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INCLUSIVE PHOTOPROTON SPECTRA FROM ^{12}C AT INTERMEDIATE ENERGIES

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ABSTRACT

Inclusive photoproton spectra have been measured at five laboratory angles and two photon energies: 159 and 198 MeV. A quasi-monochromatic photon beam, obtained by positron annihilation in-flight on a liquid hydrogen target, was used and the photon spectrum was measured on-line by a pair spectrometer. The experimental proton spectra are well described by assuming a dominant photon absorption mechanism by (n,p) quasi-deuteron pairs in the nucleus, provided that rescattering effects are taken into account.

Nuclear reaction : $^{12}C(\gamma,p)$, E_γ=159 and 198 MeV, θ_p=32.5°, 55°, 80°, 105°, and 130°; measured $d\sigma/d\Omega$; interaction and decay models; quasi-monochromatic photons.

1. Introduction

Photonuclear reactions above the Giant Dipole Resonance seem to be dominated by the photon absorption on neutron-proton pairs within the nucleus: the nucleons roughly share the energy and momentum of the probe. This absorption mechanism should be in fact favoured both by the electromagnetic interaction with the isovector exchange current $J_{[2]}$ and by the presence of tensor correlated S=1, L=0, T=0 n-p pairs of nucleons in the nuclear ground state. This description, often mentioned as quasi-deuteron model, assumes that the neutron proton dynamic correlation function can be written[1]

$$| g_{10} (|\mathbf{r}-\mathbf{r}'|)|^2 = \gamma^3 \, | \psi_d(|\mathbf{r}-\mathbf{r}'|) |^2, \qquad (1)$$

where γ is a constant having the dimension of length and ψ_d ($|\mathbf{r}-\mathbf{r}'|$) is the deuteron ground state wave function. This assumption leads to the well known proportionality between the photo-absorption cross section in a complex nucleus, $\sigma_{abs}(E_\gamma)$, and the free deuteron photodisintegration cross section, $\sigma_d(E_\gamma)$, at the same photon energy E_γ[2]:

$$\sigma_{abs}(E_\gamma) = \frac{LNZ}{A} \exp\left(- \frac{D}{E_\gamma} \right) \sigma_d(E_\gamma), \qquad (2)$$

where L is the so called Levinger factor, NZ/A stands for the number of n-p pairs per unit nuclear volume and exp $(-D/E_\gamma)$ is a damping factor due to the effect of Pauli blocking on two-particle excitation.

The validity of this model has been confirmed rather well by several experiments[3-9] at photon energies up to the pion threshold. However, in these experiments, as well as in theoretical calculations [2,11], the value of L scatters considerably. Most of the experimental ambiguities possibly come from the use of continuous bremsstrahlung beams.

The values of the constant L, as obtained from a phenomenological analysis [11] of more recent photoreaction data in light and heavy nuclei are reported in Fig.1. The open circles represent the L values determined by Tavares et al. [4] from a least-squares fit to the total photoabsorption data of Ahrens et al.[5] on light nuclei (lithium, beryllium, carbon, aluminium, and calcium) and assuming no damping effect (D=0) . These values have been divided by a factor 1.2 since Tavares and collaborators used deuteron cross section values 20% higher than those deducible from a recent σ_d data compilation [12]. For ^{16}O the L value given as open square in Fig. 1was obtained by Ricco [11] from a fit of the total absorption

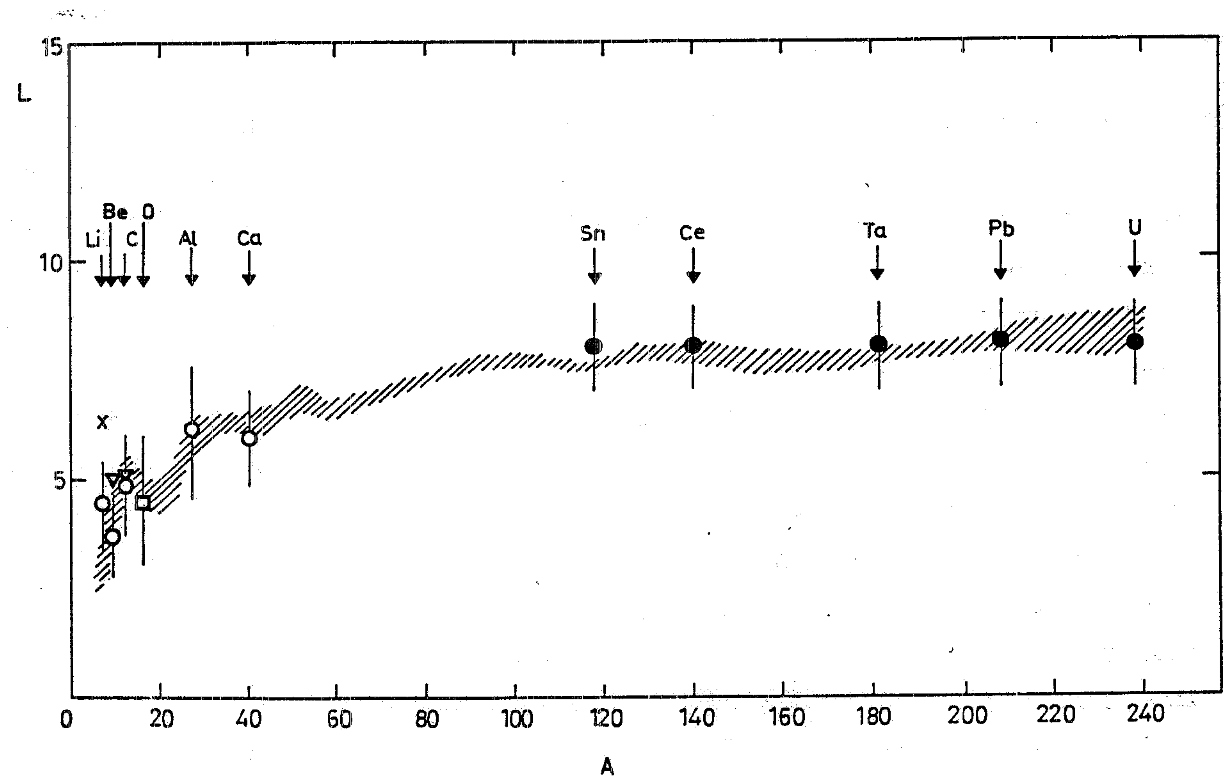

Fig. 1 Values of Levinger factor L deduced from photoreactions: open and full circles have been obtained from the analysis of the total absorption cross section measurements of Ahrens et al. [5] and Leprêtre et al. [8], open triangle and crosses are from coincidence n-p experiments of Wade et al. [7] and Homma et al.[6], open square is from a fit of Ahrens et al.[5]results; the shaded area represents the computed L values according to the original Levinger formulation[2]

data of Ahrens et al. [5] and assuming D=0.The open triangles refer to the L values determined by Homma et al.[6] from proton photoemission experiments on beryllium and carbon in the energy range from 180 to 580 MeV. The cross represents the value of L obtained by Wade et al. [7] from a (γ,pn) coincidence measurement on lithium in the energy range between 25 and 65 MeV. The full circles are the values of L for high Z nuclei (tin, cerium, tantalum,lead, and uranium) obtained by Leprêtre et al.[8] from a measurement of the inclusive $\sigma_{[2]}(E_\gamma)$ cross section and assuming D=60 MeV ($\sigma_{[2]}(E_\gamma)$ is the sum of all partial cross sections in which 1 and 2 neutrons are emitted following the absorption of a photon of energy E_γ).

According to the original Levinger formulation [2], the normalization of the quasi-deuteron wave function inside the nucleus introduces a dependence of the Levinger parameter on the inverse nuclear volume:

$$L = 13.82 \frac{A}{R^3\,[\mathrm{fm}^3]} \qquad (3)$$

The shaded area in fig.1 refers to the computed L values obtained using for R the radius of the equivalent uniform charge distribution $R=(\sqrt{5/3})\,\langle r^2 \rangle^{1/2}$,the width of this area reflecting the experimental uncertainty on R. The agreement, both in absolute value and mass dependence, confirms the validity of the model assumption.

Moreover, it must be mentioned that recently Laget [10], while keeping the original formulation of the model, proposed to associate the absorption of the photon by a quasi-deuteron pair only with the exchange part, $\sigma_d^{exch}(E_\gamma)$, in the total photodisintegration cross section $\sigma_d(E_\gamma)$ of the deuteron. For a free deuteron $\sigma_d^{exch}(E_\gamma)$ corresponds to the transition amplitude for a virtual meson to be emitted by one nucleon of the deuteron and reabsorbed by the other. A comparison of the results of such an evaluation of $\sigma_d^{exch}(E_\gamma)$, using $\pi-$ and $\rho-$meson exchange amplitudes only, with the experimental $\sigma_{[2]}(E_\gamma)$ results, obtained at Saclay[8,9] with monochromatic photons of energy between 40 and 140 MeV, showed that a rather good representation of the data was obtained with $L=11\pm2$.

The excited quasi-deuteron configuration can directly decay by single nucleon γN[13] or two-nucleon γNN[6,7] reactions, according to different energy and momentum sharing between the nucleons. The γN channel corresponds to the incident momentum shared but the energy transferred to one nucleon only, the γNN channel, instead, to both momentum and energy sharing between the two nucleons.Final state interactions may, however, produce distortion and rescattering effects leading to more complex decay channels. In fact, large (up to seven) photoneutron multiplicities have been detected in intermediate and heavy mass nuclei by recent experiments at $E_\gamma<140$ MeV[5]. The same evaporative effects should produce distortions of low energy components in the emitted photonucleon spectra.

In order to point out the role of final state interactions in the quasi-deuteron model, accurate measurements of photoproton spectra over wide energy and angular ranges are needed. Up to now , data on the photoemission of protons from various nuclei have been accumulated both in inclusive and two-nucleon coincidence experiments, especially in the energy region below the meson production threshold. At energies lower than 100 MeV some results have been obtained very recently with tagged photon experiments by Teresawa et al.[14] and Mc George et al.[15]. At energies above 180 MeV, where final state interactions are less important but the contribution of pion photoproduction affects the low energy region, photoproton spectra have been systematically measured only at fixed proton angles by Arends et al. [16] and Homma et al[6].

The aim of present measurement is to fill the gap existing in the data by providing an accurate measurement of the photoproton energy distributions at five laboratory angles (between 32.5° and 130°) and at two photon energies, 159 and 198 MeV, where the competition of real pion production is negligible. The most remarkable feature of the experiment is the use of a quasi-monochromatic photon beam, which allowed us to determine the actual number of "monochromatic photons" impinging upon the photonuclear target better than in the usual bremsstrahlung subtraction method. Moreover we were able to check unambiguously both proton detector energy calibration and response function and to perform an accurate measurement of the proton spectra down to very low energy.

2. Experimental apparatus and data analysis

The measurement was carried out using the LEALE photon beam produced at Frascati by in-flight positron annihilation. A detailed description of this facility has been given previously[17] and therefore only its major features will be summarized here. The lay-out of the experimental apparatus is schematically shown in Fig.2. The annihilation photons were obtained by allowing the positron beam (typically 16 nA average current, 150 Hz repetition frequency, and 4 μs beam burst width) to impinge upon a 0.0118 radiation lengths thick liquid hydrogen target with 0.012 cm kapton windows.

The intensity of the positron beam was continuously monitored by a non-intercepting ferrite

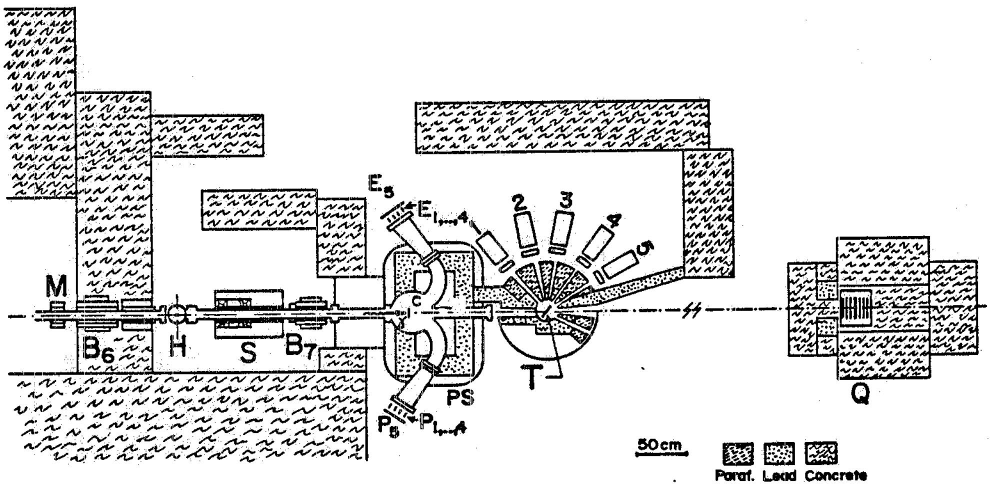

Fig. 2 The experimental set-up for the ^{12}C (γ, p) reaction study: M ferrite toroid monitor, B_6 deflecting magnet, B_7 sweeping magnet, H liquid hydrogen target, S damping magnet, PS pair spectrometer, with the relevant converter C and the associated electron (E_i) and positron (P_i) detection system, T carbon target, 1÷5 E-ΔE telescopes, Q quantameter.

toroid M set on the beam pipe immediately before the hydrogen target and measured by a Faraday cup placed on the focal plane of the dumping magnet S.

In addition to monochromatic annihilation photons, bremsstrahlung is also produced. In order to increase the annihilation-to-bremsstrahlung photon ratio, measurements were carried out collecting photons at an angle of ≈0.8° by respect to the positron axis. Moreover hydrogen and tungsten targets, of the same thickness in radiation length units, have been alternatively used. Since the tungsten target produces a nearly pure bremsstrahlung spectrum, the subtraction of the hydrogen and tungsten spectra yields essentially the annihilation component in the hydrogen spectrum, provided that the different shapes of the low-Z and high-Z bremsstrahlung photon spectra are taken into account.

The photon beam spectrum was continuously measured by a pair spectrometer PS [(18)] on-line with the experiment and the photon flux monitored by a gaussian quantameter[(19)]. The simultaneous measurement of the beam total energy and spectrum allowed a few % uncertainty in the determination of the annihilation peak intensity.

The used photon flux was typically equal to about $5 \cdot 10^6$ annihilation photons per second incident on a 180 mg/cm^2 thick graphite target, located about 4 m downstream from the hydrogen target and oriented at 45° with respect to the incident beam.

Protons from the target were detected by five ΔE-E scintillator telescopes connected on-line to a PDP 15/76 computer. Each telescope consisted of a dual scintillator counter system[(20)]. The front counter, a 3 mm thick NE 102 A scintillator, gave a measurement of the energy loss ΔE. The back counter, a 10.4 cm diameter and 12 cm thick NaI crystal, gave a measurement of the total energy E. The solid angle subtended by each telescope and relative collimators was about 16 msr.

The gain stability of each telescope was checked on-line every five minutes using two pulses generated by a green LED positioned on the edge of each scintillator as described in ref. 21. The stored data were presented on-line as a ΔE against E plot and the mass discrimination was found to be sufficiently good to unambiguously distinguish protons from other particles.

Proton spectra, in the energy range 40-200 MeV were recorded at two annihilation photon energies (159 and 198 MeV) and, simultaneously, at five lab. angles (32.5°, 55°, 80°, 105° and 130°). The annihilation peak contribution was obtained by alternatively measuring the proton spectra produced by photon beams generated in the hydrogen and tungsten radiators.

As an example in Fig. 3 are reported the photon spectra relative to the hydrogen (H) and tungsten (W) radiator targets, for equal quantameter doses. The full line curves represent the result of a Monte Carlo simulation[(22)] which also reproduces the photon total energy measured by the quantameter. In Fig. 3 the difference spectra (H-λW) is also reported (bottom plot). The normalization factor λ=0.85 for the tungsten spectrum has been evaluated in order to give the optimum bremsstrahlung cancellation.

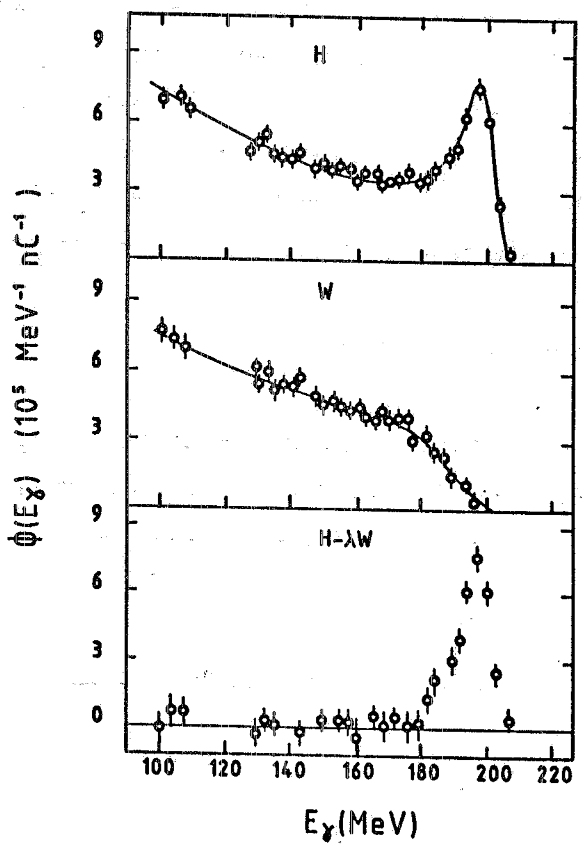

Fig. 3 Photon energy spectra from a 200 MeV positron beam impinging on hydrogen (H) (upper plot) and tungsten (W) (median plot) radiator targets. The bottom plot is the relevant difference annihilation spectrum, obtained with λ =0.85.

Since the experiment required a precise knowledge both of the absolute energy calibration and detection efficiency in the whole proton energy range, a short measurement of deuteron photodisintegration was performed at both positron energies using a liquid deuterium target, already employed in a previous experiment(23), the same detection system and the photon beam from the hydrogen radiator.The high energy peaks in the proton spectra, due to the two body d(γ,p)n disintegration induced by annihilation photons, were used for a reliable proton energy calibration.The detection efficiency as function of the proton energy deviates from an ideal step function near the threshold of the spectrum, because of different effects like:

a) uncertainty of the threshold energy determination of the spectrum due to the poor resolution of the telescopes for low energy protons;
b) long time fluctuations of the photomultiplier gain: the on-line correction performed by using the LED calibration might in some condition lead to a distortion of the spectra in the threshold region of the spectrum.

Since these distortions are similar in the deuterium and carbon proton spectra, the detection efficiency near the threshold has been assumed to be given, for each proton energy, by the ratio between the measured counting rate of protons from the d(γ,p)n reaction and the value expected from the known d(γ,p)n cross section below 100 MeV[12] and the relevant number of photons with appropriate energy measured in the bremsstrahlung spectrum.

The corrections for the energy loss by protons inside the target and in all materials between the target and the detectors were performed over the whole investigated energy range.

3. Experimental results and discussion

The differential cross sections, measured at five laboratory angles: (32°.5, 55°, 80°, 105°, 130°) and two photon energies (159 and 198 MeV) are plotted in Figs.4 and 5 as a function of

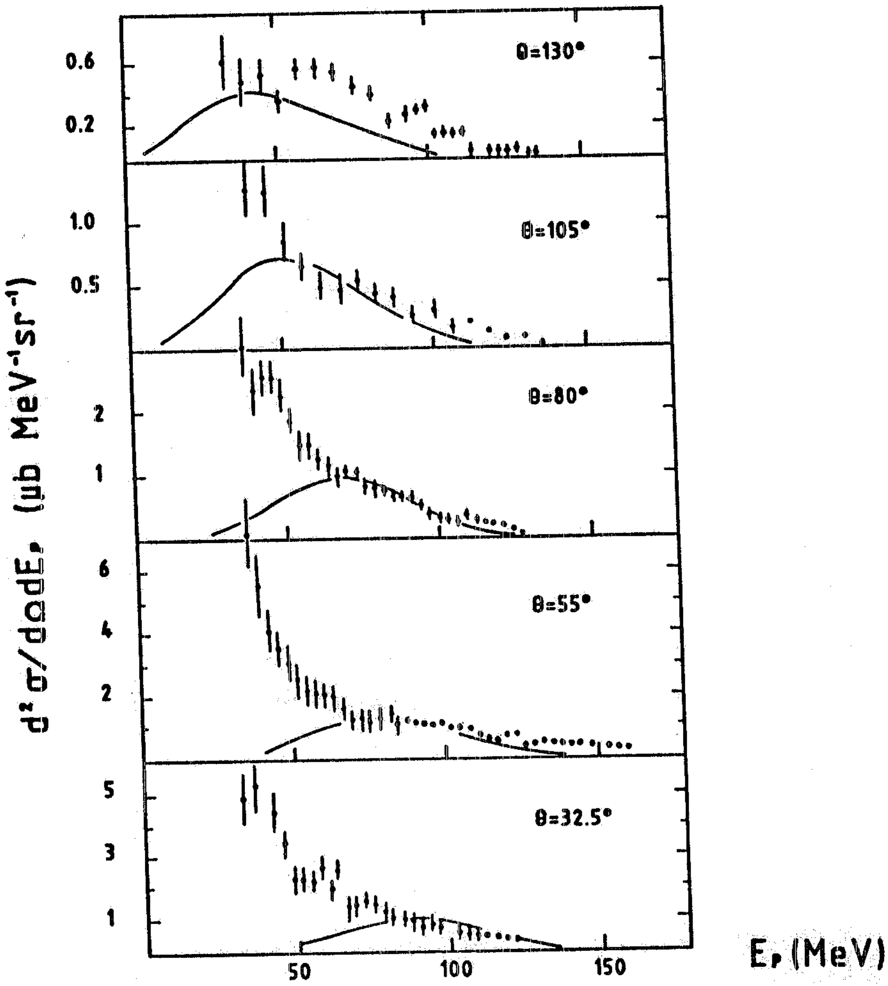

Fig. 4 Differential cross section versus proton energy for the given detection angles, obtained with annihilation photons of $E_\gamma = 159 \pm 2$ MeV energy . The full line curves are the quasi-deuteron model calculations.

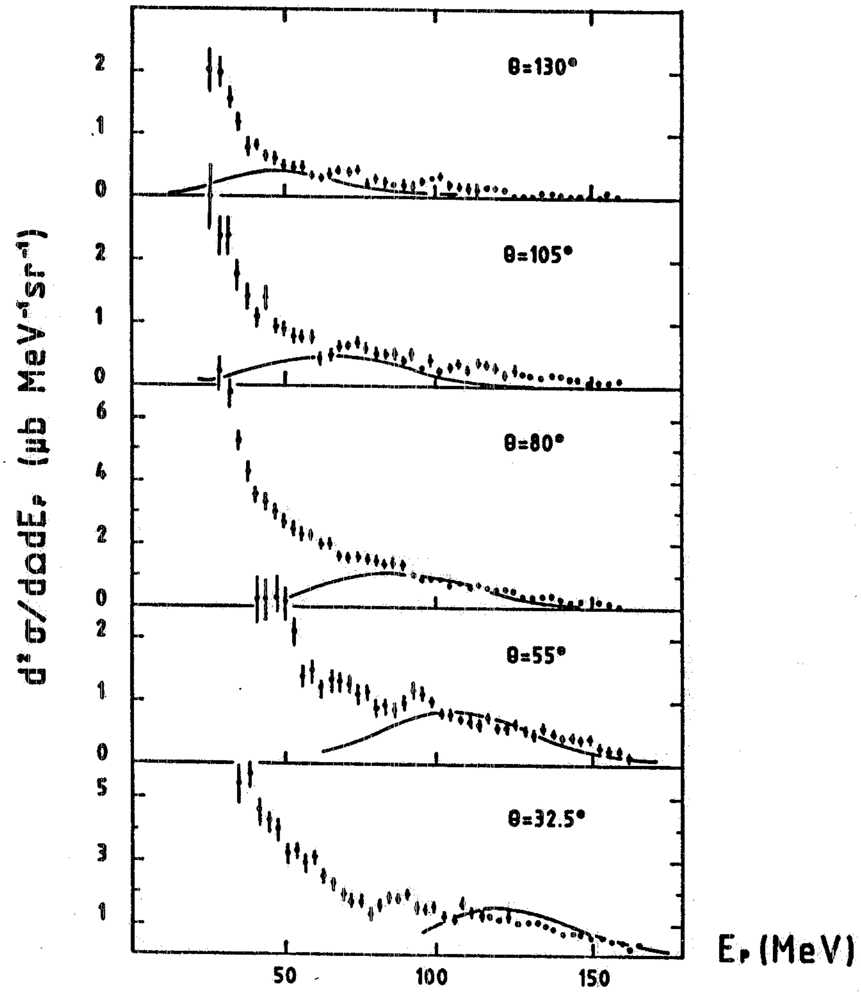

Fig. 5 Same as fig. 4 for $E_\gamma = 198 \pm 3$ MeV.

the proton energy E_p. The reported errors are statistical only and are mostly due to the H-W spectra subtraction, since the original proton data were taken within 1÷2% statistics per 3 MeV energy channel width. The measurements were made in several runs and the data from each run were separately analysed and compared. The results were systematically consistent inside the statistical uncertainty.

The simple quasi-deuteron model assumes direct decay of the excited 2p-2h configuration by emission of a n-p pair. The inclusive proton spectrum(1):

$$\frac{d\sigma(E\gamma)}{d\Omega_p dE_p} = \frac{LNZ}{A}\int\left(\frac{d\sigma(E\gamma)}{d\Omega}_p\right)_d F(P)\, J_{tot}\, d\mathbf{P}, \qquad (4)$$

results proportional to the free deuteron disintegration cross section $(d\sigma/d\Omega)_d$ folded on the internal n-p pair momentum distribution F(P), J being the Jacobian for the coordinate transformation to the center of momentum system ($\mathbf{k}_p+\mathbf{k}_n= 0$) of the quasi-deuteron.

The full line curves in Figs. 4 and 5 are the results of quasi-deuteron model calculations, performed using Eq.(4) in the kinematical conditions of this experiment. For the Levinger parameter it has been chosen the value L= 5 , according to the analysis described in Section 1[11]. The n-p pair momentum distribution was assumed of a gaussian form, which has lead to successful results in previous works[24], and the $(d\sigma/d\Omega)_d$ values were deduced by our previous experiment[23].

For both energies and at all angles the hard part of the spectra shows a reasonable agreement with the calculation, provided that the theoretical results are mutiplied by a factor 0.4. This factor should represent the attenuation of the outgoing nucleon flux due to final state interactions. The value deduced in the present experiment is in agreement with that one used by Teresawa et al.[14] in a recent $^{12}C(\gamma,p)$ experiment below E_γ=100 MeV and with those evaluated by Londergan and Nixon[25] for the reaction ^{16}O (γ,p) with a modified plane-wave treatment of the outgoing nucleon wave function. Moreover it is worth noting that the product of the used L value, 5, times the attenuation factor, 0.4, is not far from the value, $\approx$2.7, calculated by Futami and Miyazima[26] for the production of correlated neutron-proton pairs following the absorption of high energy photons after correcting for the probability that at least one of the nucleons scatters on its way out of the nucleus.

The large low energy tail extending down to the experimental threshold is probably due to rescattering effects of the outgoing nucleons and, therefore, is not accounted for by the simple quasi-deuteron model. A quantitative evaluation of final state interactions has been recently performed by Blann, Bermann, and Komoto[27] using the precompound decay approach. Precompound models treat the deexcitation of a continuum nuclear state charachterized by its excitation energy and initial particle-hole configuration and predict the particle emission versus the intranuclear scattering cascade process. In the Blann and coworkers formulation the initial 2p-2h configuration excited by quasi-deuteron absorption is simplified to a 2p-1h state (3 excitons), since the two holes are assumed completely correlated in momentum and the total particle-hole energy is restricted to a maximum of 30 MeV, the latter condition corresponding to an emphasis of excitation on the nuclear surface.To compare the theoretical predictions of this model to the experimental results, in Fig. 6 are reported the proton energy distributions, integrated over the angle, for the two annihilation photon energies: E_γ=159 MeV and E_γ= 198 MeV. The full line curves are the predictions of the quasi-deuteron model and the dashed line curves the results of precompound model calculations, normalized to the total number of measured protons. As shown the precompound plus evaporation model is able to explain the fast slope of the measured cross section below 50 MeV, but fails to reproduce the hard part of

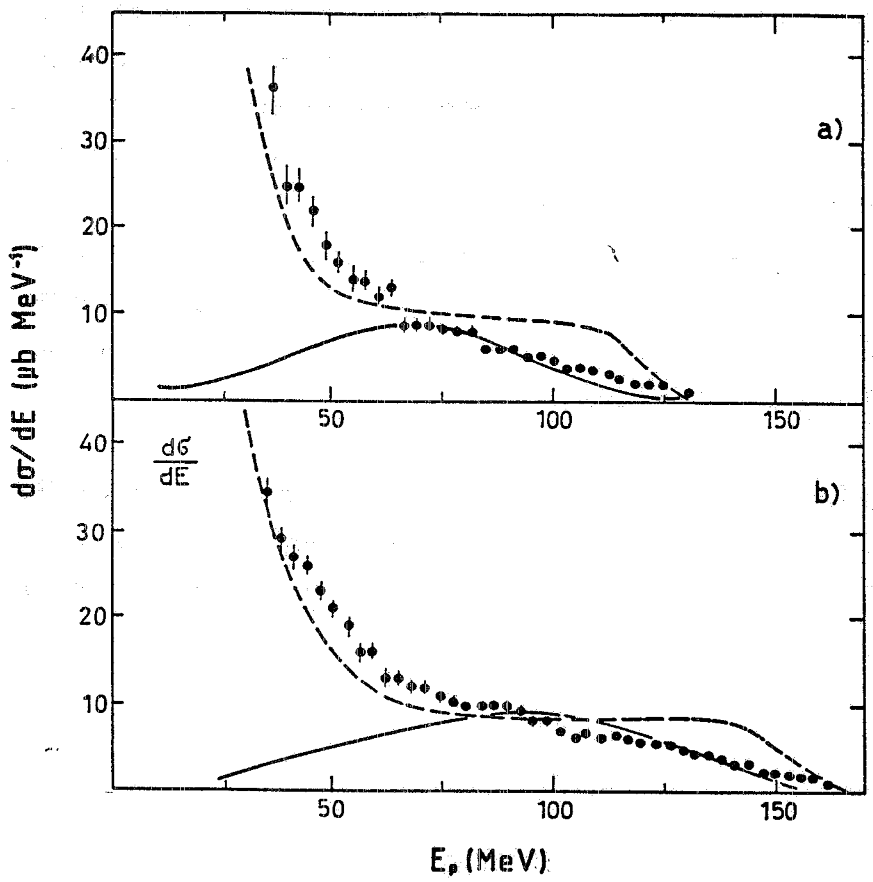

Fig. 6 Inclusive proton spectra, integrated over the angles, measured at E_γ = 159 MeV (a) and E_γ = 198 MeV (b). The full and dashed line curves are, respectively, the quasi-deuteron model and the precompound decay model calculations.

the spectrum which remains closer to the original quasi-deuteron phase space. Besides this disagreement, perhaps due to the still limited dynamics of the 3 excitons configuration in the Blann et al. calculations(27), the results of this experiment confirm the importance of final state interactions in the quasi-deuteron model, also at intermediate energy, and show the ability of the precompound model to provide a quantitative description of nuclear rescattering effects.

4. Conclusions

The use of a quasi-monochromatic photon beam to study the photoproton emission from $^{12}C(\gamma, p)$ reaction made possible an accurate measurement of the proton spectra down to very low energy.

The presently available theoretical calculations are not able to quantitatively reproduce the measured spectra in the whole proton energy range. The measurement shows that photoabsorption by correlated n-p pairs is the predominant mechanism at intermediate photon energies and might describe the experimental results provided that nucleon-nucleon final state interactions are properly taken into account.

The above conclusions suggest that informations on dynamical correlations in nuclei can be obtained by the (γ,np) reaction only through kinematically complete experiments performed at sufficiently high photon energy to select events where the final state interaction effects are not so severe to mask any initial state property.

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