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PHOTONUCLEAR REACTIONS AT FRASCATI

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PHOTONUCLEAR REACTIONS AT FRASCATI

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ABSTRACT

An outline is presented of the ongoing research in photonuclear reactions at the Frascati photon facilities: LADON and LEALE.

1. Introduction

This brief outline of ongoing research program in nuclear physics at Frascati will be restricted to experiments using the two local photon facilities called LADON and LEALE. In addition to the work described below, nuclear physic groups are also involved in experimental program carried out elsewhere, specifically: a) the study of inclusive and esclusive quasi-elastic electron scattering from nuclei, at the ALS of Saclay; b) the study of elastic and inelastic interactions between light ions, at the Saturne synchrotron of Saclay; c) the study of antiproton-nucleus interactions, at the LEAR storage ring of CERN, and d) the production of a monochromatic photon beam by laser light Compton scattering off the electron of the BNL X-ray machine.

2. The facilities

The source of γ-ray named LADON [(1)] is laser light Compton back-scattered off ultrarelativistic electrons in the Adone storage ring. The Compton scattering takes place within an optical cavity that is superposed into a straight section of the storage ring and where the interaction takes place between compact bunches of electrons and phase-locked travelling pulses of concentrated laser power.

The source of photons named LEALE [(2)] is in-flight positron annihilation on a liquid hydrogen target, having a thickness of 0.018 radiation lenghts.

The salient features of these gamma sources are summarized in Table I.

TABLE I - Energy range (ΔE_γ), intensity (I), resolution ($\delta E_\gamma / E_\gamma$) and linear polarization degree (P) of the LADON and LEALE beams. For the latter, given figures refer to a photon collection angle respectively equal to 0°, case (a), and 1°, case (b).

Facility	ΔE_γ(MeV)		I (s^{-1})	$\delta E_\gamma/E_\gamma$(%)	P (%)
LADON	5 ÷ 78.7		1 ÷ 2 10^5	2 ÷ 8	100
LEALE	100 ÷ 300	a)	6 ÷ 20 10^6	3 ÷ 2	0
		b)	3 ÷ 2 10^6	3 ÷ 9	0

3. Recent results

3.a) Deuteron photodisintegration differential cross section

The differential cross section of this fundamental process has been measured accurately both with LADON and LEALE photon beams. Let me recall for convenience the general expression of the differential cross section for this process:

$$d\sigma / d\Omega = I_o(\vartheta) + P I_1(\vartheta) \cos 2\varphi = I_o(\vartheta)\left[1 + P\,\Sigma(\vartheta) \cos 2\varphi\right],$$

where φ is the angle between the polarization and the reaction planes and ϑ is the center of mass (CM) angle between the proton and photon momenta; P is the degree of linear polarization of the photon beam and $\Sigma(\vartheta) = I_1(\vartheta)/I_o(\vartheta)$ is a parameter which describes the azimuthal asymmetry in the differential cross section due to the polarization of the incident beam.

The measurements performed with the LADON beam[3] employed a cylinder of deuterated liquid scintillator NE 230 (3.81 cm diameter and 10.16 cm height) both as a target and proton detector. Five neutron detectors, independently movable in the reaction plane, covered an angular range from 15° to 165°. Each neutron detector consisted of a cylindrical container, 30 cm in diameter and 15 cm deep, filled with NE 213 liquid scintillator. The gamma ray background was drastically reduced by pulse-shape discrimination in the target and in the neutron counters. Protons and neutrons were detected in coincidence with the electron bunch in the Adone storage ring and the events recorded via CAMAC by a PDP 11/34 computer. The beam intensity was continuously monitored by a lead glass counter which also served as gamma beam stopper.

By measuring the photoneutron yields at nine angles and in series of alternate runs at $\varphi = 0$ and $\varphi = \pi/2$ under same experimental conditions, the angular distributions of $I_o(\vartheta)$, $I_1(\vartheta)$ and $\Sigma(\vartheta)$ were determined. The results obtained are plotted in Fig. 1 as a function of the CM neutron angle $\vartheta_n = (\pi - \vartheta)$ for the given laboratory photon energies. For comparison purposes, two theoretical curves are presented in all figures: the dashed lines have been obtained by Arenhövel[4] and independently by Cambi et al[5], using the Reid soft-core (RSC) N-N potential. The full lines have been obtained by using the version B of the De Tourreil-Sprung (DTS-B) potential. In all these calculations, multipoles up to L= 4 have been included and MEC and IC contributions have been added to the standard Partovi theory.

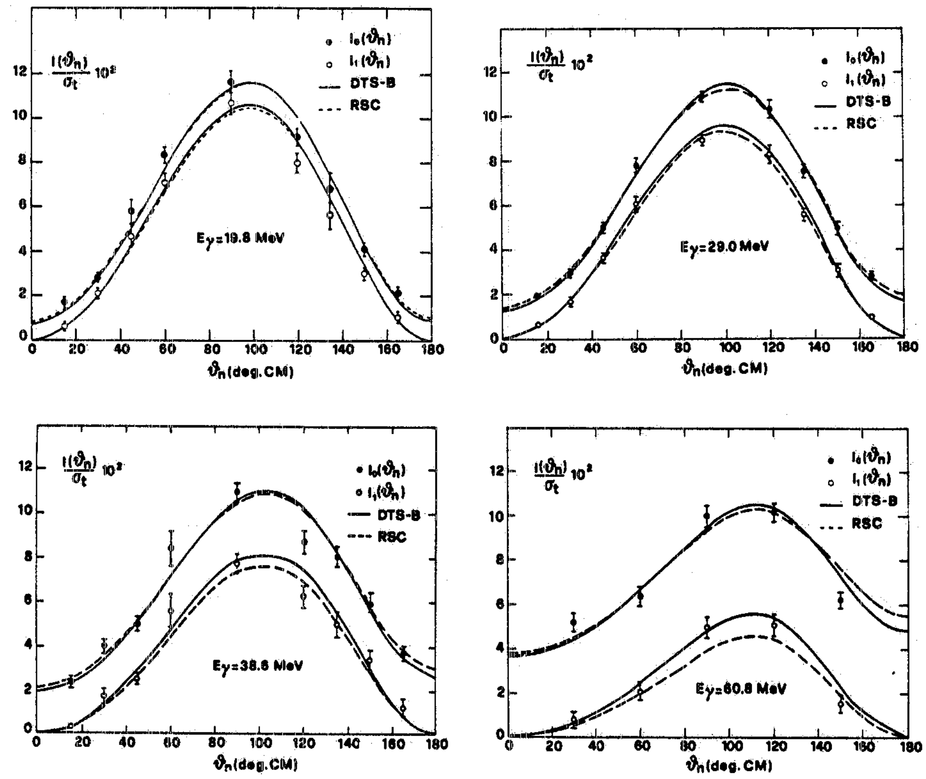

FIG. 1 - Plots of $I_o(\vartheta)/\sigma_t$ and of $I_1(\vartheta)/\sigma_t$ as a function of the CM neutron angles ϑ_n at the given photon energies. Dashed and solid lines represent theoretical calculations of Refs. 4 and 5 with the Reid soft-core (RSC) and De Tourreil-Sprung (DTS-B) potentials, respectively.

The role of the mesonic and isobar degrees of freedom is clearly shown in Fig. 2, where a plot of the asymmetry $\Sigma(\vartheta_n = \pi/2)$ versus the photon energy is given. In the figure the LADON data are compared with the results of earlier experiments and with the theoretical RSC calculation carried out by Arenhövel[4]. The dashed line corresponds to the standard Partovi approximation; the solid line contains also the MEC and IC contributions.

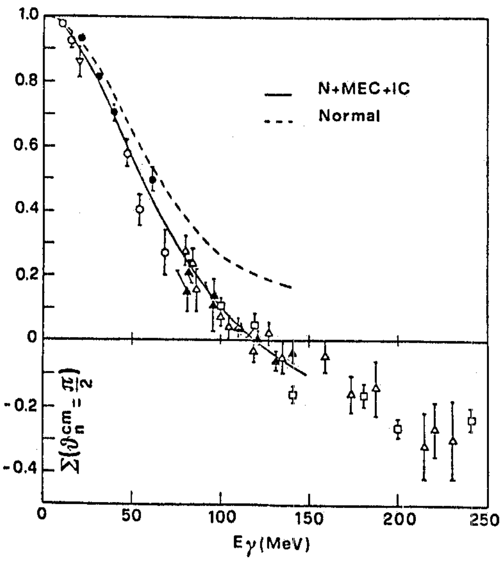

FIG. 2 - Plot of the asymmetry factor $\Sigma(\vartheta_n = \pi/2)$ vs. laboratory gamma-ray energy. The LADON old (open circles, Ref. 3) and new data (solid circles) are compared with the results of Liu (solid and open triangles, Ref. 6), Del Bianco et al. (inverted open triangle, Ref. 7), Gorbenko et al. (open squares, Ref. 8). The theoretical curves have been obtained in Ref. 4 with the RSC potential. The dashed line corresponds to the standard Partovi approximation; the solid line reflects the inclusion of MEC and IC corrections.

In the measurement performed with the LEALE beam [9] particular care was paid to the beam monitoring: the positron intensity was monitored both by a nonintercepting ferrite toroid and a Faraday cup. The photon energy spectrum was monitored by a quantameter. The target was a vertical mylar cylinder (4.0 cm diameter, 10 cm high, wall thickness 0.08 mm) filled with liquid deuterium. The deuterium density was kept constant within 2% by a continuous monitoring of the deuterium vapor pressure. Protons were detected by five E, ΔE telescopes, at five angles (32.5°, 55°, 80°, 105° and 130° in the lab.) and seven positron energies (100, 120, 140, 180, 200, 220 and 255 MeV). The ΔE counter was a 3 mm thick NE 102A scintillator, the E counter a 5 cm radius x 12 cm high NaI crystal. The events were recorded by a PDP 15/76 computer. Measurements were made in several runs distributed over two years and data from each run were separately analyzed and compared. The results were consistent among each other within ±5%. For all positron energies and proton angles the mass discrimination was found to be sufficiently good to distinguish unambiguously protons from other particles. All measured proton energy spectra showed evident peaks whose positions and shapes resulted correctly related to the relevant annihilation photon peaks.

The results of the differential cross sections in the CM system are given, as solid dots, in Fig. 3 for the given laboratory photon energies. The points have been averaged over an energy bin ΔE_γ = 10 MeV. The quoted errors are statistically only and do not include a ±5% systematic uncertainty on the absolute value. Fig. 3 also shows the results of other recent measurements, specifically the neutron capture experiment of Meyer et al.[11], and three photodisintegration experiments: the tagged-photons study by Arends et al.[12], the 0° experiment by Hughes et al[13] and the 180° experiment by Altoff et al.[14].

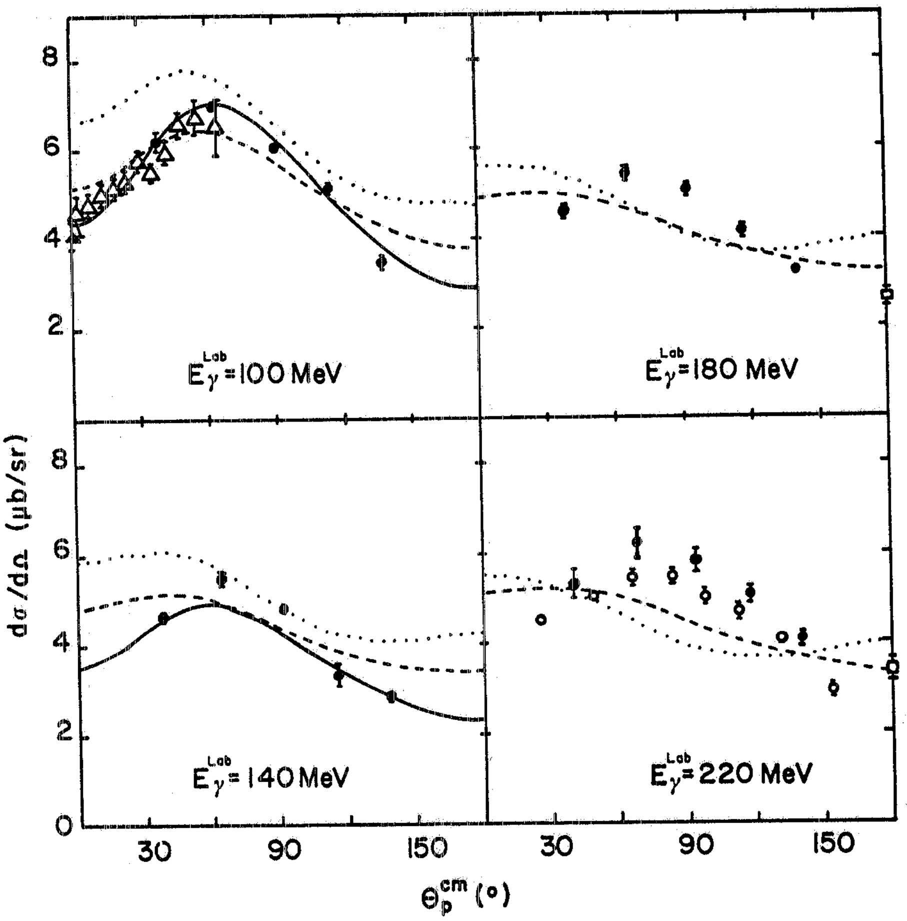

FIG. 3 - d(γ,p)n differential cross section for the given photon energies. The LEALE data (solid dots) are compared to most recent experimental results and theoretical predictions: △ , Ref. (11); ▲ , Ref. (13); o, Ref. (12); □ , Ref. (14); solid line, Ref. (5) dashed line, Ref. (15); dotted line Ref.(16). LEALE points and those of Ref. (12) do not include systematic errors (±5% and ±4% respectively).

The data of Meyer et al.[(11)] are found to be in agreement with the LEALE results within their experimental errors, which include systematic contributions except for the uncertainty on the nucleon-nucleon cross section. The Bonn tagged photon data[(12)] include only statistical errors; when we take into account their (±4%) and the LEALE (±5%) systematic uncertainties, the two measurements are compatible. Moreover it may be work while to note that the LEALE data in the 100÷140 MeV range are well compatible with the fit obtained by De Pascale et al.[(17)] from a critical analysis of all the d(γ,p)n data in the 6÷140 MeV range, published before 1982.

Also shown in Fig. 3 are the results of the most recent calculations: the dashed line has been obtained by Laget[(15)] using an expansion of the photodisintegration amplitude in terms of dominant diagrams. The dotted curve is a result from Leidemann and Arenhövel[16] who have extended their low energy calculation beyond the pion photoproduction threshold with explicit Δ degrees of freedom in a coupled-channels treatement. The full line is from Cambi, Mosconi and Ricci[5] who have studied the effect of higher-order contributions to the one-and two-body charge densities.

An analysis of these data and a comparison with the theory are to be presented at this workshop[18], consequently I shall not try to compete by commenting here on the various theoretical approaches. I limit myself to stress the importance of the agreement among measurements of the d(γ,p)n differential cross section performed by using three very different techniques, like quasi-monochromatic photons, tagged photons, neutron pick up reactions.

3.b) Photoproton emission from carbon

Using the LEALE photon beam the $^{12}C(\gamma,p)$ reaction has been studied in order to investigate the role of the quasi-deuteron mechanism in the photoabsorption process. The same experimental apparatus described for the deuteron differential cross-section measurement was used. Proton energy spectra were measured at five lab. angles (32.5°, 55°, 80°, 105°, and 130°) and two positron energies (160 and 200 MeV). A $\sim$250 mg/cm^2 thick carbon target was used.

The analysis of these data and a comparison with the theory are to be presented at this workshop[18], therefore I limit myself only to mention this work.

3.c) Photofission cross-section measurements

The investigation of nuclear fission at intermediate energies is important not only for fission physics itself, but also to study the total photoabsorption cross section. In fact, as was pointed out by Vinogradov et al.[19], the fissilities of transuranium nuclei in the energy region 100-1000 MeV are close to unit and fission cross sections pratically coincide with the total ones. For lighter nuclei the fissility seems to decrease probably because fast protons and neutrons can be emitted from the nucleus with the same probability.

The LEALE beam has been used to determine the photofission cross section for ^{238}U[20], natural Bi[21] and Au, in the energy region from 100 to 280 MeV. I will show here only the results of the ^{238}U photofission measurements.

The fission fragment yields were measured at 17 positron energies from 120 up to 280 MeV, with 10 MeV steps, and collecting the annihilation photons at an angle $\sim$1° respect to the positron line of flight. The total energy of the photon beam was monitored by a quantameter; furthemore the photon energy spectrum was measured on-line by a pair spectrometer. The fission fragments were detected by means of glass sandwiches[22] containing a thin target of UF_4 deposited by thermal evaporation onto the surface of one of two glass plates. The fission cross sections were deduced from the measured yields by means of an appropriate unfolding method[23].

Fig. 4 shows the LEALE results of the normalized cross section per nucleon (solid triangles) together with relevant values deduced at Bonn with a tagged photon beam[24] (solid circles and squares). The excellent agreement among experimental points from different experiments emphasizes the reliability of measurements performed with quasi-monochromatic photon beams. For comparison in Fig. 4 are also shown the total absorption cross sections (normalized to the number of nucleons per target nucleus) for ^{9}Be (open circles) and ^{208}Pb[26] (open squares). For all nuclei the results are in good agreement. This corroborates that at high photon energy the probability for the emission of fission fragments following a hadronic photoreaction is close to unit for the two uranium isotopes.

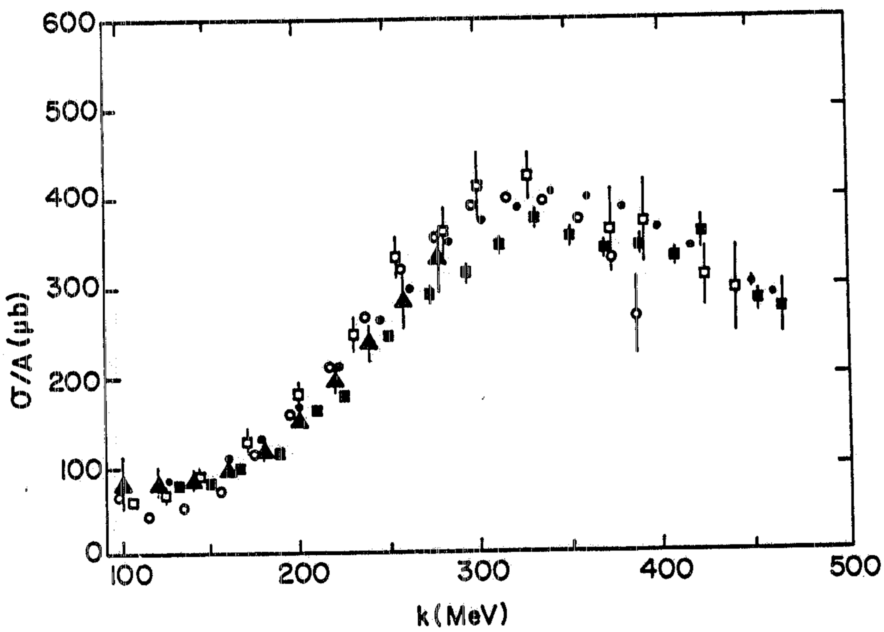

FIG. 4 - Normalized cross section per nucleon versus the photon energy K. The LEALE results (▲) are compared with ^{235}U (■) and ^{238}U (●) photofission measurements from ref. (24), and with total photoabsorption cross sections for ^{9}Be (○), from ref. (25) and ^{208}Pb (□), from ref. (26).

4. Ongoing experiments

4.a) Deuteron photodisintegration total cross section.

Taking advantage of the monochromaticity of its beam, the LADON group is presently measuring the deuteron photodisintegration total cross section with 5% total accuracy, for investigating the short range nucleon-nucleon interaction.

A gaseous deuterium target is employed. The gas is kept at high pressure inside an aluminium cylinder (1.5 cm diameter, 14 cm high and 0.2 mm wall thickness) closed at its end by two Macrolon plugs. The detector, surrounding the target, consists of a NE 213 liquid scintillator contained inside a glass box that is also the light guide to which two EMI 9823KB photomultipliers are optically coupled. The target can be filled with the hydrogen to enable the subtraction of the electromagnetic-type background.

Preliminary results[27] obtained at five energies (19.3, 28.8, 38.3, 47.8 and 56.9 MeV) are shown in Fig. 5 together with the values deduced by the LEALE group by fitting their measured differential cross sections with a second order polynomial in cos ϑ[28]. The shaded band represents the best experimental evaluation of the total cross section obtained by De Pascale et al.[17] from the above mentioned analysis of existing data in the 6-140 MeV range.

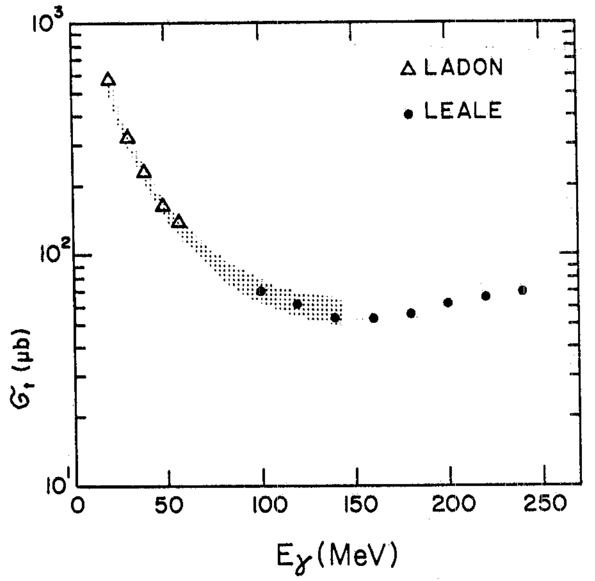

FIG. 5 - Deuteron photodisintegration total cross section: △ LADON (ref. 27), • LEALE (ref. 28), the shaded band is a fit obtained from a critical analysis of all data published before 1982 (ref. 17).

4.b) Deuteron photodisintegration: forward- and backward-angle differential cross section

Another important aspect of deuteron photodisintegration studies involves the forward and backward differential cross section for unpolarized photons. This is because one is sensitive to 1) the D deuteron state, 2) non central forces in the np continuum, 3) the relativistic spin dependence of the photodisintegration operator, and 4) meson exchange effects.

Only two measurements exist in literature: the Mainz[12] quasi-monochromatic photon results, at ϑ_p =0° and E_γ =20-120 MeV, and the Bonn[14] bremsstrahlung data, at $\vartheta_p \simeq$ 180° and E_γ = 200-700 MeV. The original Mainz data have been recently confirmed by neutron radiative capture measurements at E_n = 72 MeV[29] and E_n = 185 MeV[11]. Recent calculations[5,30] have shown that the ϑ_p = 0° cross section is not sensitive to reasonable variations of the NN force and that inclusion of the relativistic spin-orbit contribution to the E1 operator can account for the data.

To clarify the situation with more precise data the LEALE group is starting a measurement of the forward- to backward-angle differential cross section ratio in the energy range between 100 MeV and 140 MeV. The protons ejected from the target are deflected by a magnet cylindrical in shape (120 cm diameter, 20 cm gap) having a hole at the center ($\Phi = 48$ cm) where the liquid deuterium target can be inserted. Three E- ΔE telescope, set rispectively at 0°, 90° and 180°, measure the proton energy spectra. The apparatus has been installed and the first runs are scheduled for the end of the year.

4.c) The LADON crystal ball

The LADON beam intensity, although improved, is still rather low in comparison with photon sources obtained through more traditional techniques. Therefore, in order to overcome this limitation an experimental apparatus for photonuclear researches with a very large solid angle, approaching 4π, has been designed. This apparatus consists of a NaI (Tl) crystal ball 50 cm diameter, composed of 112 crystals each viewed by a photomultiplier. A bore of 9 cm along a diameter of the sphere allows the passage of the beam. A 2 mm layer of CaF_2, placed on the face of the ball looking at the internal hole, allows pulse-shape discrimination between photons and protons. The sphere is divided into 16 equal sections by planes intersecting on the beam axis. Each sector is subdivided into seven parts, each covering an equal interval of $\cos\vartheta$. In this way each of the 112 crystals covers the same solid angle as viewed from a target placed in the centre of the sphere.

At present the detector has been completely assembled and placed on the beam for studying its energy resolution. Measurements have shown an energy resolution increasing with the energy from $\sim$8% at 20 MeV up to $\sim$18% at 80 MeV.

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