TOTAL PHOTONUCLEAR ABSORPTION CROSS SECTION OF Pb MEASURED WITH QUASI-MONOCHROMATIC PHOTONS BETWEEN 25 AND 106 MeV

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The $\sigma(\gamma, xn)$ cross sections of Pb have been measured above the giant dipole resonance region up to 106 MeV with a quasi-monochromatic photon beam obtained by the annihilation in flight of monochromatic positrons. The total cross section decreases linearly with energy from 20 mb at 35 MeV to 12 mb at 106 MeV. The integrated cross section up to 140 MeV amounts to (1.80 ± 0.2) classical dipole sums.

The total cross section for the interaction of photons with nuclei in the energy region between the giant dipole resonance and the photopion threshold has interesting nuclear structure implications associated both with the photon interaction mechanism and with sum rules related to the total energy integrated cross section.

Photonuclear cross sections in this energy region have been determined at Mainz for a few light nuclei by subtracting calculated values of non-nuclear photon cross sections from very carefully measured total photon interaction cross sections [1]. It seems impractical to extend such measurements to heavy nuclei such as Pb, in part because the nuclear cross sections are somewhat less than 0.1% of the total interaction cross section (at $E_\gamma \approx 80$ MeV), and in part because of the uncertainty in the calculated non-nuclear cross section.

For nuclei in the $Z > 20$ region, the photonuclear cross section can probably be determined most reliably by measuring the nuclear decay products. We were able to make such measurements for Pb in this energy region because of two special experimental arrangements at the 600 MeV Linac at Saclay. The experimental arrangement provided a source of quasi-monochromatic photons whose energy could be varied up to 106 MeV. The second experimental facility is a very efficient, stable neutron detector of which the background has been determined accurately.

The quasi-monochromatic photons were obtained by the annihilation in flight of monoenergetic positrons in a LiH target [2]. The ratio of annihilation to bremsstrahlung photons was enhanced over what it would be at zero degrees with respect to the positron beam by using the photons emitted at non-zero angles. For example near 50 MeV this ratio was increased by a factor of 15 by using the photons emitted at an angle of about 4°; at this angle the intensity of annihilation photons was only 2% of that at zero degrees. With a 40 nA beam of monoenergetic positrons it was possible to irradiate a 3 cm diameter spot on the Pb target situated at about 11 m from the γ-source with 4×10^4 monochromatic quanta per second.

Photoneutrons were detected with a high-efficiency, 4π neutron detector filled with 250 ℓ of gadolinium-loaded liquid scintillator [3]. When a multineutron event occurs, the neutron lifetimes in the detector differ, and the neutrons are captured by the gadolinium at different times within a range of roughly 25 μs after their emission. The detected photonuclear events can thus be classified according to the number of emitted neutrons independent of whether some of these events may have included the emission of protons or light nuclei. The sum of all the partial cross sections which correspond to the emission of x neutrons is called $\sigma(\gamma, xn)$.

In this letter, we will discuss only the total cross section obtained by adding the cross sections corresponding to different values of x. It is convenient to define a partial sum, Σ_i, where the subscript, i, indicates the lowest value of x that is included,

$$\Sigma_i \equiv \sum_{x=i}^{\infty} \sigma(\gamma, xn).$$

The total photonuclear cross section, σ_t, corresponds to Σ_0. For heavy nuclei, such as Pb, the Coulomb barrier severely inhibits the emission of charged particles, and one would expect that Σ_1 would be a reasonably accurate measure of σ_t. It should be emphasized that the expectation that one or more neutrons will be emitted following the photon excitation of Pb at energies above 30 MeV does not imply any prejudice about the photon interaction mechanism. Even if high-energy photons interacted directly with protons or with p–n pairs in the nucleus, as suggested in the quasi-deuteron model [4], one would expect secondary neutron emission to be very probable.

The first part of the experiment consisted of attempting to measure $\sigma(\gamma, xn)$ at some 25 energies between 25 MeV and 106 MeV using a 2 mm thick Pb target. The resulting data suggested that a subtle but important background existed for $\sigma(\gamma, 1n)$ due to the atomic interaction of photons in the Pb target. Therefore a second set of measurements was performed at six different photon energies using four Pb targets with thicknesses of 0.5, 1, 2, and 4 mm. At these six energies we obtained values for Σ_1, the sum of all partial cross sections involving the emission of

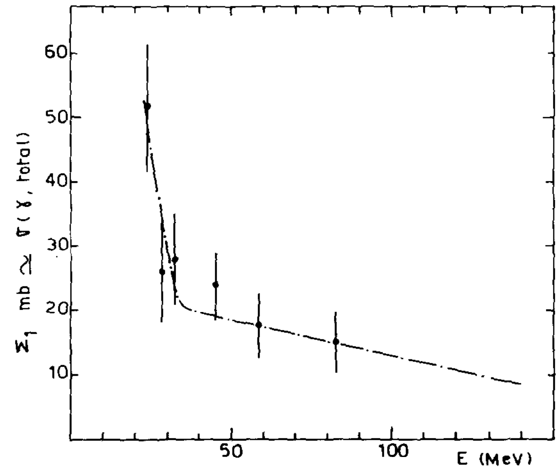

Fig. 1. Measured $\Sigma_1 = \Sigma_{x=1}^{\infty} \sigma(\gamma, xn) \approx \sigma_t$ values for Pb. The average $\Sigma_2 = \Sigma_{x=2}^{\infty} \sigma(\gamma, xn)$ results, taken from fig. 2 and represented by a dotted line, are also given for comparison.

at least one neutron. The results are shown in fig. 1. The relatively large experimental errors are dominated by uncertainties in $\sigma(\gamma, 1n)$ caused by target related background which produces single detectable neutrons.

The experiment produced no statistically significant evidence for photonuclear events in which only a single neutron was emitted. This can be seen in fig. 1 where the dashed curve shows the values obtained for Σ_2 from the data shown in fig. 2. The fact that the dashed curve corresponding to Σ_2 fits the data points representing Σ_1 in fig. 1 implies that $\Sigma_1 \approx \Sigma_2$, or equivalently, $\sigma(\gamma, 1n) \approx 0$. A discussion of the precise upper limit which the experiment sets on $\sigma(\gamma, 1n)$ is complicated and will have to be deferred until later.

Most of the data in fig. 2 come from the first part of the experiment in which the 2 mm Pb target was used; the data obtained from the experiments with different target thicknesses are also included, and they verify that Σ_2 was measured accurately with the 2 mm target. In the energy region from 25 MeV to somewhat above 30 MeV the cross section falls at a rate that might be expected from the high-energy portion of the giant dipole resonance. However, above about 35 MeV the measured cross section is much higher than would be implied by a Lorentz energy dependence adjusted to fit the giant dipole resonance. The energy dependence is reasonably represented by a straight line from 35 to 106 MeV; a least-squares fit

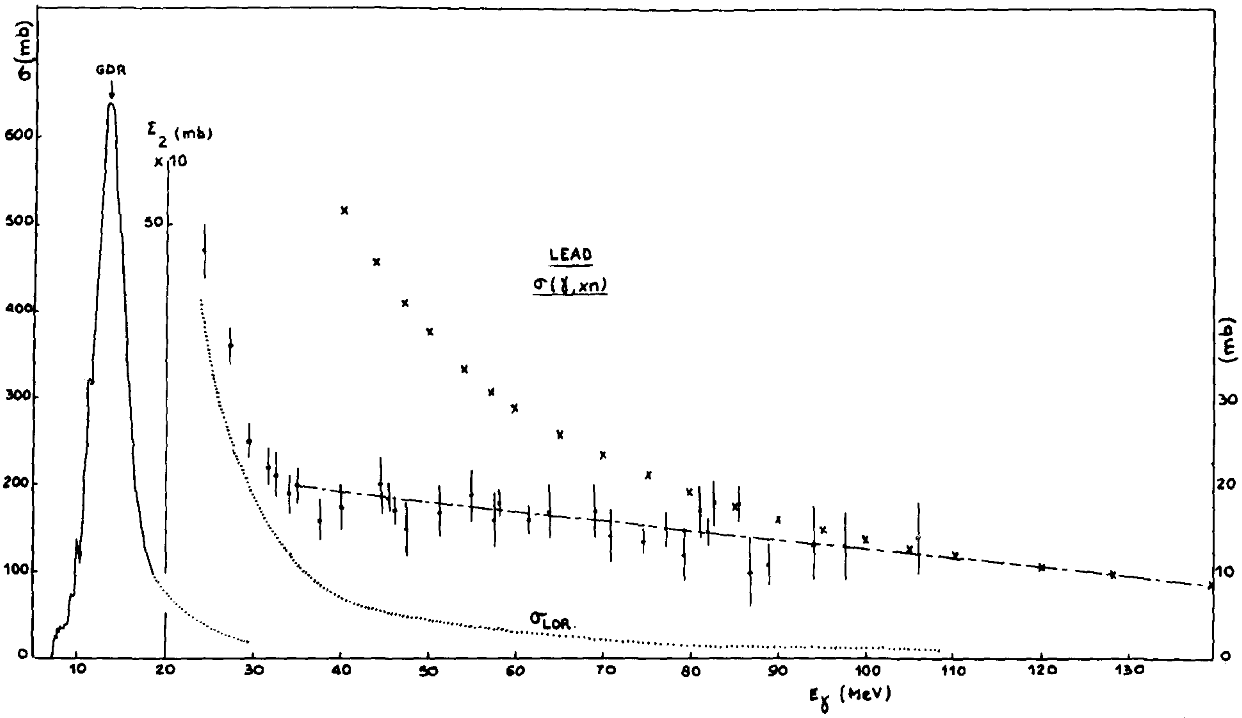

Fig. 2. Photoneutron cross sections of Pb. (1) The experimental points give $\Sigma_2 \approx \Sigma_{x=2}^{\infty}\sigma(\gamma, xn)$. (2) The dot–dash line represents a least-squares fit to the experimental Σ_2 values from 35 to 106 MeV with an rms error of 2 mb. (3) Old Saclay data, covering the giant dipole resonance up to 30 MeV [6], are shown as a solid line. (4) The dotted line represents a Lorentz line fit to the experimental σ_t data in the giant dipole resonance region [6] with σ_0 = 640 mb, E_0 = 13.4 MeV and Γ = 4.05 MeV. (5) Crosses represent the quasi-deuteron cross section $\sigma_{QD} = 4.6(NZ/A)\sigma_D$.

passes through 20 mb at 35 MeV and 12 mb at 110 MeV. We do not know of any theory which gives a quantitative prediction for this observed energy dependence. However, above 100 MeV this straight line is practically identical to the quasi-deuteron cross section,

$$\sigma_{QD}(E) = L(NZ/A)\sigma_D(E),$$

where the Levinger parameter, L, has been set equal to 4.6 which is the value found in Mainz for $A < 40$ nuclei, and where σ_D is the free-deuteron photodisintegration cross section. Clearly, for energies below 100 MeV it would be necessary to reduce $\sigma_{QD}(E)$ with an appropriate quenching factor [5] to fit the data.

It is convenient to express the energy integrated cross section in terms of the classical dipole sum, $S = 60NZ/A$, which is 2980 MeV mb for ^{208}Pb. In order to get a good estimate for the total integrated cross section, we will use our measured value of Σ_2; this value is obviously a lower limit to σ_t, but as explained above, we feel that $\Sigma_2 \approx \sigma_t$.

The present experiment gives

$$\int_{25\ \mathrm{MeV}}^{106\ \mathrm{MeV}} \Sigma_2(E)\mathrm{d}E = 1465 \pm 160\ \mathrm{MeV\ mb}$$

$$= (0.49 \pm 0.05)S.$$

To this must be added the integrated cross section, previously measured at Saclay [6] up to 25 MeV, which amounts to $1.17 \pm 0.08\,S$. The two sets of measurements thus give

$$\int_{0}^{106\ \mathrm{MeV}} \sigma_t \mathrm{d}E = (1.66 \pm 0.13)S.$$

Because both the Mainz experimental data and some theoretical predictions are integrated up to the pion threshold at 140 MeV, we extrapolate our least-squares fit to a straight line up to this energy. The data thus lead to

$$\int_0^{140\,\mathrm{MeV}} \sigma_t\, \mathrm{d}E \approx (1.80 \pm 0.2)S.$$

Such measurements of the total photonuclear absorption cross section, σ_t, extended up to the pion photoproduction threshold, $E \approx 140$ MeV, are important since they give access to the enhancement factor K, which, within the dipole approximation framework, can be written as

$$\int_0^{140\,\mathrm{MeV}} \sigma_t\, \mathrm{d}E = (1 + K)S,$$

where

$$K = (AM/NZ\hbar^2)\langle\psi_0|[\mathrm{D}_z, [V, D_z]]|\psi_0\rangle;$$

D_z is the electric dipole operator, V the nucleon–nucleon potential, and $|\psi_0\rangle$ the ground state wave function.

Whereas a value of $K = 0.4$ was often quoted for heavy nuclei a decade ago, our measurements correspond to $K = 0.80$. The Mainz data gave $K = 1.13$, 1.0 and 1.15 for ^{16}O, ^{27}Al and ^{40}Ca, respectively. The similarity of these K values is consistent with the very consistent A-dependence implied by the recent re-evaluation by Weise [7] of the dispersion relation sum rule of Gell-Mann, Goldberger and Thirring.

Although recent microscopic computations do not provide us with a K-value for Pb, the Saclay result lies between the calculated value of $K = 1.0$, given by Weng et al. [8], and $K = 0.6$, given by Fink et al. [9] for such light nuclei as ^{16}O or ^{40}Ca. Since it is the two-body correlations in the ground-state wavefunction $|\psi_0\rangle$ and the effect of the tensor force in the potential V which lead to the above cited K values for light nuclei, we hope that the present experimental result of $K = 0.8$ will stimulate calculations including the same effects for heavy nuclei.

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