(^{14}C)$ is obtained by subtracting the two-proton separation energy from the missing energy $E_{\mathrm{m}} = \omega - T_1 - T_2 - T_{^{14}\mathrm{C}}$ where ω is the energy transfer, T_1 and T_2 are the kinetic energies of proton #1 and #2, respectively, and $T_{^{14}\mathrm{C}}$ is the kinetic energy of the recoiling ^{14}C nucleus. It was calculated from the measured missing momentum P_{m} as $T_{^{14}\mathrm{C}} = P_{\mathrm{m}}^2/(2\,m_{^{14}\mathrm{C}})$ using $\mathbf{p}_{^{14}\mathrm{C}} = \mathbf{P}_{\mathrm{m}}$. The spectrum was taken in the missing momentum interval $-90\,\mathrm{MeV/c} \leq P_{\mathrm{m}} \leq 90\,\mathrm{MeV/c}$ where we adopted the convention that P_{m} is taken positive when $\mathbf{P}_{\mathrm{m}}$ points in the direction of $\mathbf{q}$. In Fig. 2, random coincidences were subtracted. The excitation energy resolution achieved was about 1 MeV. The data were corrected for inefficiencies and normalized to the triple coincidence acceptance of the set-up. We did not yet apply radiative corrections. We note in passing that the spectrum of Fig. 2 looks quite different from that published in Ref. [13]. One reason might be that only missing momenta above 100 MeV/c were accessible in the NIKHEF experiment. Consequently, higher spin states were preferentially populated, whereas the probability for exciting the ground state in ^{14}C is largest at $P_{\mathrm{m}} = 0\,\mathrm{MeV/c}$ (see below).

As in the two-proton pickup reactions $^{16}O(n,^3He)$ (see [26]) and $^{16}O(^6Li,^8B)$ (Ref. [27]) leading to ^{14}C, two-hole states with respect to the target nucleus ^{16}O were preferentially excited in the two-proton knockout reaction $^{16}O(e,e'pp)^{14}C$. These states are (cf. Fig. 2) the ground state of ^{14}C (main configuration $(1p_{1/2})^{-2}$) the two 2^+ states (main configuration $(1p_{1/2},1p_{3/2})^{-1}$) at 7 and 8.3 MeV, respectively, and a 1^+ state at 11.3 MeV with main configuration $(1p_{1/2},1p_{3/2})^{-1}$. Above assignment of configurations was adopted from a calculation [14] of the two-proton spectral function in ^{16}O. Only one 2^+ state is predicted [14] to lie below 10 MeV excitation energy in ^{14}C. Experimentally, there are two at $E^*(^{14}C) = 7$ and 8.3 MeV (cf. Fig. 2). This fragmentation probably arises from core polarization effects not considered in Ref. [14]. When comparing with theory, one has to sum over the experimental cross sections for these two states. A second 0^+ state is expected [14] to be populated at $E^*(^{14}C) = 9.75\,\mathrm{MeV}$ (main configuration $(1p_{3/2})^{-2}$). The second 2^+ state (main configuration also $(1p_{3/2})^{-2}$) is predicted to lie at $E^*(^{14}C) = 13.14\,\mathrm{MeV}$. There may be even more isolated 2-hole states in the continuum, for instance around 15 and 20 MeV excitation energy. All these states will only become accessible in experiments with much higher statistics.

According to Ref. [14], low lying levels in the residual nucleus ^{14}C are chiefly excited by only a limited number of partial waves in the reaction $^{16}O(e,e'pp)$. For instance, the ground state of ^{14}C and the first 2^+ state at $< E^*(^{14}C) >= 7.7\,\mathrm{MeV}$ are mainly excited via the emission of a $^1S_0$ proton pair with angular momentum $L = 0$ and 2, respectively, the 1^+ at $E^*(^{14}C) = 11.3\,\mathrm{MeV}$ by $^3P, L = 1$ pairs. The relative excitation probability for these states should vary with the missing (or proton pair) momentum sampled in the reaction $^{16}O(e,e'pp)^{14}C$. This is clearly borne out in Fig. 2 to 4. Whereas it is the $L = 0$ partial wave that contributes most at missing momentum $< P_{\mathrm{m}} >= 0\,\mathrm{MeV/c}$ (Fig. 2), the $L = 1$ and 2 partial waves take over at $< P_{\mathrm{m}} >= 70$ (Fig. 3) and 125 MeV/c (Fig. 4). Consequently, the cross sections for populating the 2^+ and 1^+ states at 7, 8.3 and 11.3 MeV strongly increase with increasing P_{m} in comparison to the cross section for exciting the 0^+ ground state. However, the statistics, again, are not yet sufficient to establish a missing momentum distribution for the different states excited in the reaction $^{16}O(e,e'pp)^{14}C$. We aim at accumulating the necessary statistics in the beamtime requested in this proposal.

As mentioned before, it is the ${}^1S_0$ proton pair configuration that is expected to be the most sensitive to SRC. Therefore, SRC should strongly influence the probability for exciting the 0^+ ground state and the first 2^+ state in ${}^{14}C$, whereas, according to Ref. [15], the cross sections for higher lying states might also include contributions from 2-body currents arising, for instance, from the excitation of the Δ resonance. Fig. 5 to 7 show calculated missing momentum distributions for the first excited 0^+, 2^+ and 1^+ states in ${}^{14}C$ populated in the reaction ${}^{16}O(e,e'pp)$. The kinematical conditions assumed were those proposed in this paper.[1] Two realistic NN potentials, the Bonn-A and the Reid soft core potential, were considered. Apparently, some global features of the data are well reproduced: the probability for populating the ${}^{14}C$ ground state decreases, the probability for exciting the 1^+ state at 11.3 MeV increases with rising missing momentum. The calculated cross section for exciting the 2^+ states around 7.7 MeV, however, appears to be much too small at any missing momentum.

In summary, we propose to measure the reaction ${}^{16}O(e,e'pp){}^{14}C, E_{\mathrm{beam}} = 855\,\mathrm{MeV}$ in super-parallel kinematics at four central missing momenta $P_{\mathrm{m}} = -70, 0, +70, +125\,\mathrm{MeV}$. We further propose to improve the statistics of the pilot runs by at least a factor of 3 in order to be able to measure missing momentum distributions for the first and second 0^+ and 2^+ states and the spin 1 states in ${}^{14}C$ and compare them with recent model calculations that include different SRC by applying different realistic NN potentials. The kinematics $P_{\mathrm{m}} = -70\,\mathrm{MeV}$ was added to the kinematics of the feasibility study because, there, the sensivity regarding the use of different NN potentials in the calculation of the cross sections for populating the ground state and first excited 2^+ state in ${}^{14}C$ seems to be particularly high (cf. Figs. 5 and 6).

3. Beamtime request

From the spectra displayed in Fig. 2 to 4, the estimated beam time for improving statistics by at least a factor of three and add a fourth kinematical setting at $P_{\mathrm{m}} = -70\,\mathrm{MeV}$ is as follows:

$(3 \times 2 + 3) \times 60$ hours = **540 hours** beam on target

Taking into account an overhead of 30% we request a total beam time of

540 hours / 0.7 = **770 hours**.

[1]The calculations were performed by C. Giusti; for details concerning the ingredients of the model, see sect. 1 and Ref. [15]

References

[1] Enrico Fermi, Nuclear Physics, The University of Chicago Press (1948) 111

[2] K.A. Brueckner et al., Phys. Rev. 95 (1954) 217

[3] H.A. Bethe, Phys. Rev. 103 (1956) 1353

[4] J. Goldstone, Proc. Roy. Soc. (London) A 239 (1957) 267

[5] L. Lapikás, Nucl. Phys. A 553 (1993) 297 c

[6] C. Mahaux and R. Sartor, Adv. Nucl. Phys. 20 (1991) 61

[7] H. Müther and W.H. Dickhoff, Phys. Rev. C 49 (1994) R17

[8] L.J.H.M. Kester et al., Phys. Lett. B 344 (1995) 79

[9] J. Ryckebusch et al., Phys. Lett. B 350 (1995) 1

[10] I. Blomqvist et al., Phys. Lett. B 344 (1995) 85

[11] I. Bobeldijk et al., Phys. Rev. Lett. 73 (1994) 2684

[12] K. Gottfried, Nucl. Phys. 5 (1958) 557

[13] C.J.G. Onderwater et al., Phys. Rev. Lett. 78 (1997) 4893

[14] W.J.W. Geurts et al., Phys. Rev. C 54 (1996) 1144

[15] C. Giusti et al., Preprint Univ. of Pavia (1997), submitted to Phys. Rev. C, and private communication

[16] P. Barreau et al., Nucl. Phys. A 402 (1983) 515

[17] J. Ryckebusch, Phys. Lett. B 383 (1996) 1

[18] J. Ryckebusch et al., Preprint Univ. of Gent (1997), accepted for publication in Nucl. Phys. A, and private communication

[19] C. Giusti and F. D. Pacati, Nucl. Phys. A 535 (1991) 573

[20] C. Giusti and F. D. Pacati, Nucl. Phys. A 615 (1996) 373

[21] P. Wilhelm et al., Preprint Univ. of Mainz (1997), Los Alamos archive nucl-th/9702031, submitted to Z. Physik

[22] A. Nadasen et al., Phys. Rev. C 23 (1981) 1023

[23] I. Blomqvist et al., Preprint Univ. of Mainz (1997), submitted to Phys. Lett. B

[24] I. Blomqvist et al., Preprint Univ. of Mainz (1997), submitted to Nucl. Instr. and Meth.

[25] N. Voegler and J. Friedrich, Nucl. Instr. and Meth. 198 (1982) 293

[26] F. Ajzenberg-Selove, Nucl. Phys. A 523 (1991) 1

[27] R.B. Weisenmiller et al., Phys. Rev. C 13 (1976) 1330

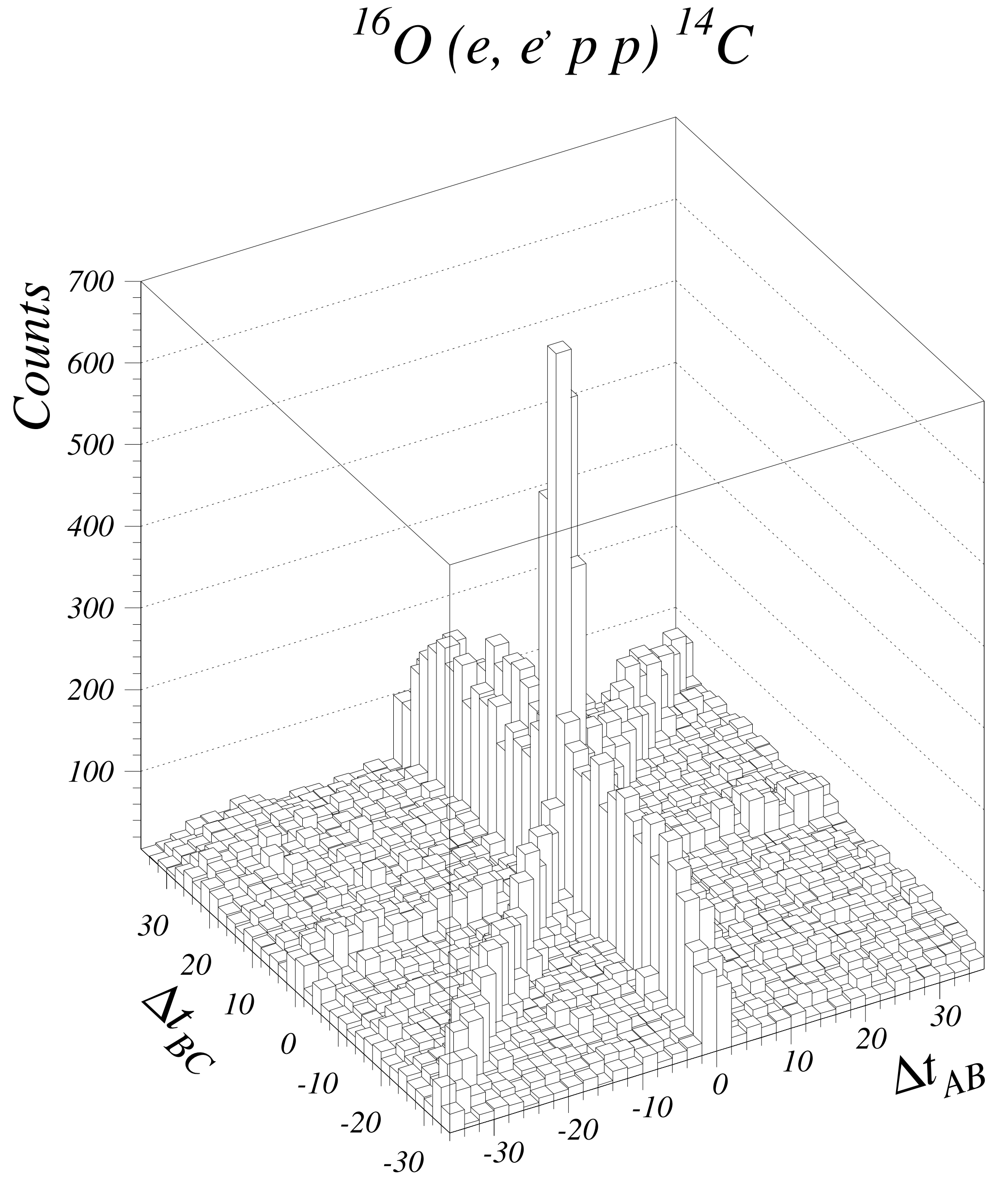

Figure 1: Online coincidence time spectrum at a central missing momentum $< P_{\rm m} >= 0\,{\rm MeV/c}$. $\Delta t_{\rm AB}$ denotes the time difference (in ns) between the electrons observed in spectrometer B and the forward emitted protons detected in spectrometer A, $\Delta t_{\rm BC}$ is the time difference (again in ns) between the scattered electrons and the backward emitted protons observed in spectrometer C.

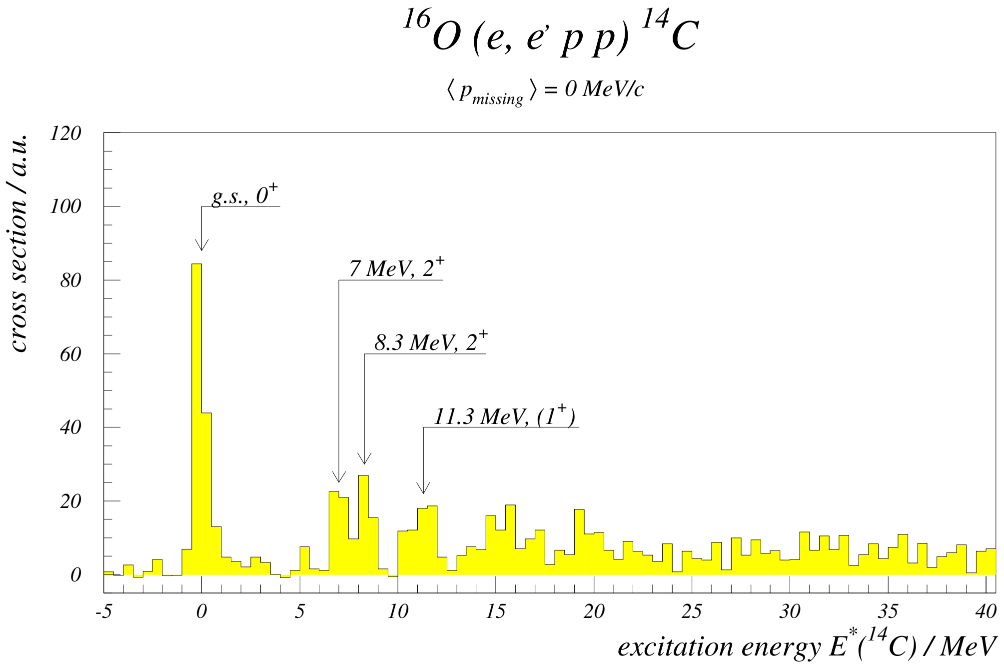

Figure 2: Nine-fold differential cross section of the reaction $^{16}O(e, e'pp)$ as a function of the excitation energy in the residual nucleus ^{14}C at a central missing momentum of $< P_{\mathrm{m}} >= 0\,\mathrm{MeV/c}$. The arbitrary units have been scaled to approximately represent the counts accumulated.

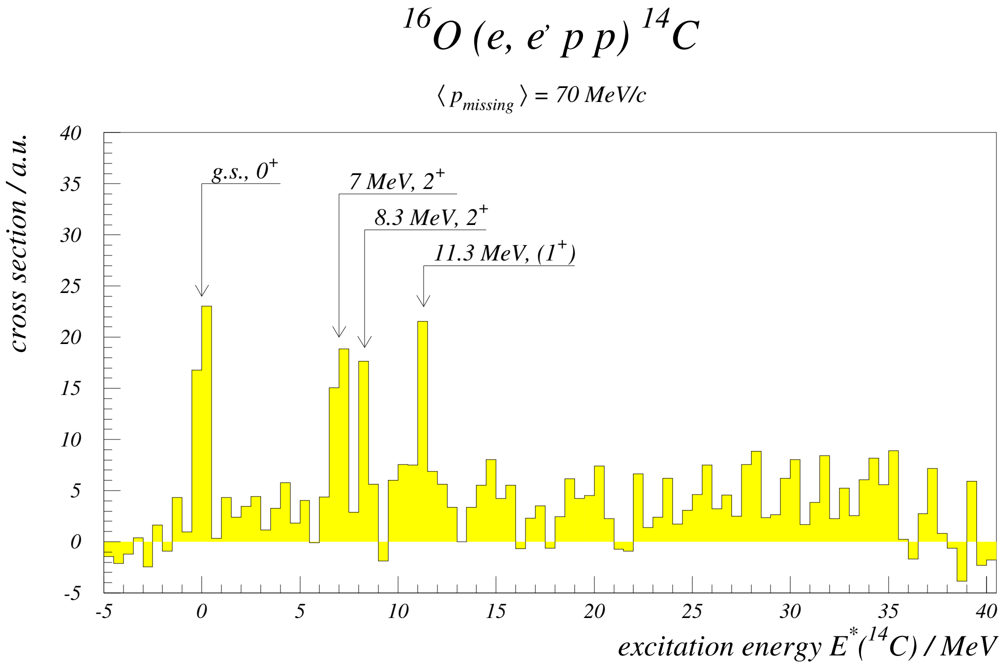

Figure 3: Same as Fig. 2 but for a central missing momentum $< P_{\rm m} >= 70\,{\rm MeV/c}$.

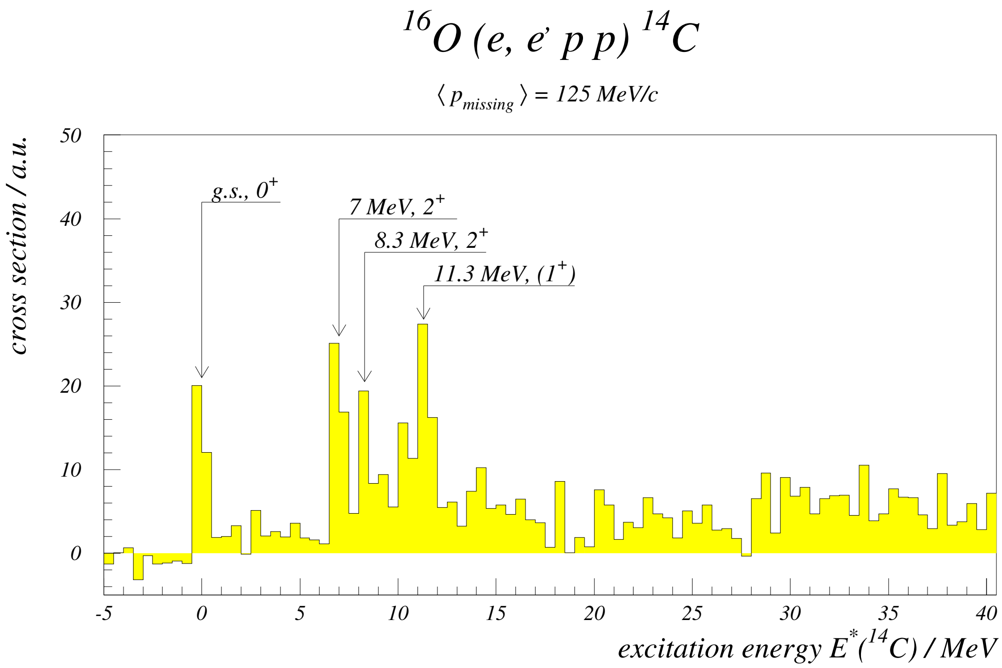

Figure 4: Same as Fig. 2 but for a central misssing momentum $< P_{\rm m} >= 125\,{\rm MeV/c}$.

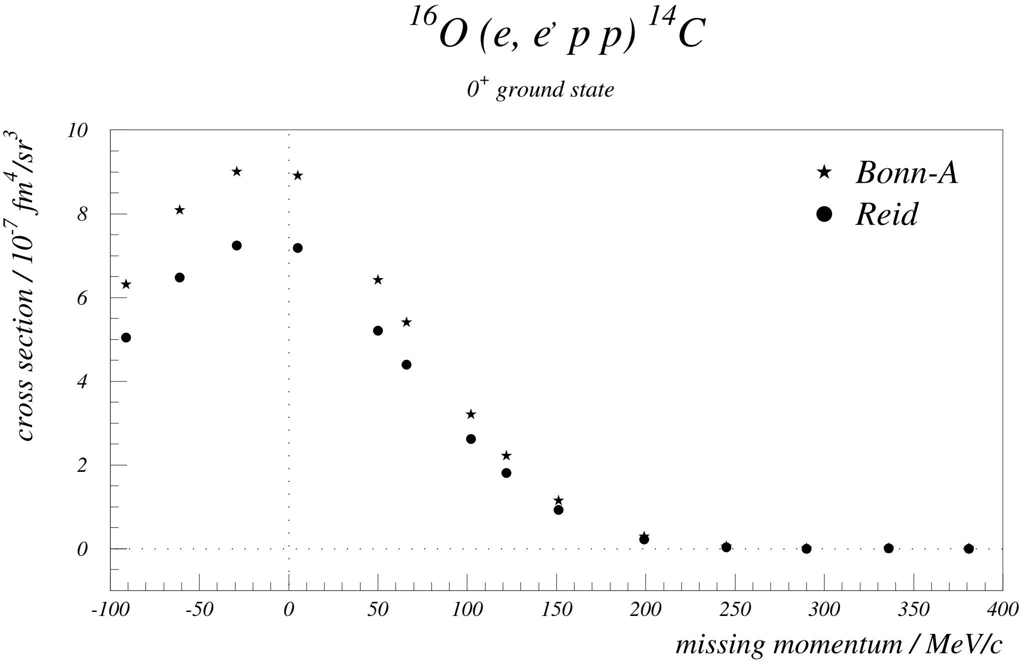

Figure 5: Nine-fold differential cross section for the reaction $^{16}O(e,e'pp)^{14}C_{g.s.}$ calculated by C. Giusti according to Ref. [15] as a function of missing momentum P_{m}. Two realistic nucleon-nucleon potentials, the Bonn-A (stars) and the Reid soft core potential (dots), are considered.

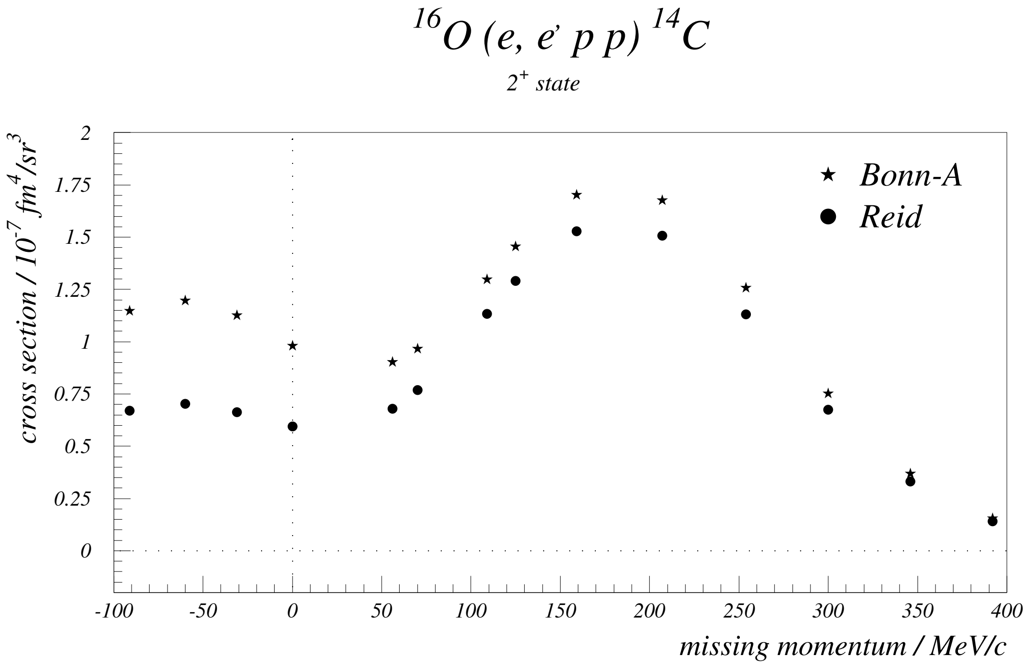

Figure 6: Same as Fig. 5 but for the 2^{+} state at $E^{*}(^{14}C) = 7.7\,\mathrm{MeV}$.

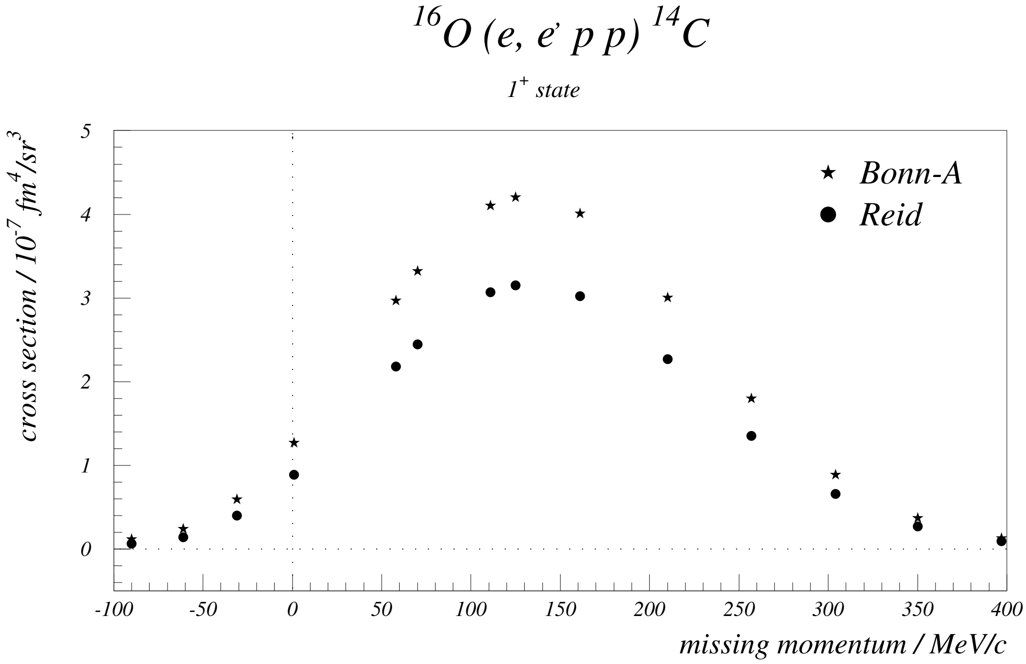

Figure 7: Same as Fig. 5 but for the 1^{+} state at $E^{*}(^{14}C) = 11.3\,\mathrm{MeV}$.