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## Proposal Title

"Photoabsorption and Photofission of Nuclei"

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# Photoabsorption and Photofission of Nuclei

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# Abstract

We propose to measure, from 0.4 to 1.9 GeV, the total photoabsorption cross sections using the photo-hadronic method for C, Al, Cu, Sn, and Pb, and the photofission cross sections for $^{238}$U, $^{237}$Np, and $^{232}$Th. The aim of these measurements is to study the excitation and interaction of baryon resonances in nuclei, the onset of the shadowing effect, the prediction of the Weise sum rule, and the total fission probabilities of actinides across this energy region. The experiment can be performed in Hall B as soon as the tagging facility is ready. Most of the experimental set-up needed for the proposal (targets, detectors, etc.) already exists and has been used successfully for similar measurements below 1.2 GeV. The requirements on the photon beam, such as its maximum energy, intensity, spot size, and divergence, are not rigid. The experiment will also be a good first test of the tagged-photon facility, both at low incident photon flux (for total photoabsorption) and high flux (for photofission). The required beam time is 180 hours. The time schedule for the measurements will be chosen such that it will in neither interfere with nor delay the installation of the CLAS spectrometer. We plan to extend this program by using the CLAS detector to measure the exclusive photoreaction cross sections and to obtain the branching ratios for non-fission events and their characteristic properties.

# 1. Motivation

## A. Photoabsorption

The total photonuclear absorption cross section has been measured over a wide range in mass number and photon energy, yielding information on the influence of the nuclear medium on the intrinsic properties of nucleons in nuclei, as well as on the hadronic nature of the photon. In the Δ-resonance region,[1,2] the data for the total cross section per nucleon, measured for various nuclei from $^{6}$Li to $^{238}$U, show that the resonance shape and strength is nearly universal, thus indicating an incoherent volume-photoabsorption mechanism (see Fig. 1a). The response of bound nucleons differs from that for the free nucleon, mainly because of Fermi motion, Pauli blocking, and the propagation and interaction of the Δ in the nucleus; however, the total strength of the interaction in this region is conserved.

Above about 2 GeV, on the contrary, the total cross section shows some coherent behavior; its A dependence can be written as $\sigma_{\gamma A} = A^{\alpha}\ \sigma_{\gamma N}$, where A is the mass number and $\sigma_{\gamma N}$ is the cross section for a free nucleon. The present experimental data at very high energies suggest a value $\alpha \approx 0.9$, intermediate between volume absorption, $\alpha = 1$, typical of a bare electromagnetic probe, and surface absorption, $\alpha = 2/3$, typical of a hadronic probe. This is the well known shadowing effect, that is usually explained in the framework of the Vector-Meson-Dominance (VMD) Model. The available experimental data show a shadowing-like behavior at energies as low as 1.8 GeV; however, the amount of shadowing found in various studies is contradictory and does not agree quantitatively with theoretical predictions.[3] The energy dependence of the total cross section in the few-GeV region can be described well by a Regge behavior of the form $\sigma_{\gamma A}(k) = a + b \cdot k^{-1/2}$, where k is the photon energy (see Fig. 1b).

Until a few years ago, in the energy region between 0.5 and 1.8 GeV, data were scarce and inaccurate. There were precise data only for the proton[4] and the deuteron.[5] There also were some low-precision data for Be, C, Cu, and U obtained at Erevan,[6,7] sparsely spread in photon energy and fluctuating considerably more than the quoted experimental uncertainties (see Fig. 2).

Very recently, three measurements, using three different experimental techniques, have been performed at Frascati in the energy range between 0.2 and 1.2 GeV:

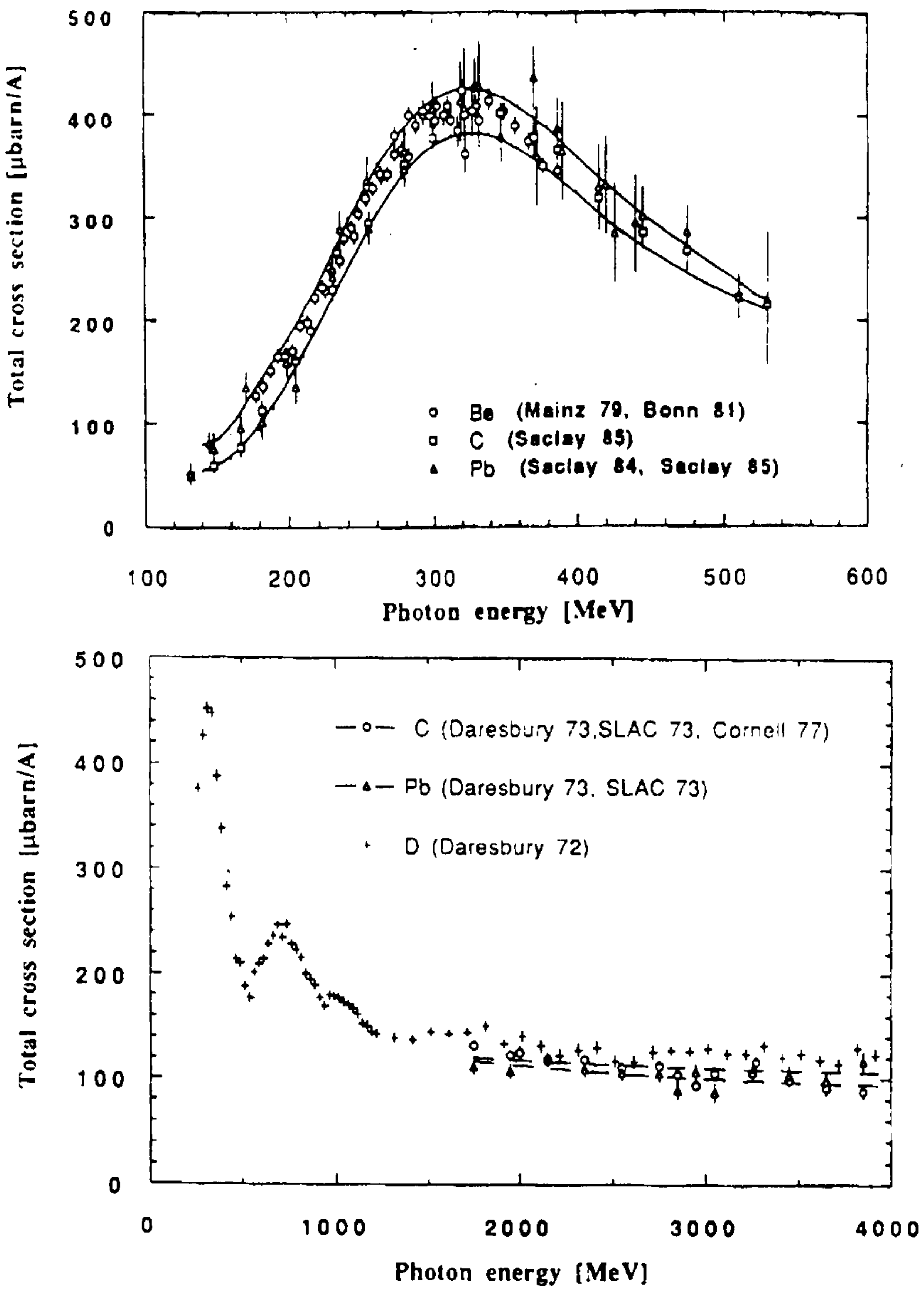

**Fig. 1** a) Some experimental values of the total photo-absorption cross section over the Δ energy region; the region between the solid curves constitutes the universal behavior.

b) Experimental values of the total cross section for deuterium, carbon, and lead in the few GeV region. Also shown are the Regge-form fits to the experimental data [$\sigma(k) = a + b \cdot k^{-1/2}$].

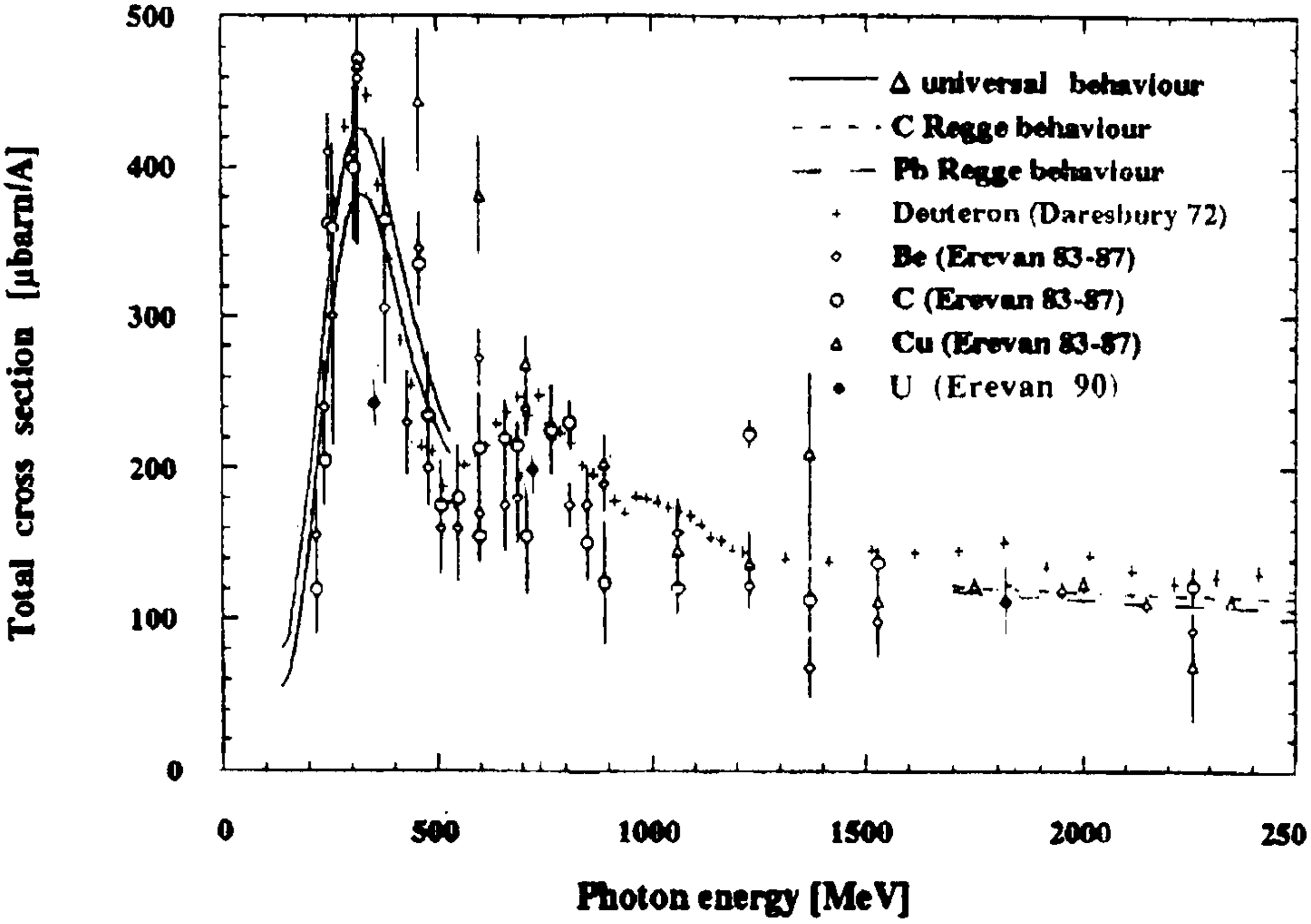

Fig. 2 Cross sections for Be, C, Cu, and $^{238}$U in the intermediate-energy region, showing as well the Δ universal behavior and the few-GeV Regge behavior.

a) simultaneous measurements of the photofission cross sections for $^{238}$U and $^{232}$Th, using parallel-plate avalanche detectors (PPADs)[8];

b) total cross-section measurements on Li, C, Al, Cu, Sn, and Pb with the photo-hadronic method, using a NaI crystal as the hadronic detector and a lead-glass counter as the electromagnetic detector[9];

c) total cross-section measurements on Be and C with the transmission technique, using a BGO crystal as the photon spectrometer.[10]

In Fig. 3, the Frascati results on C, obtained with the photo-hadronic method and with the transmission method, together with those on $^{238}$U, obtained with photofission, are compared with the available deuteron[5] data over the entire energy range and with the universal nuclear behavior in the $\Delta$ region. From these comparisons we conclude that:

(i) The results of the three measurements are in excellent agreement with each other, showing good control of systematic errors and confirming that the fission probability of $^{238}$U is very close to one up to 1.2 GeV.

(ii) In the energy region below 0.5 GeV, the values of the cross section per nucleon, $\sigma_{\gamma A}/A$, reproduce, within the systematic errors, the well known $\Delta$-resonance shape and strength obtained at other laboratories on various nuclei.

(iii) There is no evidence of excitation of the higher baryon resonances that are clearly seen in the photon absorption by free protons and deuterons as peaks at energies of $\approx$0.7 and $\approx$1.0 GeV, which correspond mainly to the $D_{13}(1520)$ and $F_{15}(1680)$ resonances. In the range between 0.6 and 1.2 GeV, the strength is reduced approximately by 10-20% with respect to the deuteron, while it is conserved in the range 0.3 to 0.6 GeV. This unexpected behavior of the higher nucleon resonances in nuclei has been confirmed by the data on $^{238}$U recently obtained up to 0.8 GeV at Mainz.[11]

(iv) No evident A-dependence seems to appear from currently available data on different nuclei, but more definite conclusions must await the final results of the ongoing analysis of the data obtained on all of the nuclei studied.

In order to give a physical interpretation of these results, in particular those of point (iii), we have developed a model[12] in which, beginning with the excitation of nucleon resonances deduced from experimental results on the proton and the deuteron, we attempt

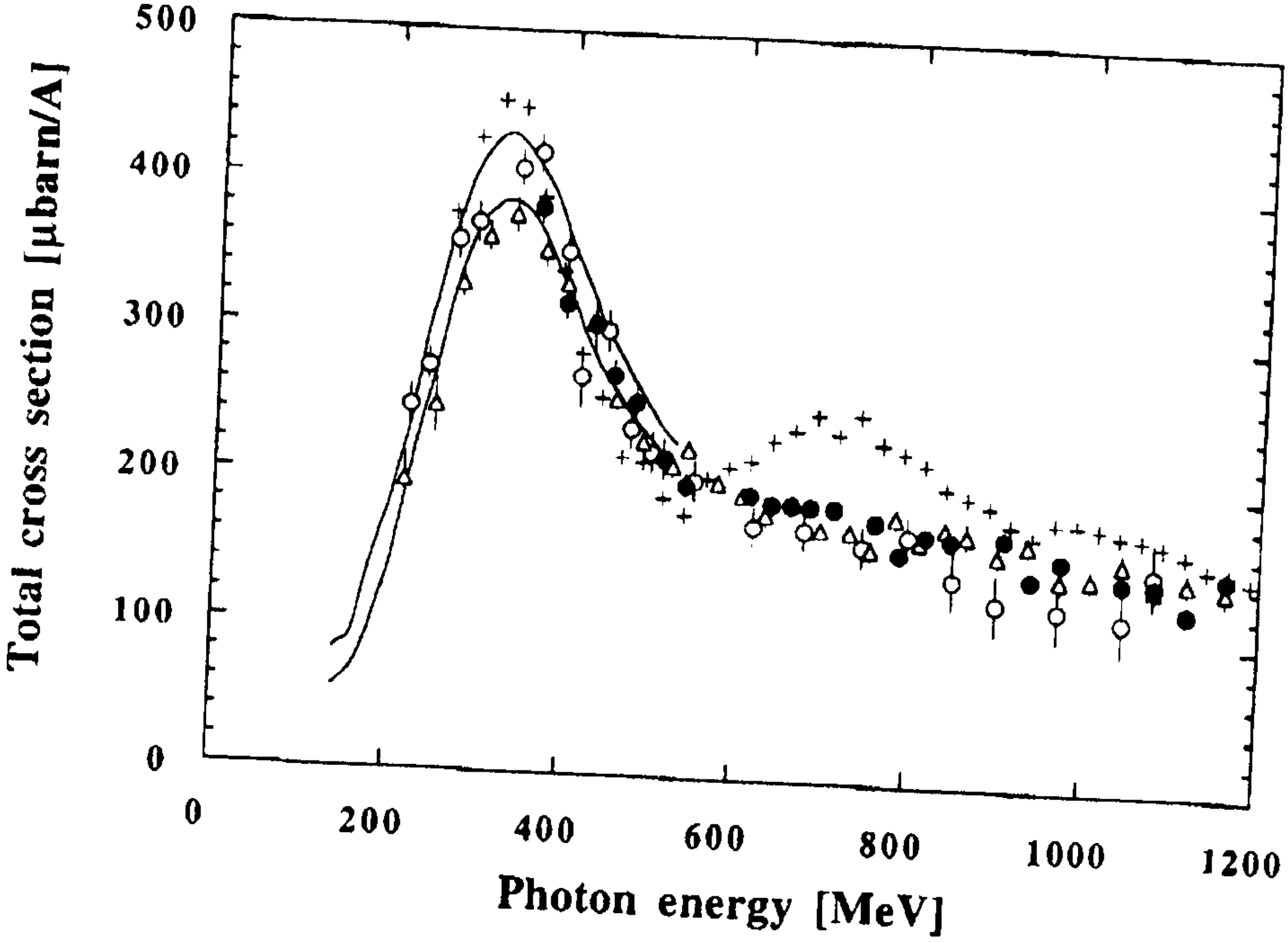

**Fig. 3** The Frascati data on C, obtained both with the photo-hadronic method (solid circles) and the transmission method (open circles), and on $^{238}$U (open triangles), compared with the deuterium data and with the universal nuclear behavior in the Δ region.

to understand these processes inside nuclei. Within the framework of this model, we account for:

a) the Fermi motion described by a Fermi-gas model with $P_F$ = 280 MeV/c;

b) the Pauli blocking factor; and

c) the interaction of the produced N* resonances with the surrounding nucleons.

Concerning point c), the N*N => NN cross sections were used as free parameters necessary to reproduce the experimental results on $^{238}$U. As shown in Fig. 4, this model is able to reproduce fairly well the nonresonant behavior of the Frascati data, assuming an interaction cross section of about 20 mb for the $\Delta$ (which is in good agreement with the experimental values inferred from inverse reactions) and one of about 80 mb for the $D_{13}$ and $F_{15}$ resonances. Furthermore, the model clearly overestimates both the Frascati results near 1 GeV and the Regge behavior of the Daresbury data above 1.8 GeV.

Therefore, to account for this reduction of the strength, one has to resort to other causes, such as the onset of the shadowing effect or perhaps the damping of the excitation of higher resonances in the nuclear medium. This damping might be more effective for deformed resonances like the $D_{13}$(1520) and the $F_{15}$(1680) which correspond to states of nonzero orbital angular momentum, than for spherical ones like the $\Delta$ [$P_{33}$(1232)], which is excited by a simple quark spin flip.

According to the VMD model, the coherence length $\lambda$ of the hadronic fluctuation of the real photon is proportional to the photon energy k and inversely proportional to the square of the hadronic mass $\mu$: $\lambda = 2k/\mu^2$. Hence, for example, a $\rho$-meson intermediate state of 10 GeV has a coherence length of about 7 fm, comparable to the size of a nucleus and therefore large enough to induce shadowing; whereas a shadowing-like effect at an energy as low as 1 GeV cannot be attributed to vector mesons, but perhaps only to a lower mass nonresonant hadronic state made up of two pions with the same quantum numbers as the photon.

Moreover, the low- and high-energy regions are connected by sum rules, and this connection has been used to establish constraints for the integrated total photonuclear cross section in the nucleon resonance region by taking account of the behavior of photon interactions at asymptotic energies. In particular, Weise[13] has shown that one can reconcile the data for the enhancement factor below pion threshold with those for the shadowing effect at high energies with a dispersion-relation approach, and has proposed

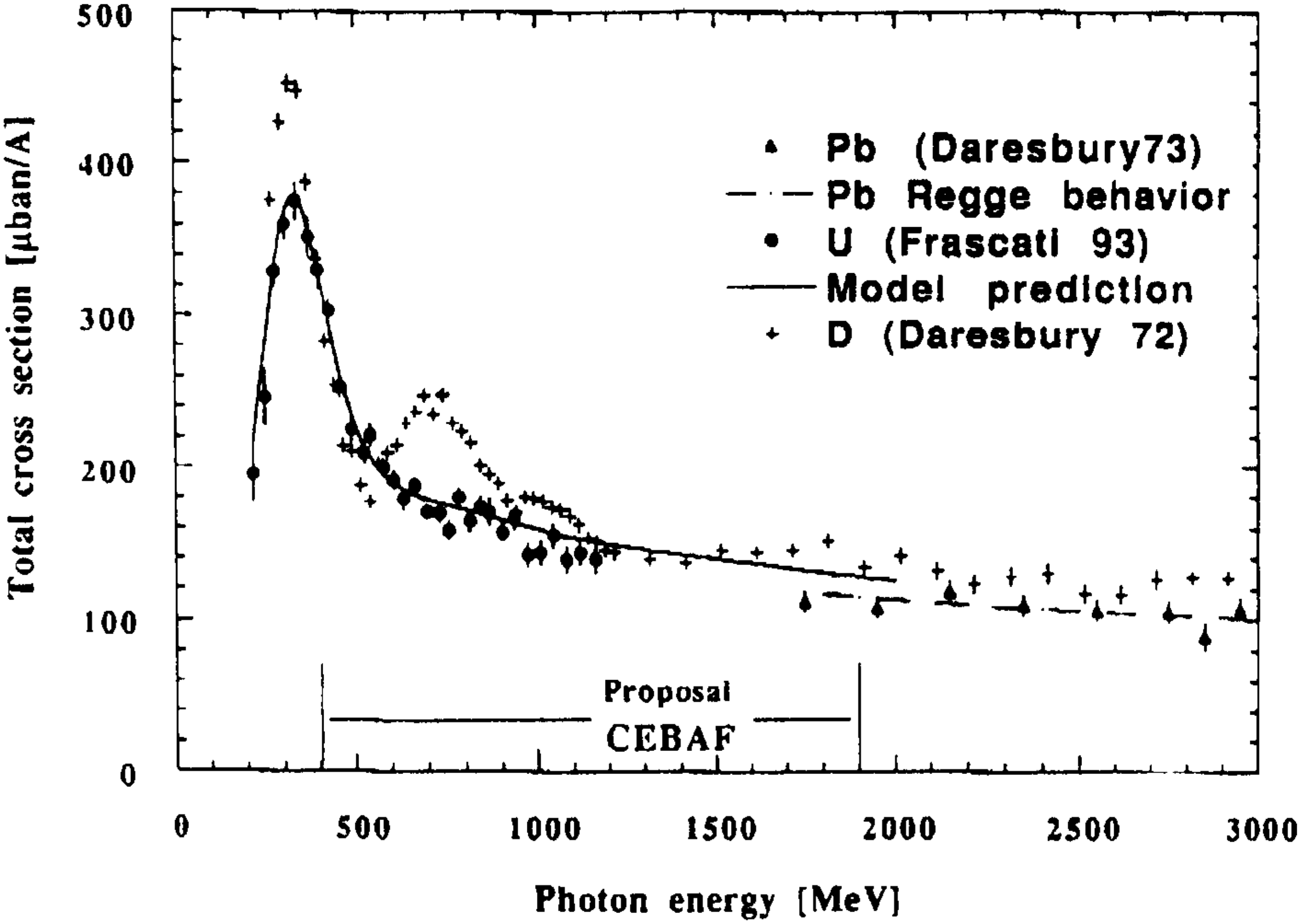

**Fig. 4** Comparison of the $^{238}$U and Pb data with the result of a theoretical calculation from Ref. 12.

that some non-negligible shadowing effects in nuclei should manifest themselves in the nucleon-resonance region.

### B. Photofission

Turning to the photofission data, Fig. 5 shows a comparison between the more recent monochromatic-photon data on uranium. It is important to note the lack of data in the region between 1.2 and 2 GeV. For this reason we compare the Frascati data with the extrapolation to lower energies of a Regge form $(a+b \cdot k^{-\frac{1}{2}})$ fitted to the total cross section for $^{238}U$ measured at Cornell with the photo-hadronic method. The agreement between the Frascati data and the fit supports the assumption that the fissility of $^{238}U$ can be assumed to be equal to one in the GeV region as well, and that the photofission method is a useful technique with which to measure the total cross section of fissile nuclei.

Figure 6 shows the fissility of $^{232}Th$ measured recently at Frascati,[14] together with the low-energy data from Saclay[15] and a datum obtained with 1-GeV protons.[16] The nuclear photofissility of $^{232}Th$ was determined with respect to that of $^{238}U$, whose photofission cross section in the same energy range was measured simultaneously, assuming a photofissility equal to one for $^{238}U$. Also shown in this figure is a simple fit of the form $\ln W_f(k)=A-Bk^{-1/2}$, that seems to reproduce well the energy behavior of the data, as well as the prediction of a Monte-Carlo calculation based on an intranuclear-cascade (INC) and evaporation model. The agreement between the calculated and the measured fissility is reasonable. From the analysis of these figures we conclude:

i) The $^{238}U$ photofissility has an almost constant value, consistent with one in very different energy regimes, namely, in the absorption of the photon by an n-p pair in the quasideuteron region and in the resonance excitation through pion production up to 1.2 GeV. The general expectation is that this experimental finding should be valid at higher energy as well, and in such a case the photofission measurement will be a valid and alternative method for measuring the total photonuclear cross section. But if this expectation were not to be borne out, then several interesting questions would arise:

- What is the branching ratio for non-fission events?
- What is their nature? That is,
- What kinds of processes leave the residual nucleus cold? Do such processes take place preferentially on the nuclear surface? If so, then

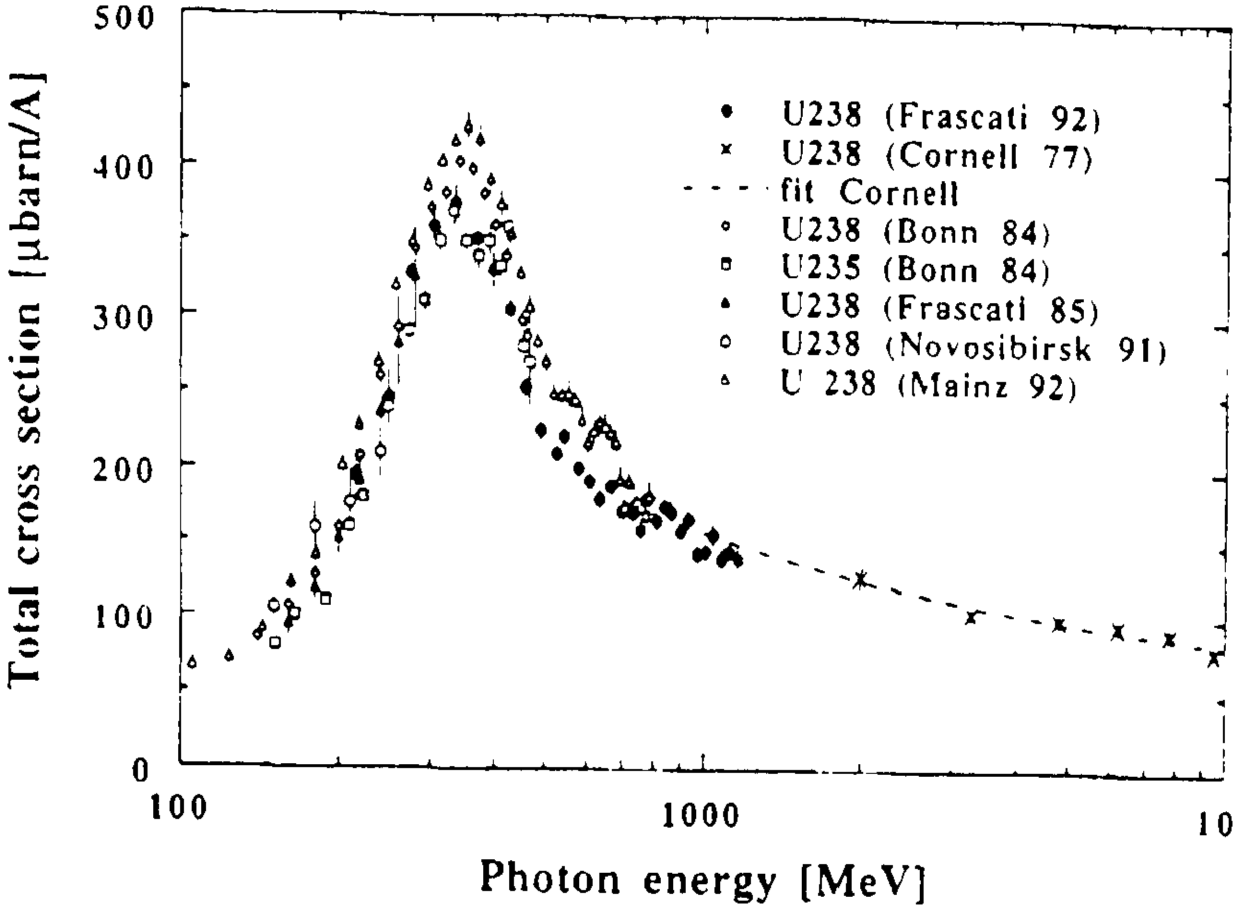

**Fig. 5** Comparison among the more recent monochromatic-photon data on uranium in the literature. The dotted line is a fit in the Regge form [$\sigma(k) = a + b \cdot k^{-1/2}$] to the high-energy data.

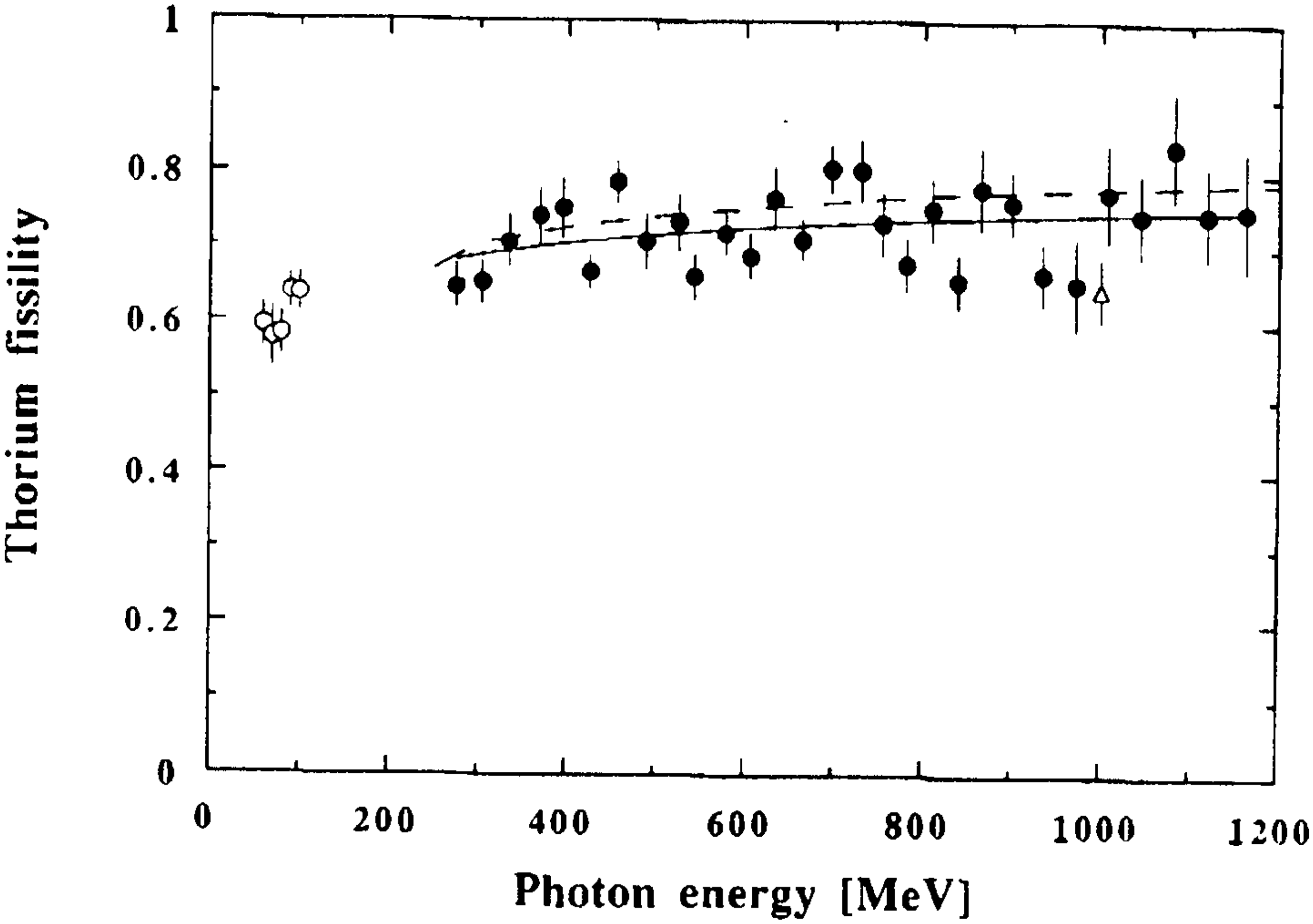

**Fig. 6** Photofissility values for $^{232}$Th obtained as described in the text (solid circles). Also shown are data obtained with the same procedure and extracted from Refs. 15 (open circles) and 16 (open triangles). The solid line is a fit of the form $\ln W_f(k) = A - Bk^{-1/2}$; the dashed line is the result of an intranuclear-cascade calculation.

- What is the effect of the nuclear medium on such processes? Are strong many-body forces important?

ii) In the energy range from 0.25 to 1.2 GeV, the fissility values $W_f$ for $^{232}$Th lie approximately between 0.6 and 0.8, showing a weak but clear increase with energy, demonstrating that for this nucleus the saturation value is not yet reached. This particular behavior of $^{232}$Th is surprising in that it is quite different from other heavier actinides, which reach a fissility of nearly 1.0 at much lower energies. One possible explanation for this behavior is simply that the fissionability $Z^2/A$ is too small. Another suggestion[17] attributes this behavior to a smaller transparency of $^{232}$Th, while the presence of a direct fission component could contribute to the slow increase with the energy.

At lower energies, namely, 0.06 to 0.24 GeV, it has been reported[18] that the fissility of $^{237}$Np exceeds that of $^{238}$U by 20-40%. If this surprising behavior were to be confirmed, most of our other notions of medium- and high-energy photofission would have to be rethought; therefore, we propose to measure the fissility of $^{237}$Np as well.

From the discussion above, it is clear that an accurate knowledge of the photoabsorption and photofission cross sections over the entire nucleon-resonance region, between 0.2 and 2 GeV, is very desirable. We propose to use the Hall B tagged-photon beam to obtain data, both on photofission and photoabsorption, that will fill the important gap between the low-energy and the high-energy data (see also Fig. 7), and in so doing to give definitive answers to the above fundamental questions in nuclear physics.

### C. Extension to Higher Energies

This proposal should be regarded as the first, crucial, stage of a series of total photoabsorption and photofission measurements to be done at CEBAF. It is evident from Figs. 1b and 4 that there is much to be learned even from an extension to 4 GeV. Between 2 and 4 GeV, the nature of photon interactions makes the transition to the Vector-Dominance Model, and nuclear shadowing should become more definite. Perhaps more to the point, the existing low-quality data seem to exhibit a very large discrepancy between deuterium and carbon or lead; is this discrepancy real? And between 4 and 6 GeV, do we enter an energy region where hard processes make themselves felt? How short does the incident photon wavelength need to be to approach a point-like interaction?

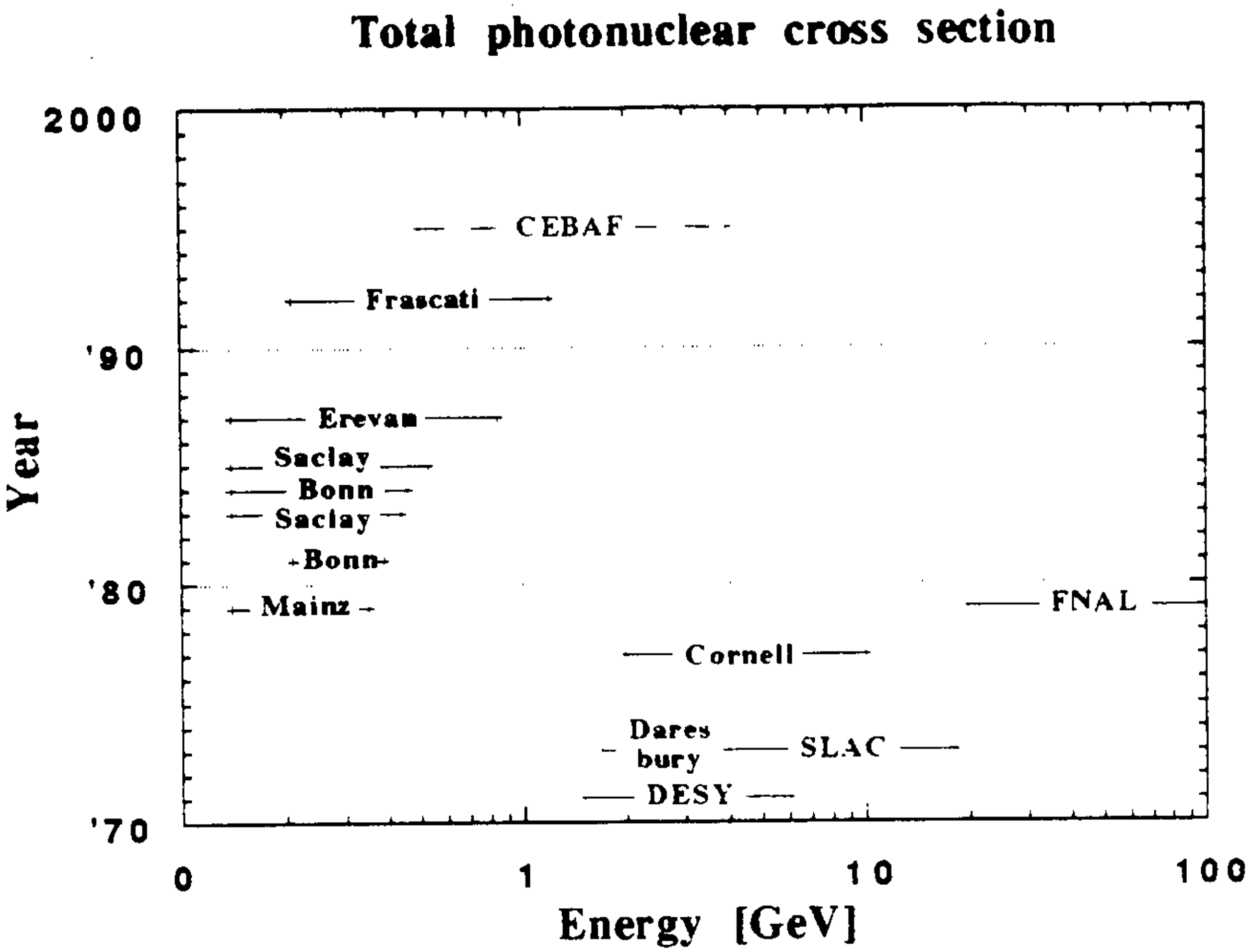

**Fig. 7** The energy ranges covered by different laboratories at which total photonuclear cross sections have been measured. Clearly, CEBAF is needed to link the "low-energy" data with the "high-energy" data.

One thing is sure: the total photoabsorption cross section will be a vital benchmark that will constrain our perception of the interaction mechanism, and a high-quality measurement of this quantity as a function of energy and mass number will be required for our deeper understanding of nuclear physics.

## 2. Relation to other CEBAF Experiments

The physics questions outlined above overlap significantly with those of proposal 89-002.[19] Moreover, several phenomena of interest discussed above which also overlap experiments proposed by all three of the Hall B Collaborations may also appear in the data to be acquired here. One example is: How do the underlying nucleon resonances manifest themselves in the total hadronic and photofission cross sections? For instance, the modification of the $\Delta$ resonance in nuclear matter and the degrees of freedom appropriate to a description of any such modification are targeted for study in proposals 89-017[20] and 89-037[21]; these phenomena could also be explored by their influence on the total photoabsorption and photofission cross sections in the measurements outlined here. The extension of these ideas from the $\Delta$ resonance to other nucleon resonances could be made from the results to be obtained in proposal 89-036,[22] which will study, as a function of A, the local and short-range properties of nuclear matter via backward particle production, and perhaps as well in the proposals 89-039[23] and 91-008,[24] which should provide insight into the isospin-1/2 content of the nucleon-resonance spectrum via $\eta$ and $\eta'$ electro- and photoproduction.

As outlined in this brief discussion, the photoabsorption and the photofission measurements sketched above will complement at an early time the knowledge base to be obtained from a broad spectrum of CEBAF experiments, and thus will be extremely useful in exploring many of the fundamental questions to be answered with CEBAF concerning the structure of the nucleon and the modification of its behavior in the nuclear medium.

## 3. Experiment

We propose to measure the total photoabsorption cross sections for C, Al, Cu, Sn, and Pb with the photo-hadronic method and the photofission cross sections on $^{238}U$, $^{237}Np$, and $^{232}Th$, in the energy range from 0.4 to 1.9 GeV.

### A. Photoabsorption

The photo-hadronic method consists in measuring the photoproduction rate of hadronic events, rejecting the vastly preponderant electromagnetic events by an angular separation. This method, applied successfully in all measurements of total cross sections above the $\Delta$ resonance and also used in the Frascati program, provides a direct and absolute measurement of the total nuclear photoabsorption cross section. The photon beam will interact in a 0.1-radiation length ($X_0$) thick target of C, Al, Cu, Sn, or Pb. A NaI crystal hadron detector (HD), which consists of three cylindrical sectors, each 32 cm long and 15 cm thick, surrounding the target will detect the charged particles and neutral pions produced by the photon interaction in the target, while the electromagnetically produced particles and photons, which nearly all are emitted close to the photon direction, will be vetoed by a lead-glass shower detector (SD) positioned $\approx 70$ cm downstream. Hadronic absorption of a photon of a given energy will then be indicated by a coincidence between signals from one tagging channel and the HD without a coincidence pulse in the SD above a fixed threshold. The total number of photons in the *i*th energy bin hitting the target is determined by the coincidence of signals from the SD and the counters defining the *i*th channel of the tagging system.

The beam intensity will be adjusted to keep random coincidence rates at a level below 10% of the rate of the real events; nevertheless, random coincidences will be measured and then subtracted off line.

Electromagnetic processes were simulated by a modified version of the Geant-3 code in which we introduced the measured energy and angular distribution of pair production in the energy range of interest.

For the hadronic processes we have used a Monte-Carlo simulation based on the Barashenkov *et al.*[25] cascade-evaporative model. This code accounts for the photon interaction with nucleons through one-pion and two-pion production processes in resonant and nonresonant states; then the photoproduced hadrons undergo an intranuclear cascade, leaving the residual nucleus in an excited state that emits low-energy evaporation nucleons and light nuclei. Simulations have been performed between 0.3 and 1.2 GeV, but the code will be improved to include processes resulting in more than two pions emitted in order to be used at higher energies.

The response function of the hadronic detector was simulated using the result of the cascade-evaporative code together with a modified version of the Geant-3 code in which we have introduced the measured hadronic cross sections in NaI at energies below 1 GeV. For example, Fig. 8a shows the energy carried in the HD by the various hadrons generated by photons between 0.6 and 1.2 GeV in the carbon target. In Fig. 8b, the simulated total energy deposited in the HD is compared with the measured spectrum. From this comparison we can see the good agreement between the simulated and measured spectra over the whole range of energy released and we can deduce the small corrections for the undetected events below the HD threshold. For a fixed threshold of about 35 MeV, the corrections are approximately 2%.

The corrections for the angular acceptance of the HD and its contamination due to the electromagnetic events not vetoed by the SD were evaluated by moving the targets upstream and downstream inside the HD. In Fig. 9 we show the on-line cross-section values measured at two energies ($E_0$ = 1.5 GeV and $E_0$ = 0.85 GeV) for different carbon-target positions, as a function of the ummeasured solid angle $\theta^2$ forward of the HD. The arrow indicates the standard angle that corresponds to the target placed in the center of the HD, which is the position for the cross-section measurements. The cross-section values are fitted by a curve $a - b\theta^2 + (c/\theta^2)$ where a is the hadronic cross section for an ideal $4\pi$ HD, $-b\theta^2$ represents the loss of hadronic events in the forward hole of the HD, and $c/\theta^2$ represents the contamination of electromagnetic events due to the pairs produced in the target, which is relevant only when the target is moved upstream towards values of $\theta^2$ smaller than the standard one. For both of these corrections, the values deduced from this measurement agree well with the predictions of the Monte-Carlo calculations.

It is worth noting that we expect that the off-line software analysis and corrections to the data for detector solid angles, efficiencies, and the like, will not affect the on-line

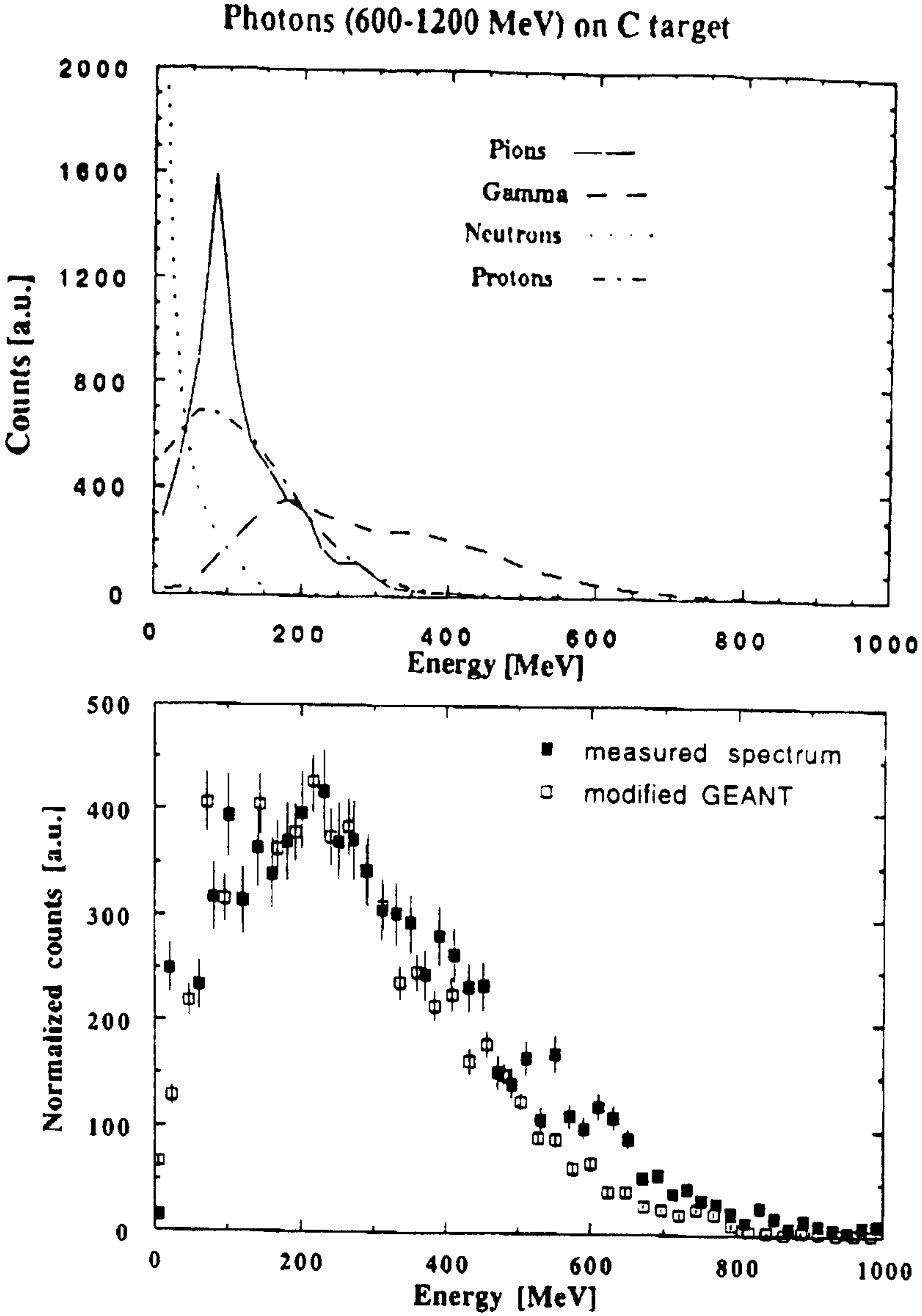

**Fig. 8** a) Simulation of the energy spectra of emitted hadrons produced by 0.6-1.2 GeV photons on a carbon target (the gammas come from $\pi^0$ decay).
b) The simulated total energy released by all of the hadrons produced by 0.6-1.2 GeV photons on a carbon target, compared with the measured spectrum.

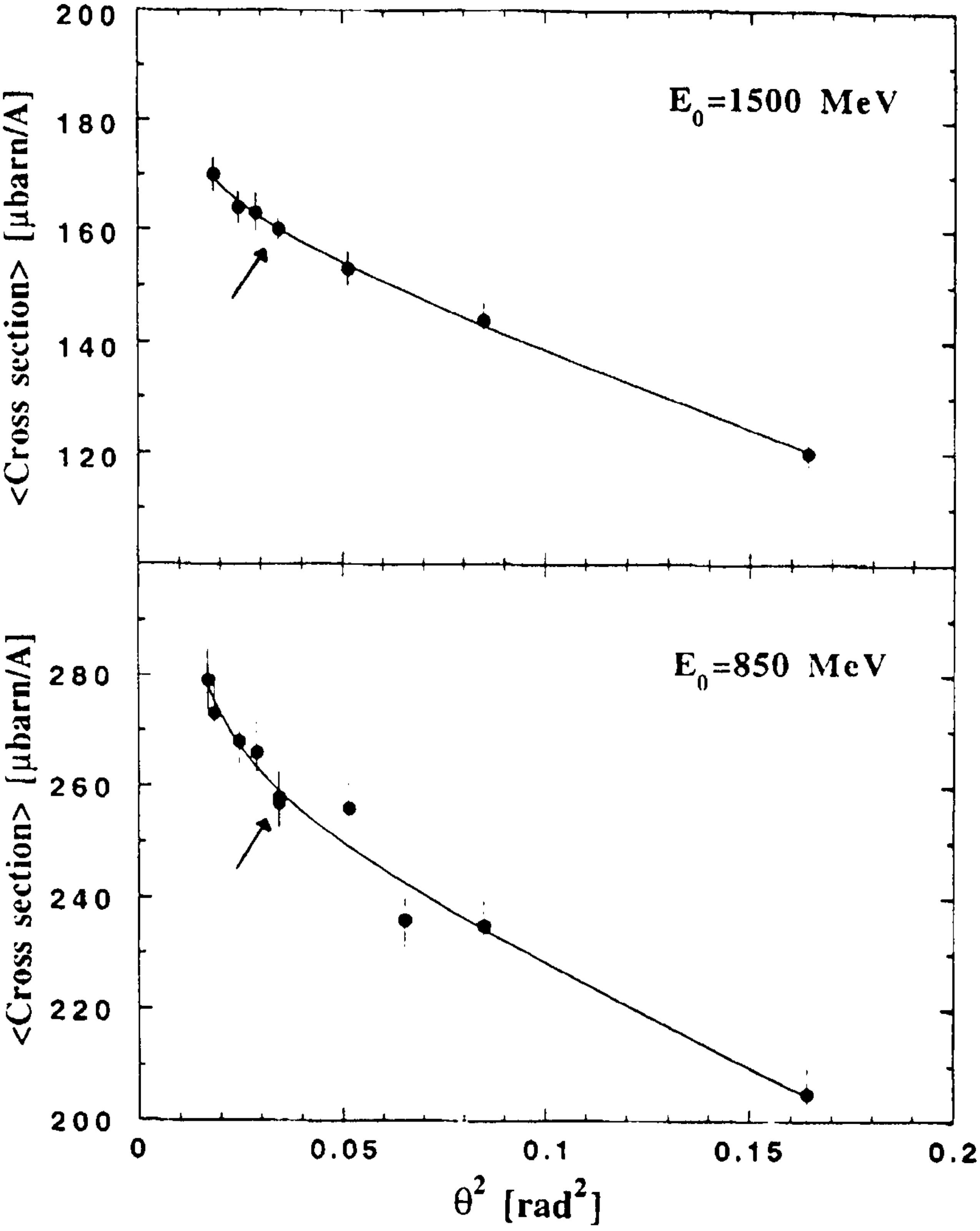

**Fig. 9** On-line cross-section values measured at different positions of the carbon target, as a function of the unmeasured solid angle $\theta^2$ forward of the HD. The cross-section values are fitted by a curve a - b$\theta^2$ + (c/$\theta^2$), described in the text, that takes into account the corrections both for the angular acceptance of the HD and for its contamination by the electromagnetic events not vetoed by the SD.

results by more than 5-6%, and that we estimate the total error to be approximately 5%, broken down as follows:

- Corrections

Loss of hadronic events below the HD threshold: $\approx$ 4%.
Loss of hadronic events above the SD threshold: $\approx$ 1%.
Electromagnetic events contaminating the HD: $\approx$ 3%.
Total maximum correction to on-line data: $\approx$ 5-6%.

- Uncertainties

Photon beam flux: $\delta I_\gamma \approx 2\%$.
Target thickness: $\delta t \approx 2\%$.
Detector efficiency $\delta\varepsilon \approx 3\%$.
Total systematic uncertainty $\approx$ 4%.
Total uncertainty (statistical + systematic) $\approx$ 5% (some are correlated).

### B. Photofission

From the recent measurements performed at Frascati below 1.2 GeV on $^{238}$U and $^{232}$Th, there is evidence that the photofission cross section for $^{238}$U is very nearly as large as its total photonuclear cross section, whereas for $^{232}$Th the fissility shows a clear increase with the energy, approaching approximately 0.8. This means that if a $^{238}$U nucleus absorbs a medium- or high-energy photon, it almost always fissions, and even for $^{232}$Th, fission usually takes place. Since the fission process liberates about 200 MeV in addition to the energy of the incident photon, a fission event is easy to detect with a PPAD. Thus, it is possible to measure the photofission cross section by detecting fission events with a relatively simple and inexpensive detector which can have an efficiency of nearly 100%. Simultaneous measurements on $^{238}$U, $^{237}$Np, and $^{232}$Th will be possible because the thin target foils do not noticeably attenuate the photon beam. PPADs have been used to detect the fission fragments in many photo- and electrofission experiments. Except for problems associated with a pulsed, high-current electron beam, these detectors have performed extremely well, and certainly are the detectors of choice for the experiment proposed here. The PPAD detector system that we are designing for use at CEBAF will be similar to one that we have used previously,[26] and will make use of a sample foil thickness of 0.2 mg/cm$^2$, a voltage of $\approx$ 500 V between the foil and the board of the PPAD, and an equal mixture of argon and isobutane as the filling gas; the pressure and the voltage will be optimized for a maximum signal from the fission fragments. The total solid angle subtended at the target foils by the PPADs will be $\approx 50\%$ of $4\pi$ (since the two fission fragments are emitted nearly back-to-back in the laboratory).

The simplest scheme for performing these measurements is illustrated in Fig. 10(a). Three PPADs, each containing a fission foil for one of the three nuclei under study, are arranged as three independent detectors, with the foils perpendicular to the incident photon beam. This minimizes the foil size, and hence the amount of fissionable material, but also maximizes the amount of necessary beam time. Since the sample foils can be tilted at a small angle with respect to the incident photon beam, thus making them thick to photons while keeping them thin to the emerging fission fragments, a large factor in effective thickness can be readily achieved, resulting in even smaller beam-time requirements. The arrangement shown in Fig. 10(b), with the foils tilted at an angle of arcsin(0.2) = 11.5 deg, uses the beam more efficiently by nearly a factor of five, at the cost of the need to produce larger fission foils. The arrangement shown in Fig. 10(c) improves on this scheme even more by using more PPADs (and foils), and not only improves the counting rate by another factor of nearly three by brute force, but also opens the possibility of studying more than three nuclear species simultaneously ($^{235}$U, for example, is another good candidate for study). It should be noted that every one of the experimental arrangements illustrated in Fig. 10 is compact (less than 40 cm long) so that it would fit into the space occupied by the NaI detector in the photoabsorption experiment, and also would easily fit into the target position in the CLAS, even if the minitoroid is used (to reject unwanted electronic background events). It should be noted as well that because of the thick backings of the target foils, there can be no cross-talk between PPADs; and because of the low true counting rate in any given PPAD, there would be no tracking ambiguity for protons or pions that enter the CLAS from a fission event.

Using a tagged-photon flux of $5 \times 10^7$ sec$^{-1}$, a fission-fragment detector efficiency of 100%, a PPAD solid angle equal to 50%, and a target-foil thickness of 0.2 mg/cm$^2$ in the arrangement depicted in Fig. 10(a), one obtains a counting rate of 0.37 sec$^{-1}$ for $^{238}$U, 0.37 sec$^{-1}$ for $^{237}$Np, and 0.30 sec$^{-1}$ for $^{232}$Th. At this rate, 48 energy bins each with 3% statistics will require about 50 hours of data acquisition. For the arrangement of Fig. 10(b), 2% statistics will require only 23 hours, and 50 hours of data acquisition will result in 1.3% statistics.

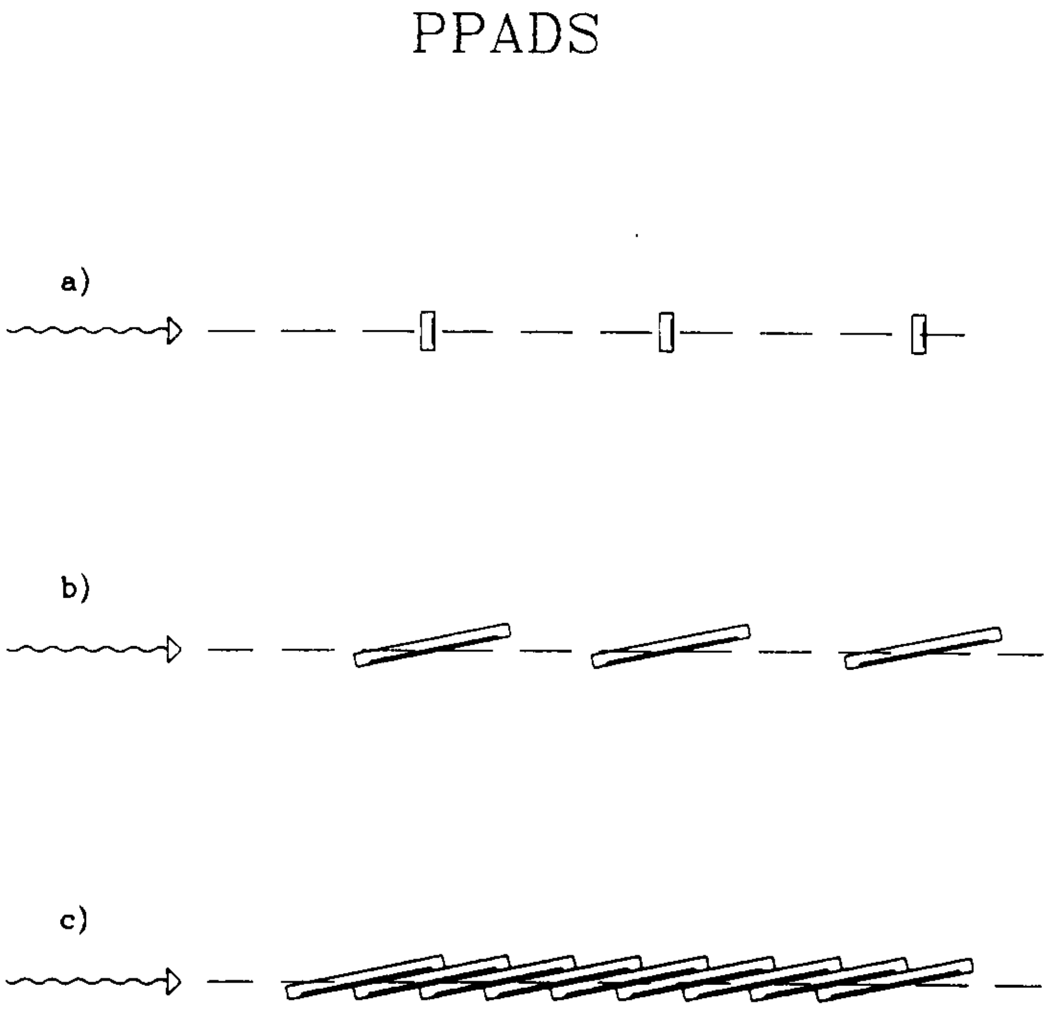

**Fig. 10** Three alternative experimental arrangements for the proposed photofission measurements: (a) with fission foils (and PPADs) perpendicular to the direction of the incident photon beam; (b) tilted at an angle of 11.5 deg; and (c) tilted as in (b) but with 3 times the number of PPADs and foils.

Data runs will be carried out with an electron beam energy of 2 GeV in order to cover the interesting energy range from 0.4 to 1.9 GeV with tagged photons. The 48 timing counters of the photon tagger alone will yield adequate statistics per bin, because high photon-energy resolution is not needed for these measurements.

The space required by the equipment for both of these experiments is less than 2 meters along the beam line, so that the entire facility could be installed between the tagging magnet and the CLAS detector.

We plan to supplement these inclusive measurements when the CLAS becomes operative, both by measuring the exclusive channels within the available acceptance of the spectrometer (as proposed in a previous proposal on measurement of the total hadronic cross section[19]) and by measuring the properties of the non-fission events using the CLAS in anticoincidence with a fission fragment.[27]

## 4. Requirements

a) Incident beam

Electron energy: $E_0 = 2.0$ GeV

Photon energy range: $\Delta k = 0.4\text{-}1.9$ GeV ($0.2\text{-}0.95E_0$)

Photon energy resolution: $\delta k/k \cong 3.3\%$ over the 48 timing counters

Photon beam intensity:

$I_\gamma \cong 5\times10^2$ tagged photons /s-channel for photoabsorption

$I_\gamma \cong 1\times10^6$ tagged photons /s-channel for photofission.

The former will be obtained by defocusing the electron beam and using a carbon-fiber radiator, the latter with a conventional radiator.

Photon beam diameter on the target: $\O_\gamma \cong 1$ cm

b) Photoabsorption targets (to be provided by the Frascati-Genova group)

Nuclei: C, Al, Cu, Sn, Pb

Target thickness: $0.1X_0$

c) Hadron detector (HD) (to be provided by the Frascati-Genova group)

Detector: NaI cylindrical annulus, $\O_{int} = 5$ cm, $\O_{ext} = 21$ cm, length = 32 cm

Solid angle: $\Delta\Omega_{HD} = 98.4\%$ of $4\pi$

Charged-hadron and $\pi^0$ fraction detected: $\varepsilon_{HD} > 96\%$

d) Shower detector (SD) (to be provided by the Frascati-Genova group)

Detector: Lead Glass SF6, of thickness $17X_0$

Solid angle in the forward direction: $\Delta\Omega_{SD} = 13.7$ msr

Electromagnetic fraction: $\varepsilon_{SD} > 99.99\%$

e) Photofission target foils (to be provided by the INR group)

Nuclei: $^{238}$U, $^{237}$Np, and $^{232}$Th, of thickness 0.2 mg/cm$^2$

f) Parallel plate avalanche detectors (PPADs) (to be provided by the GWU and Sao Paulo groups)

Solid angle: $\Delta\Omega_{PPAD} \cong 6.28$ sr

Fission fragment detector efficiency: $\varepsilon_{PPAD} \sim 100\%$

g) Run time

Statistical uncertainty desired: 2% for each nucleus and energy channel for photoabsorption, 3% for photofission (but see above for ways to improve this figure)

| Nucleus | A | t<br>(cm) | $\rho$<br>(g/cm$^3$) | $\sigma$<br>(mb) | rate/h/ch | hours |
|---|---|---|---|---|---|---|
| C | 12 | 1.9 | 1.8 | 1.5 | 460 | 5.5 |
| Al | 27 | 0.89 | 2.7 | 3.3 | 317 | 8.0 |
| Cu | 63 | 0.14 | 9.0 | 7.5 | 162 | 15.5 |
| Sn | 118 | 0.12 | 7.3 | 14 | 112 | 22.5 |
| Pb | 208 | 0.06 | 11.3 | 25 | 88 | 28.5 |
| Th | 232 | $1.7 \times 10^{-5}$ | 11.7 | 24 | 22 | 50 |
| Np | 237 | $0.9 \times 10^{-5}$ | 20.4 | 30 | 25 | simultaneous with Th |
| U | 238 | $1.0 \times 10^{-5}$ | 18.9 | 30 | 25 | simultaneous with Th |
|  |  |  |  |  |  |  |
| Total |  |  |  |  |  | 130 |

Sample-out and sample-blank measurements, backgrounds, hadronic and electromagnetic event-correction runs, PPAD set up: 50 hours

Total run time: 180 hours

# Collaboration

The Frascati-Genova collaboration has considerable experience in performing experiments with real photons in the 100-1200 MeV region. This group has implemented two monochromatic photon beams at Frascati, one from positron in-flight annihilation on a hydrogen target[28] and the other from the tagging of the bremsstrahlung produced on an internal target by electrons circulating in the Adone storage ring.[29] Three different measurements on total photoabsorption cross sections for nuclei have been carried out very recently.[8-10] Moreover, several photofission measurements have been performed with both of the Frascati beams.[30,31]

The George Washington group has extensive experience in performing low- and medium-energy photofission and electrofission measurements at the Livermore, Sao Paulo, and MIT/Bates accelerators,[26,32,33] utilizing a variety of neutron and fission detectors, including PPADs. This group is also involved in the design and construction of the focal-plane detector array for the photon tagger.

B.G. Ritchie is responsible for the readout electronics for the photon tagger.

J.D.T. Arruda Neto has much experience in electrofission measurements, carried out at Sao Paulo and Tohoku, utilizing both fission-track detectors and PPADs.[33,34]

A.S. Iljinov and M.V. Mebel have provided their INC Monte-Carlo code for photofission and photoabsorption and are working to extend it up to 2 GeV. L.A. Kondratyuk and M. Krivoruchenko are working on the theoretical implication of the Frascati results.[12] V. Nedorezov and G. Ya. Kezerashvili have carried out photofission experiments at Novosibirsk.[18]

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