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Abstract

We present the results of an absolute measurement of the photoabsorption cross section on Li, C, Al, Cu, Sn, and Pb between 300–1200 MeV. In the Δ region our results confirm that the strength is conserved, while in the higher resonances region they show a 7–15% damping and a possible mass-number dependence of the photoabsorption cross section.

The total nuclear photoabsorption cross section measurements recently carried out at Frascati with 200–1200 MeV tagged photons on ^{238}U [1], Be and C [2,3] have revealed that in these nuclei there is no evidence of the excitation of the $D_{13}(1520)$ and $F_{15}(1680)$ resonances clearly seen in the photoabsorption on hydrogen [4] and deuteron [5] and there is a damping of the absolute value of the cross section per nucleon compared with the relevant quantity obtained from the deuteron data. On the contrary, the $P_{33}(1232)$ resonance is only slightly distorted in agreement with the previous data available in the literature [6,7]. This experimental finding has been confirmed by the recent Mainz data on the photofission cross section for ^{238}U [8] and ^{235}U [9] up to 800 MeV.

This unexpected result has triggered the interest of several theorists who have proposed different approaches in order to account for this effect and justify why the elementary photo-nucleon absorption process is modified inside the nuclei. Kondratyuk et al. [10] fitted the experimental cross section using a phenomenological model which considers a higher collision cross section for the higher-mass nucleonic resonances in the nuclei, thus producing a significant broadening of the D_{13} and F_{15} resonances, much bigger than the one for the P_{33}. Alberico et al. [11] found similar results by employing a simple resonance–hole model and assuming that the nuclear medium strongly increases the width of all resonances above the Δ. In both the above approaches the strength of the resonances is conserved and spread out over a wide energy range.

Other approaches which can damp the strength of the resonances have been considered: Giannini et al. [12] have predicted a 10–20% damping of the excitation of the higher mass resonances inside the nuclei, using a non-relativistic quark model with an oscillator potential that accounts for the quark exchange between the overlapping nucleons. On the contrary, Akulinichev

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et al. [13], employing a similar non-relativistic quark model and short range repulsion to analyze the suppression mechanism for the D_{13} excitation due to the overlap of nucleons, concluded that this effect is negligible.

A very different approach, suggested by Piller et al. [14], showed that a $\approx 5\%$ damping of the absolute value of the photoabsorption cross section around 1 GeV might be interpreted in terms of the shadowing due the low mass tail of the hadronic mass spectral function, as successfully used in describing the shadowing in deep-inelastic electron scattering [15].

Finally, we mention that Weise has provided a sum rule prediction which, employing a dispersion relation approach to reconcile the data for the enhancement factor value observed in the photoabsorption below 140 MeV and the shadowing effect observed above 2 GeV, suggests a strong nuclear medium effect in the whole resonance region [16].

In order to disentangle from these and other possible explanations, one needs an accurate knowledge of the absolute value of the photoabsorption cross section in the nucleon resonance region, over a broad range of mass numbers.

In this paper we present the total photoabsorption cross section measurements on Li, C, Al, Cu, Sn, and Pb carried out at Frascati between 300 and 1200 MeV. We used the *Jet Target* tagged photon beam [17] and the photohadronic method, which consists in measuring the photoproduction rate of hadronic events rejecting the vastly preponderant electromagnetic events by an angular separation. The basis of this method is that the products of the pure electromagnetic interactions are contained in an extremely small forward angular cone, while the products of the hadronic interactions are more broadly distributed in angle. It is worth noticing that this method is the one that allows a direct and absolute measurement of the total photoabsorption cross section over a wide mass-number range. Details on this technique can be found in our previous paper [3], where we gave partial results on C and an overall check of the apparatus through a measurement on deuteron.

The used targets were cylinders, 3 cm in diameter and thickness $0.1X_0$ (X_0 being the radiation length) for Al, Cu, Sn, and Pb, $0.08X_0$ for C, and $0.025X_0$ for Li. A NaI crystal surrounding the target detected the charged particles and neutral pions product of the photonuclear interaction in the target, while the electromagnetic events forward emitted were vetoed by a lead glass counter.

The response function of the hadron detector was studied by simulating the photon interaction in the target with a Monte Carlo code based on the Barashenkov et al. [18] cascade-evaporative model and evaluating the energy released in the hadron detector by the photoproduced hadrons, using a modified version of the Geant-3 code [19]. The predictions of the very different angular distribution of hadronic and electromagnetic events were experimentally checked changing the solid angles defined both by the hadronic and shower detectors, simply moving them upstream and downstream with respect to the target position. Also the predictions of the final state total energy were checked by comparison with the measurements of the energy released in both the detectors [19].

From the comparisons of these simulations with the described test measurements, we estimated that, above 600 MeV, the overall corrections to the hadron detection efficiency are $\approx 9\%$ for Pb and $\approx 6\%$ for Li, respectively, and the electromagnetic contamination is $\leqslant 2\%$ for Pb and $\ll 1\%$ for Li. In the Δ region, these corrections increase up to a factor of two. However, it is worth noticing that the electromagnetic contamination has the opposite sign with respect to the hadronic corrections, the former increasing the measured cross section. In conclusion, for the higher-mass nucleon resonance region all the Monte Carlo corrections affected the on-line results less than 6–7%.

We collected data at four machine energy settings ($E_0 = 730$, 850, 1200, and 1500 MeV): the good overlaps observed between the different data sets evidence the good control of the systematic errors. Moreover the measurements were made in several runs distributed over half a year and the data from each run were separately analyzed and compared. This provided a further check for systematic errors arising from factors in the experimental conditions which might have varied from run to run. The systematic errors were essentially due to uncertainties in the photon beam flux ($\approx 2\%$), in the target thickness (≈ 0.5–1.5%) and mainly in the calibration and threshold efficiency of both the lead-glass and NaI detectors (above 600 MeV this contribution is constant with energy and increases from $\approx 2\%$ to $\approx 6.5\%$ with the target mass number A, while, in the Δ region, where it depends both on energy and A, it varies from $\approx 4.5\%$ to $\approx 7.5\%$). In conclusion, the total systematic errors are constant with energy and increase

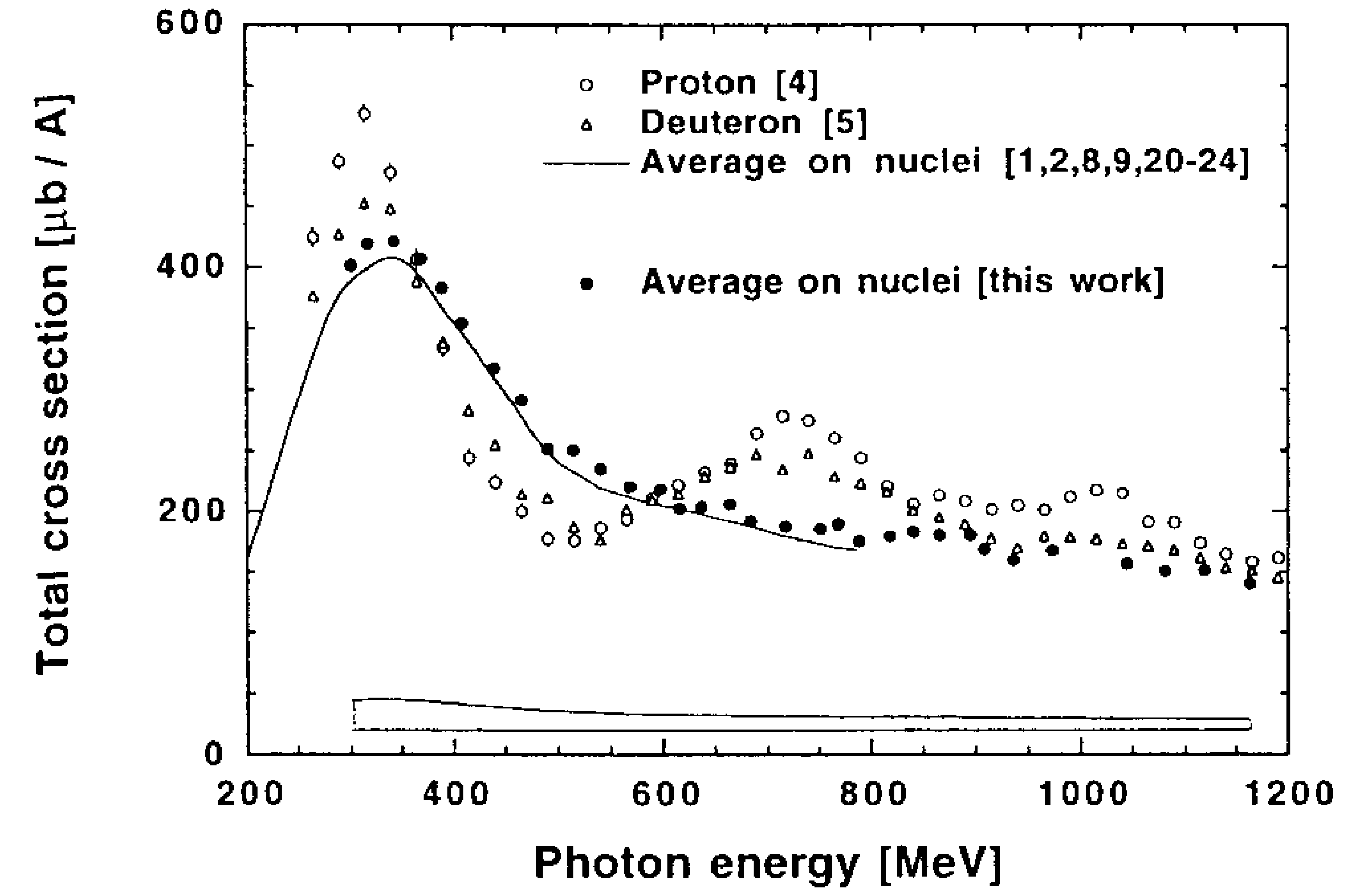

Fig. 1. Comparison between the total photoabsorption cross section normalized to the mass number A, obtained from the average of the present results for Li, C, Al, Cu, Sn, Pb, with the Daresbury proton and deuteron data, and with the average behavior derived from several nuclear data. The band at the bottom indicates the systematic uncertainties of our data. Statistical errors of all data points are generally smaller than symbol sizes, while the total uncertainty of the average behavior is about 3–4%.

with A from $\approx 3\%$ to $\approx 7\%$ in the D_{13} and F_{15} resonance regions, which are of chief interest to this work, and vary from $\approx 5\%$ to $\approx 8\%$ in the Δ region.

In Fig. 1 is shown the total cross section normalized to A, obtained from the average of the values for all the six nuclei studied by the present experiment. Also shown are the proton and deuteron data measured at Daresbury [4,5] and the average nuclear behavior derived from a set of about 350 data points on different nuclei provided by several experiments [1,2,8,9,20–25]. As it is seen, our results are in excellent agreement with the absolute value and the shape of the average behavior in the whole energy region, while, compared with the proton and deuteron data, confirm both the absence of the resonance structures and the damping of the absolute value of the total cross section in the D_{13} and F_{15} energy region already seen in our previous measurements [1–3].

In order to carefully evaluate the damping factor, we calculated the integral Σ_A of the measured total cross sections in the P_{33}, D_{13} and F_{15} energy regions for all the studied nuclei. The integrals for the D_{13} and F_{15} energy regions were calculated over an energy range of $2\Gamma_r$, where Γ_r are the resonances widths as reported in the Particle Data Book [26], while for the P_{33} energy region the data allowed to calculate the integral only over one Γ_r on the high energy side of the peak.

In Fig. 2 the ratio $R_A = \Sigma_A / (Z\Sigma_p + N\Sigma_n)$, where Σ_p and Σ_n are the total photoabsorption cross sections, respectively on the proton and neutron as provided by Armstrong et al. [4,5], integrated over the relevant photon energies (specifically: $320 < E_\gamma < 440$ MeV, $600 < E_\gamma < 840$ MeV, $890 < E_\gamma < 1150$ MeV for the P_{33}, D_{13} and F_{15}, respectively) is shown. It is worth mentioning that the factor used $(Z\Sigma_p + N\Sigma_n)$ accounts properly for the non-isoscalarity of the nuclear targets, to the extent that the strenghts of the higher resonances are different for a neutron compared to a proton [4,5]. In Fig. 2 our results are compared with those obtained from other absolute cross section measurements available in the literature. As it is seen there is good agree-

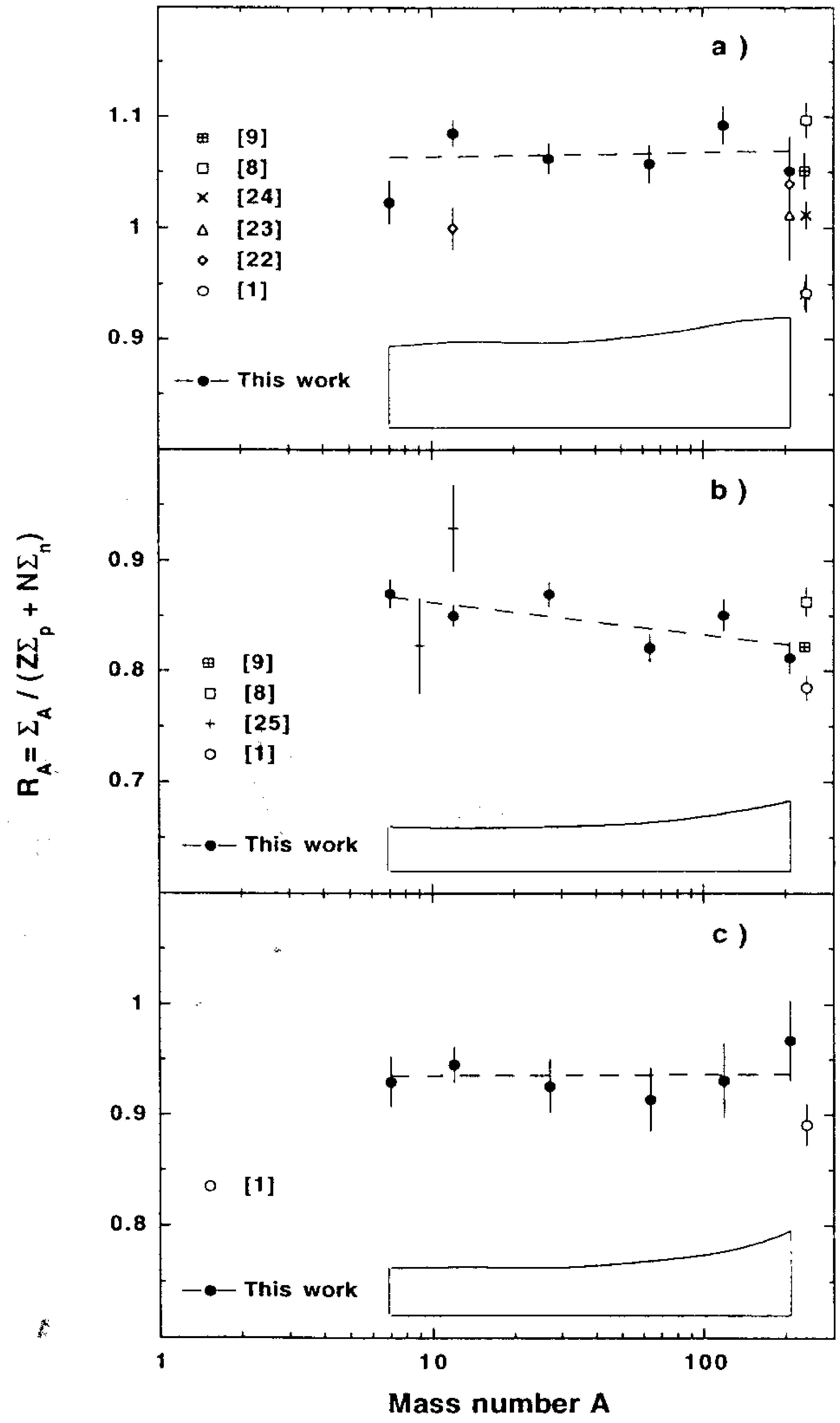

Fig. 2. Ratios R_A between the integrated cross section for nuclei Σ_A and $(Z\Sigma_p + N\Sigma_n)$, where Σ_p and Σ_n are the integrated cross section respectively for proton and neutron, and fits to our data with a power law $a \cdot A^{\alpha - 1}$ (dashed lines): (a) the Δ region (320–440 MeV), (b) the D_{13} region (600–840 MeV), (c) the F_{15} region (890–1150 MeV). The error bars include only the statistical uncertainties. The systematic uncertainties of our results are indicated by the bands at the bottoms, while they range from $\approx 7\%$ to $\approx 10\%$ for results from other experiments.

ment between our results and all those deduced from other experiments: this finding validates the following analysis to carefully establish the possible A-dependence of the damping factor of the cross section, with minimal influence of systematic errors. We used only the data provided by this experiment because it is the one which spans the whole nucleon resonance region over a broad range of mass number.

In the Δ energy region (Fig. 2a), no damping of the total cross section is found, the mean ratio being $R_A = 1.066 \pm 0.009(\text{stat.}) \pm 0.085(\text{syst.})$. The small excess with respect to unity is due to the shift toward higher energies of the Δ peak in the nuclei, the integral being made only over the high energy side of the peak. The power law of the fit $R_A = a \cdot A^{\alpha-1}$, with $(\alpha-1) = 0.002 \pm 0.009 \pm 0.007$, well confirms the A-independence of the cross section already found in this energy region.

In the D_{13} energy region (Fig. 2b), the mean ratio value $R_A = 0.848 \pm 0.009 \pm 0.045$, indicates an appreciable nuclear damping well above the total statistical and systematic errors, and the power law gives $(\alpha-1) = -0.015 \pm 0.008 \pm 0.008$ suggesting a possible A-dependence of the total cross section.

In the F_{15} energy region (Fig. 2c), from the value of the mean ratio, $R_A = 0.936 \pm 0.006 \pm 0.050$, we deduce a possible nuclear damping as found in our previous measurement [1], while the power law $(\alpha-1) = 0.000 \pm 0.007 \pm 0.008$ indicates no A-dependence of the total cross section. The lower damping value compared with the one in the D_{13} region might be ascribed to the non-resonant background contribution, more relevant in the F_{15} region than in the D_{13} one. Also a main contribution of the shadowing effect, that shows a very weak A-dependence around 1 GeV [14], might explain the different behavior in the F_{15} region with respect to the D_{13} region, where resonance excitation and broadening effect should dominate.

It is worth mentioning that should one use the normalization factor $A\sigma_D/2$ instead of $(Z\Sigma_p + N\Sigma_n)$ (where σ_D is the total photoabsorption cross section on the deuteron), the R_A values would decrease for all the studied nuclei except for carbon (e.g. by a factor 3.5% for lead in the F_{15} region).

At our knowledge, there isn't yet any theoretical model which is able to explain in quantitative and systematic way both the damping and the A-dependence of the cross section that we have found in the higher nucleonic resonance region. We think necessary both a theoretical effort, similar to the one done in the past for the Δ region, to complete the knowledge of resonance behavior in the nuclear medium, and the extension of measurements to the still unexplored region between 1.2 and 1.7 GeV, which will allow to better understand the onset of the shadowing effect and to set definite constraints to dispersive sum rules.

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