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Level density parameter at the fission saddle point from intermediate-energy photofission cross-section data

O A P Tavares and E L Medeiros

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Level density parameter at the fission saddle point from intermediate-energy photofission cross-section data*

O A P Tavares and E L Medeiros‡

Centro Brasileiro de Pesquisas Físicas - CBPF/MCT
Rua Dr. Xavier Sigaud 150,
22290-180 Rio de Janeiro-RJ, Brazil

Abstract - Nearly four hundred measured photofission cross-section values have been analysed in the framework of the current model for intermediate-energy photofission reactions to systematize the ratio $r = a_f/a_n$ of level density parameter at the fission saddle point, a_f, to that after neutron evaporation, a_n, of excited nuclides. The analysis covers twenty target nuclei extending from ^{27}Al up to ^{237}Np, most of the photofission cross sections of which have been measured in the range ~40–130 MeV at different laboratories during the last fifty years or so. The r-values could be parametrized according to $r = 1 + p/E^{*q}$, where E^* is the excitation energy, and $p > 0$ and $q \geq 0$ are parameters which depend upon the quantity Z^2/A.

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*Dedicated to the memory of Professor Kai C. Chung.

‡Author to whom correspondence should be addressed; e-mail: emil@cbpf.br

1. Introduction

Photofission reactions of heavy nuclei were predicted by Bohr and Wheeler in their pioneer 1939 paper [1] concerning the fission phenomenon. The first photofission experiments at moderate incident energies (bremsstrahlung photon beams of E_γ>50 MeV) were carried out in the early fifties by Bernardini *et al.* [2] (Bi target), Gindler and Duffield [3] (Ta, W, Au, Tl, Pb, Bi, Th, and U targets), Jungerman and Steiner [4] (Au, Bi, Th, and ^{235,238}U targets), and Minarik and Novikov [5] (^{204,206}Tl, Bi, Th, and ^{238}U targets). Since then, a number of measured photofission cross section values have been accumulated from bremsstrahlung-[6–9], and electron-induced [10–14] fission experiments of complex nuclei in the quasi-deuteron region of photonuclear absorption (∼30–140 MeV). The advance of high-energy electron accelerators associated with new techniques of production of monoenergetic (tagged) or quasi-monoenergetic (Compton backscattered, positron annihilation, coherent bremsstrahlung) photons, and the development of high-performance fission-fragment detectors (parallel-plate avalanche, position sensitive, and fission-track detectors) made it possible to obtain quite reliable cross section data at energies up to about 4 GeV [15–45].

On the other hand, most of the above-referenced photofission cross section data have been generally interpreted on the basis of a model which considers firstly the incoming photon interacting with a nucleon or cluster of nucleons (quasi-deuteron) where pions, baryon resonances, and recoiling nucleons initiate a rapid (10^{-23} s) intra-nuclear cascade process during which energy is transferred to other nucleons. Secondary pions and/or other nucleons may be generated inside the nucleus, and some of these particles may escape from or be absorbed by the nucleus. At the end of the cascade process a residual nucleus remains, and after thermodynamic equilibrium is reached, fission may occur as a result of a slow mechanism of competition between particle evaporation (neutron, proton, alpha particle, deuteron, tritium, and others) and fission experienced by the excited cascade residual. This is the so-called two-step, cascade-evaporation model for photonuclear reactions at intermediate ($0.03 \lesssim E_\gamma \lesssim 4.0$ GeV) energies (see, for instance, Refs. [18, 22, 23, 43, 46–50]).

When this current photonuclear model is used to calculate fissility-values (directly or by Monte Carlo methods) we face the problem of choosing the best values for the ratio $r = a_f/a_n$ of level density parameter at the fission saddle point, a_f, to that after neutron evaporation, a_n, to be used in the calculations. Since the final calculated fissilities are very sensitive to the r-values adopted, these have been generally evaluated semiempirically. In a previous paper [51], a detailed systematic analysis of photofissilities covering nearly two hundred experimental data obtained in the quasi-deuteron region (~30–140 MeV) of photonuclear absorption for sixteen target nuclei ranging from Al up to Bi has been performed. By assuming the two-step model as mentioned above, such an analysis enabled the authors to extract reliable r-values semiempirically, thus making it possible to satisfactorily describe the main features of photofissility of complex nuclei at ~30–140 MeV incident energies.

In the present work we extend such a study to actinide target nuclei (^{232}Th, ^{233,235,238}U, and ^{237}Np), for which cases a number of photofission cross section data (essentially from monoenergetic photons) have been also accumulated in the last twenty years [18, 21, 23, 31, 38, 39, 40–44]. Finally, a useful parametrization of r-values as a function of excitation energy and the fission parameter Z^2/A is presented.

2. Photofissility of actinide nuclei in the quasi-deuteron energy region

Nuclear photofissility, f, is the quantity which represents the total fission probability of a given nucleus (Z, A) after absorption of an incident photon of energy E_γ, and it is defined as the ratio of the photofission cross section, σ_f, to the total nuclear photoabsorption cross section, σ_a^T, both quantities being measured at the same photon energy-value, i.e.

$$f\left(Z, A, E_\gamma\right) = \frac{\sigma_f\left(Z, A, E_\gamma\right)}{\sigma_a^T\left(Z, A, E_\gamma\right)} \; . \tag{1}$$

In the photon energy-range which extends from the end of the giant dipole resonance up to the threshold for pi-meson photoproduction (~30–135 MeV) it is believed that the primary nuclear photoabsorption takes place through the interaction of the incoming photon with a neutron-proton pair (quasi-deuteron). This mechanism was first described by Levinger [52], who, afterwards, introduced a damping term to take into account Pauli-blocking effects on low energy final state nucleons [53]. Accordingly, for σ_a^T we can write

$$\sigma_a^T\left(E_\gamma\right) = LZ\left(1 - \frac{Z}{A}\right)\sigma_d\left(E_\gamma\right) f_B\left(E_\gamma\right) \; , \tag{2}$$

where $\sigma_d\left(E_\gamma\right)$ is the total photodisintegration cross section of the free deuteron, the values of which have been taken from a fit to σ_d-data as reported by Rossi *et al.* [54]. A re-evaluation of Levinger's constant, L, of nuclei throughout the Periodic Table [55] gives

$L = 6.8 - 11.2A^{-2/3} + 5.7A^{-4/3}$ ($L \approx 6.5$ for actinide nuclei). Finally,

$$f_B(E_\gamma) = c e^{-D/E_\gamma} , \tag{3}$$

where c is a constant and D is the "damping" parameter, represents the Pauli-blocking function. Both constants c and D can be found semiempirically if one observes that, among the actinides under investigation, ^{237}Np has a relatively low fission barrier ($B_{f_0} =$ 4.63 MeV), and also exhibits the greatest neutron separation energy (S_n = 6.58 MeV) (see Table 1). Therefore, ^{237}Np should have the best chance for fission, a fact which is demonstrated experimentally [23]. In this way, we can say that the photofission cross section for ^{237}Np should represent its total nuclear photoabsorption cross section, i.e.

$$\sigma_f(E_\gamma)_{\mathsf{Np}} = \sigma_a^T(E_\gamma)_{\mathsf{Np}} . \tag{4}$$

This is equivalent to saying that fissility for ^{237}Np is equal to unity and independent on incident energy. By combining (2), (3), and (4), and taking the photofission cross section data in the range 60–130 MeV reported by Sanabria *et al.* for ^{237}Np [23], a least-squares analysis gives $c = 1.93 \pm 0.14$ and $D = 98 \pm 6$ MeV. The errors indicated here come from a combination of the uncertainties associated with σ_d-values (estimated to be ~6%), σ_f-values measured for ^{237}Np (~4%), and the approximation $f = 1$, which is valid for ^{237}Np within ± 3% [23]. Since the Fermi energies for neutron and proton do not vary significantly (less than ~3%) in heavy nuclei the quantity $\sigma_a^T(E_\gamma)$ can be evaluated simply by

$$\sigma_a^T(E_\gamma) = K\sigma_d(E_\gamma)\, e^{-D/E_\gamma} , \tag{5}$$

where $K = cLZ(1 - Z/A)$ is practically constant for the actinides under analysis (the average value is $\overline{K} = 703 \pm 23$, see Table 1). The semiempirical Pauli-blocking function obtained as described above is represented in Fig. 1-a (full line with uncertainties given by the shaded area). To allow a comparison, also shown are the theoretical prediction by Chadwick *et al.* [56] (dashed-line), and the results of a Monte Carlo calculation by de Pina *et al.* [57] (full squares). It is seen that the agreement can be considered satisfactory (within less than ~10%) at energies up to about 80 MeV. As the energy increases from ~80 MeV up to 140 MeV, the present Pauli-blocking function evaluation becomes greater than the Monte Carlo estimates [57] by 12–17%, and greater than the results by Chadwick *et al.* [56] by ~5–14%. The latter two Pauli-blocking evaluations, however, can lead to fissility values larger than unity for the heaviest actinides at energies $E_\gamma \gtrsim 100$ MeV. This is the reason why a semiempirical Pauli-blocking function was chosen. Finally, the total nuclear photoabsorption cross section for actinides as given by (5) is depicted in Fig. 1-b in the energy-range 30–140 MeV. The σ_a^T-values from this curve, and the associated uncertainties (shaded area), are used together with the measured σ_f-values in definition (1) to obtain the experimental fissilities for the actinide nuclei under investigation.

3. Semiempirical values of $\mathrm{r} = \mathrm{a_f}/\mathrm{a_n}$

Following the generally accepted, current two-step model for moderate-energy (~ 30–140 MeV) photofission reactions, a quantitative description of the reaction steps aiming to obtain the nuclear fissility has been presented to some detail in a previous paper [51]. Briefly, fissility is given by the product of the average probability of formation of a residual nucleus (Z^*, A^*) with a certain excitation energy E^*, $\overline{p}_i\,(Z^*, A^*, E^*)$, times the total fission probability for this residual, $P_{f_i}^t\,(Z^*, A^*, E^*)$, summing up all possible modes of formation of residual nuclei, i.e.

$$f\,(Z, A, E_\gamma) = \sum_{i=0}^{3} \overline{p}_i\,(Z^*, A^*, E^*) \times P_{f_i}^t\,(Z^*, A^*, E^*)\ , \quad \sum_{i=0}^{3} \overline{p}_i = 1\ . \tag{6}$$

The probabilities of formation of residuals, $\overline{p}_i\,(Z^*, A^*, E^*)$, depend essentially upon the nuclear transparencies to the photodissociated neutron, $\tau_{n^*}\,(T_{n^*})$, and proton, $\tau_{p^*}\,(T_{p^*})$, in their final states (T_{n^*} and T_{p^*} are the final neutron and proton kinetic energies, respectively, which result from the quasi-deuteron photointeraction inside the nucleus). The index i specifies the four modes of formation of residual nuclei, namely, $p_0 = \tau_{n^*}\tau_{p^*}$ (escaping of both neutron and proton), $p_1 = \tau_{n^*}(1 - \tau_{p^*})$ (neutron escapes at the same time as the proton remains within the nucleus), $p_2 = \tau_{p^*}(1 - \tau_{n^*})$ (proton escapes with retention of the neutron), and $p_3 = (1 - \tau_{n^*})(1 - \tau_{p^*})$ (simultaneous retention, i.e. non-escaping, of both neutron and proton). In this latter case the residual formed is the target nucleus (Z, A) itself excited to $E^* = E_\gamma$ (for details see [49,51]). Nuclear transparencies are thus the chief quantities to be used in evaluating in what proportion different residual nuclei (and their respective excitation energies) are formed following the quasi-deuteron primary photo-interaction $\gamma+$ (n-p) $\longrightarrow$ n* + p*. It has been shown that the mode of nuclear excitation following retention of both nucleons ($E^* = E_\gamma$) is the most probable one [51], this result being also valid for actinide targets.

On the other hand, the total fission probability of excited residuals, $P_{f_i}^t$, emerges from the fission-evaporation competition process which describes the de-excitation of the residuals. Along with neutron emission, proton and alpha-particle emissions may also compete with the fission mode, especially for pre-actinide and less-massive nuclei. This is because their ground-state fission barriers, B_{f_0}, are much greater than the respective particle separation energies (see Table 1). In addition, the successive chance-fission probabilities should be considered along the evaporation chain. However, it has been verified (and, thus, generally used) that the total fission probability of residuals is governed, to a good approximation, by their first-chance fission probability [51]. This latter quantity is given by

$$f_1 = \frac{F}{1+F+G+H} , \tag{7}$$

in which F, G, and H denote, respectively, the probability of fission, proton emission, and alpha-particle emission relative to neutron emission, and they are functions of Z, A, and E^* of the fissioning nucleus. Expressions for the quantities F, G, and H (given explicitly in [49]) result from the statistical model of particle evaporation from excited nuclei as proposed by Weisskopf [58], and the liquid drop model for fission by Bohr and Wheeler [1] (subsequently developed by Vandenbosch and Huizenga [59]). Accordingly, the values for $r = a_f/a_n$ arise from the solution of equation (7), which gives

$$a\sqrt{r} - \ln\sqrt{r} - b = 0 , \tag{8}$$

where

$$a = \left\{4a_n E^* \left[1 - B_{f_0}\left(\frac{1}{E^*} - \frac{1}{B}\right)\right]\right\}^{1/2} \tag{9}$$

$$b = \left[4a_n\left(E^* - S_n\right)\right]^{1/2} + \ln\left[\frac{4\left(1+G+H\right)A^{2/3}\left(E^* - S_n\right)}{15a\left(\frac{1}{f_1} - 1\right)}\right] , \tag{10}$$

valid for photon energies $E_\gamma \gtrsim B_{f_0}$. (In Eq. (9), B represents the total nuclear binding energy.)

For non-actinide nuclei, fissility-values, f (calculated or coming from the experiment), are related to f_1 through $f(Z, A, E_\gamma) \approx 2\overline{p} f_1(Z, A, E_\gamma)$, where $\overline{p}$ is the average probability for non-escaping of both neutron and proton from the target nucleus [51]. For actinides, in turn, the approximation $f(Z, A, E_\gamma) \approx f_1(Z, A, E_\gamma)$ can be considered quite satisfactory. This is because the term $\overline{p}_3 P_{f_3}$ in (6) largely predominates over the other contributions to fission (in particular, $\overline{p}_0 P_{f_0} = 0$). In addition, since the height of the effective fission barrier ($B_f = B_{f_0}(1 - E^*/B)$) for actinides is less than their respective neutron separation energy, S_n, by 1 MeV or more (see Table 1), the chance for successive neutron evaporation becomes small, therefore, favoring strongly the first-chance fission probability. Besides, the relatively high values of the effective Coulomb barrier for protons (~10 MeV) and alpha particles (~20 MeV) make negligible the emission of these charged particles during the competition with fission, therefore, leading to $G = H = 0$.

In both the previous [51] and present analyses, we adopted for the level-density parameter of the residual nucleus after neutron evaporation the expression

$$a_n = \widetilde{a}\left\{1 + [1 - \exp(-0.051E^*)]\frac{\Delta M}{E^*}\right\} \tag{11}$$

proposed by Iljinov *et al.* [60]. Here, ΔM (expressed in MeV) is the shell correction in the calculated nuclear mass as tabulated in [61], and

$$\widetilde{a} = 0.114A + 0.098A^{2/3}\ \ \mathrm{MeV}^{-1} \tag{12}$$

is the asymptotic value of a_n (a small correction on E^* due to pairing energy effects has been neglected in (11)). The constants which appear in (12) are adjustable parameters resulting from the phenomenological systematics of the level densities studied for several hundred excited nuclides without considering collective effects (for details see [60]). Finally, the values of particle separation energies, S_i ($i = \mathrm{n, p}, \alpha$), the quantities B_{f_0} and ΔM, and total nuclear binding energy, B, can be appreciated in Table 1 for various target nuclei investigated.

4. Results and discussion

The values of $r = a_f/a_n$ obtained by means of the routine calculation described in the precedent section have been reported for non-actinide nuclei in [51]. Results could be fitted to a general expression of the form

$$r = 1 + \frac{p(Z,A)}{E^{*q(Z,A)}}\ , \tag{13}$$

in which $p > 0$ and $q > 0$ are constants determined by least-squares analyses, and E^* is expressed in MeV. The p- and q-values resulting from nearly two hundred semiempirical determinations of r-values are tabulated for sixteen nuclei ranging from Al to Bi [51]. Figure 2 reports a sample of these results.

For the actinide nuclei here analysed, in turn, results are depicted in Fig. 3, which shows that the semiempirical r-values (points) are distributed around an average value $\overline{r}$ (weighted average, horizontal lines) for each target nucleus. This means that, for photon energies $E_\gamma \geq 40$ MeV, the ratio $r = a_f/a_n$ can be considered independent (within less than 3% deviation) on excitation energy, thus giving $q(Z, A) = 0$ in Eq. (13) for all actinides. In addition, the average a_f/a_n-values are found to fit the least-squares straight line

$$\bar{r} = 1 + \alpha\left(Z^2/A - \beta\right) , \tag{14}$$

where $\alpha = 0.030 \pm 0.004$ and $\beta = 34.0 \pm 0.2$ ($\chi^2_\nu = 0.50$), which is valid for actinides of $Z^2/A > 34.0$. The $\bar{r}$-values evaluated from Eq. (14) ($1.0 < \bar{r} \lesssim 1.1$) can be thought as the asymptotical values of the ratio a_f/a_n for actinide nuclei, in the sense that r does not vary anywhere from 40 MeV on, and, in these cases, $p(Z, A) = \alpha(Z^2/A - \beta)$.

Finally, the p- and q-values for all complex nuclei studied up to now (excepting ^{178}Hf) are plotted as function of parameter Z^2/A (Fig. 4, full circles). Preliminary trends for both parameters p and q are represented by the lines (drawn by eye) passing through the points. These trends seem to indicate the existence of shell effects near 82- and 126-neutron shell closures. These may be probably related to the enhancement of the height of the fission barriers at these neutron shell closures. However, we remark that the number of target nuclei considered so far in such an analysis is still very scarce (only a total of 20 target nuclei!), thus making difficult to define a quite reliable correlation of p and q with parameter Z^2/A in the entire mass region from Al to Np (in particular, results for ^{178}Hf have been not considered in Fig. 4 for its q-value was ~30% lower than the expected, and the p-value differed by more than one order of magnitude from the expected). Besides, it is known that intermediate-energy photofission cross section data for target nuclei in the Z^2/A intervals ~12.0–24.0 (cobalt–cerium) and ~33.0–34.8 (polonium–actinium) are not available at all in the literature. In spite of such physical limitations, however, we may use for the time being values for the ratio a_f/a_n as parameterized by Eq. (13) with parameters p and q defined by the trends depicted in Fig. 4. Such a_f/a_n-ratios may be used, for instance, in obtaining photofissilities at intermediate-energy of nuclei not yet experimentally investigated, or in refined Monte Carlo (or direct) calculations of the fission-evaporation competition process for highly excited residual nuclides.

Figure 4 shows also a change in slope both in p and q parameters at $Z^2/A \approx 35$. This behavior may be related to a change in slope in the fission barrier height near ^{232}Th, which is clearly seen when the fission barriers are plotted against Z^2/A. The fission barrier heights mentioned here are the calculated macroscopic component of the barrier plus the shell effect correction for the ground-state nuclear mass, as reported by Itkis *et al.* [62].

5. Conclusion

In the course of the present work, the available experimental data on photofission cross section for ^{232}Th, ^{233,235,238}U, and ^{237}Np nuclei measured with monochromatic photons in the quasi-deuteron energy range (~40–130 MeV) have been used to deduce semiempirical values for the level density parameter ratio $r = a_f/a_n$. The current, two-step (primary quasi-deuteron photoabsorption followed by the evaporation-fission competition process) model for moderate-energy photofission reactions has been the model assumed throughout. The r-values obtained in this way are found not to vary significantly with excitation energy in the range considered here. The average $\overline{r}$-value has been found to increase with increasing of parameter Z^2/A according to $\overline{r} = 1+\alpha\,(Z^2/A - \beta)$, where $\alpha = 0.030 \pm 0.004$ and $\beta = 34.0 \pm 0.2$. This result (valid for all actinide targets) and previous ones for non-actinide nuclei as well [51] have been systematized by a two-parameter formula of the type $a_f/a_n = 1+p\,(Z,A)\,/E^{*q(Z,A)}$. When plotted against Z^2/A, both parameters p and q seem to exhibit structures around the neutron numbers $N = 82$ and $N = 126$ (Fig. 4), which may be due to shell effects at these neutron-shell closures. Unfortunately, the number of nuclei so far investigated is still too small to allow for a better definition of the trends for $p\,(Z^2/A)$ and $q\,(Z^2/A)$. However, we believe that the present parameterization of the semiempirical a_f/a_n-values can be used advantageously in direct and/or Monte Carlo calculations aiming to evaluate fissilities of various nuclear photoreactions.

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Table 1: Values of the nuclear quantities used to systematize the level-density parameter ratio $r = a_f/a_n$.

Target nucleus	Z^2/A	K^b	$\triangle M^c$ (MeV)	$B^c_{f_0}$ (MeV)	S^d_n (MeV)	S^d_p (MeV)	S^d_α (MeV)	B^e (MeV)	$\tilde{a}^f$ (MeV^{-1})
^{27}Al	6.26	38	−1.46	42.20	13.06	8.27	10.09	225	3.960
$^{48}Ti^a$	10.08	71	0.27	49.30	11.63	11.44	9.44	419	6.766
^{51}V	10.37	76	−1.56	52.80	11.05	8.06	10.29	446	7.162
– – –	– – –	– – –	– – –	– – –	– – –	– – –	– – –	– – –	– – –
^{154}Sm	24.96	238	0.89	41.20	7.97	9.09	1.20	1267	20.372
^{174}Yb	28.16	270	−1.33	31.71	7.46	7.98	−0.74	1407	22.890
$^{178}Hf^a$	29.12	277	−1.08	28.73	7.63	7.34	−2.08	1433	23.393
^{181}Ta	29.44	281	−1.60	26.93	7.58	5.94	−1.52	1452	23.770
$^{184}W^a$	29.76	286	−1.77	25.23	7.41	7.70	−1.66	1473	24.146
$^{186}Re^a$	30.24	289	−2.16	23.51	6.18	5.83	−2.08	1484	24.397
$^{190}Os^a$	30.40	295	−2.81	22.79	7.79	8.02	−1.38	1513	24.899
$^{195}Pt^a$	31.20	303	−4.79	22.12	6.10	7.57	−1.16	1546	25.525
^{197}Au	31.68	306	−6.08	21.81	8.07	5.78	−0.95	1559	25.776
$^{204}Tl^a$	32.16	316	−10.87	23.07	6.65	6.36	−0.49	1607	26.652
^{208}Pb	32.33	322	−13.42	24.36	7.37	8.01	−0.52	1636	27.152
$^{207}Pb^a$	32.48	321	−13.12	23.68	6.74	7.49	−0.39	1629	27.027
^{209}Bi	32.96	325	−12.18	22.37	7.46	3.80	−3.14	1640	27.277
– – –	– – –	– – –	– – –	– – –	– – –	– – –	– – –	– – –	– – –
^{232}Th	34.91	692	−0.25	5.23	6.44	7.76	−4.08	1767	30.148
^{238}U	35.56	709	−1.16	4.92	6.15	7.62	−4.27	1802	30.896
^{235}U	36.02	703	−0.80	4.77	5.30	6.71	−4.68	1784	30.522
^{233}U	36.33	699	−0.51	4.60	5.76	6.31	−4.91	1772	30.273
^{237}Np	36.49	710	−1.13	4.63	6.58	4.86	−4.96	1795	30.771

[a] Mean mass number of the naturally occurring isotopes.

[b] This is given by $K = cLZ(1 - Z/A)$, where $c = 1.0$ for non-actinide nuclei (see [49]).

[c] Values taken from the tables by Myers [61].

[d] Tabulated values in [63].

[e] Tabulated values in [64].

[f] See Eq. (12).

Figure Captions

Fig. 1 Pauli-blocking function, $f_B(E_\gamma)$ (part a), and total nuclear photoabsorption cross section, $\sigma_a^T(E_\gamma)$ (part b), for actinides plotted versus photon energy, E_γ. In a) the full line is the result of the present analysis (Eq. (3)), and the shaded region is the associated uncertainty; the dashed-line represents the prediction by Chadwick *et al.* [56], and full squares are the results by a Monte Carlo calculation by de Pina *et al.* [57]. The curve in b) represents $\sigma_a^T(E_\gamma)$ defined by Eq. (5) in the text, and the shaded area is the associated untertainty.

Fig. 2 Level density parameter ratio, $r = a_f/a_n$, plotted against excitation energy for a choice of nuclei as indicated. For the sake of better clarity we choose to represent $r-1$ versus E^* in log $\times$ log scales following Eq. (13). Points represent semiempirical r-values from photofissility data as quoted in [51], and the straight lines are best fits to the points. Error bars are less than the symbol size.

Fig. 3 Semiempirical r-values obtained for various actinides as indicated. The horizontal lines represent the weighted average r-values, and the shaded areas their associated uncertainties (within 2σ). Different symbols refer to different photofission experiments from which the r-values have been deduced: ○, Ref. [43]; □, Ref. [31]; ●, Ref. [23]; ◇, Ref. [41]; ▲, Ref. [18]; ▽, Ref. [21]; ▼, Ref. [39]; ◆, Ref. [38]; ■, Ref. [44]; ★, Ref. [42].

Fig. 4 Dependence of parameters p (part a) and q (part b) in Eq. (13) on Z^2/A. Points represent results of the present analysis for actinides ($Z^2/A \gtrsim 34.0$), and of the previous study [51] for pre-actinide ($31.0 \lesssim Z^2/A \lesssim 34.0$), intermediate-mass ($24.0 \lesssim Z^2/A \lesssim 31.0$), and less-massive ($6.0 \lesssim Z^2/A \lesssim 24.0$) complex nuclei. The lines (drawn by eye) are to indicate the trends of p and q. For the majority of cases the error bars ($\lesssim$10% in p and $\lesssim$3% in q) become unseen.

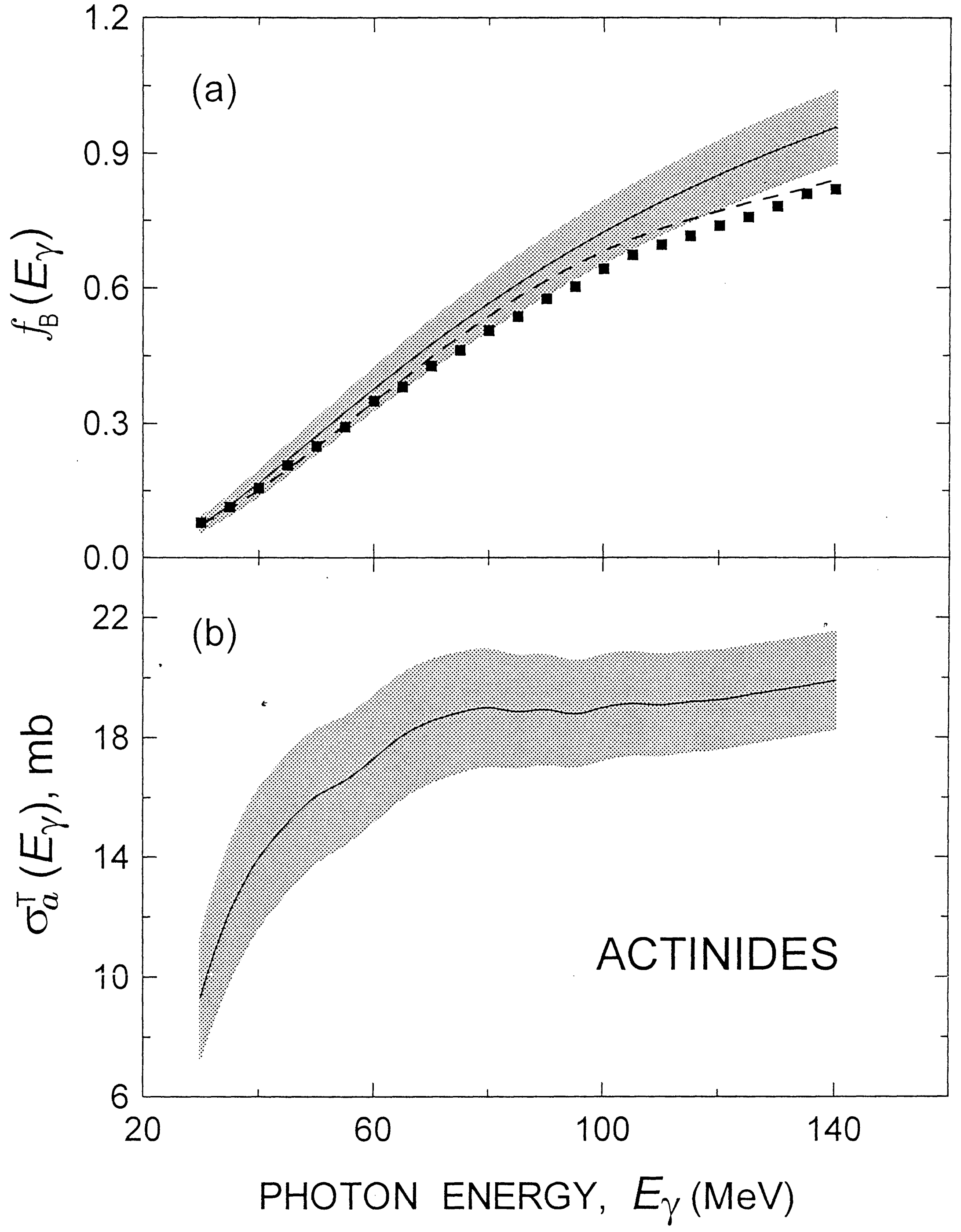

(a)
(b)
1.2
0.9
0.6
0.3
0.0
22
18
14
10
6
20
60
100
140
$f_B(E_\gamma)$
$\sigma_a^T(E_\gamma)$, mb
ACTINIDES
PHOTON ENERGY, E_γ (MeV)

Fig. 1

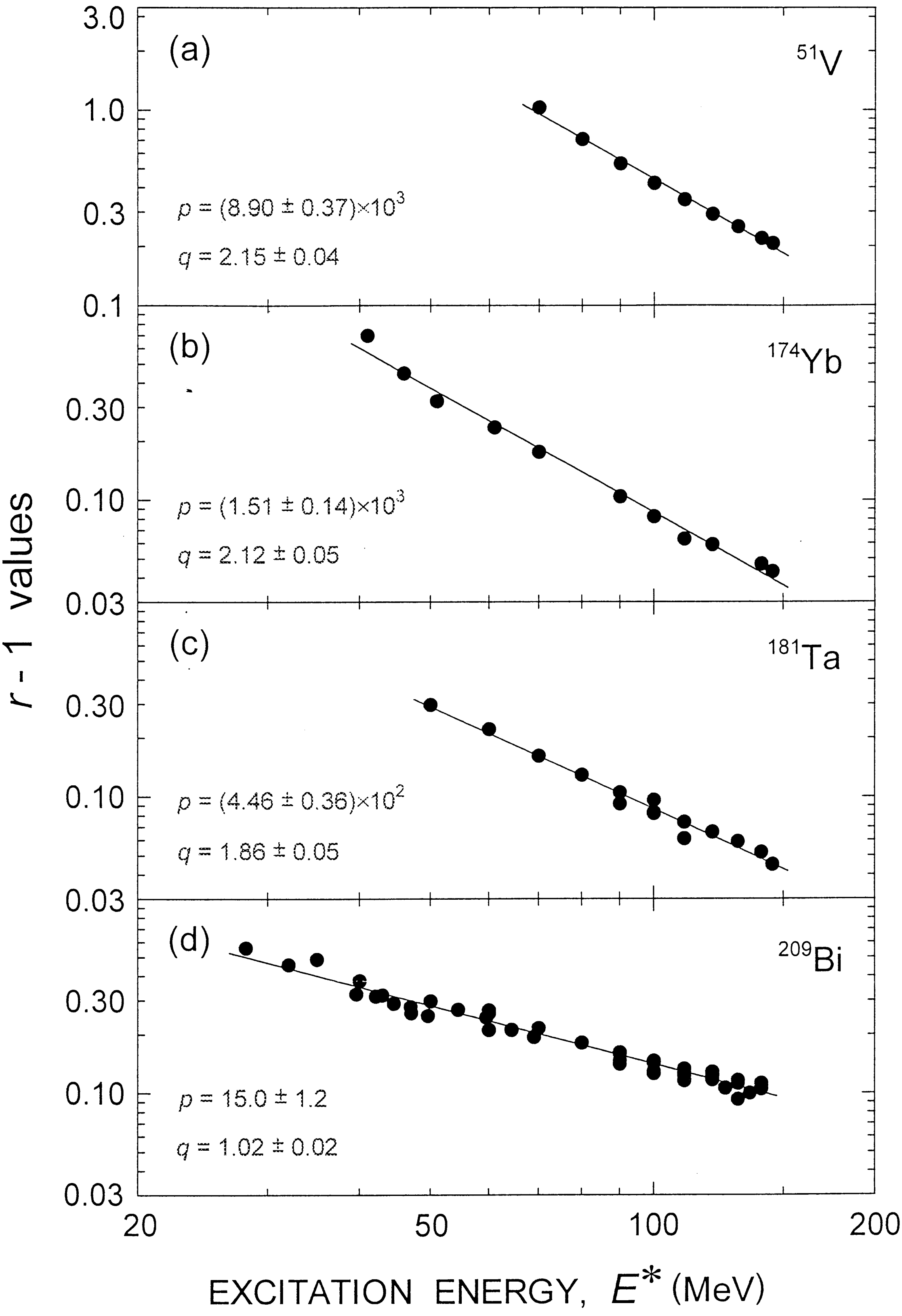
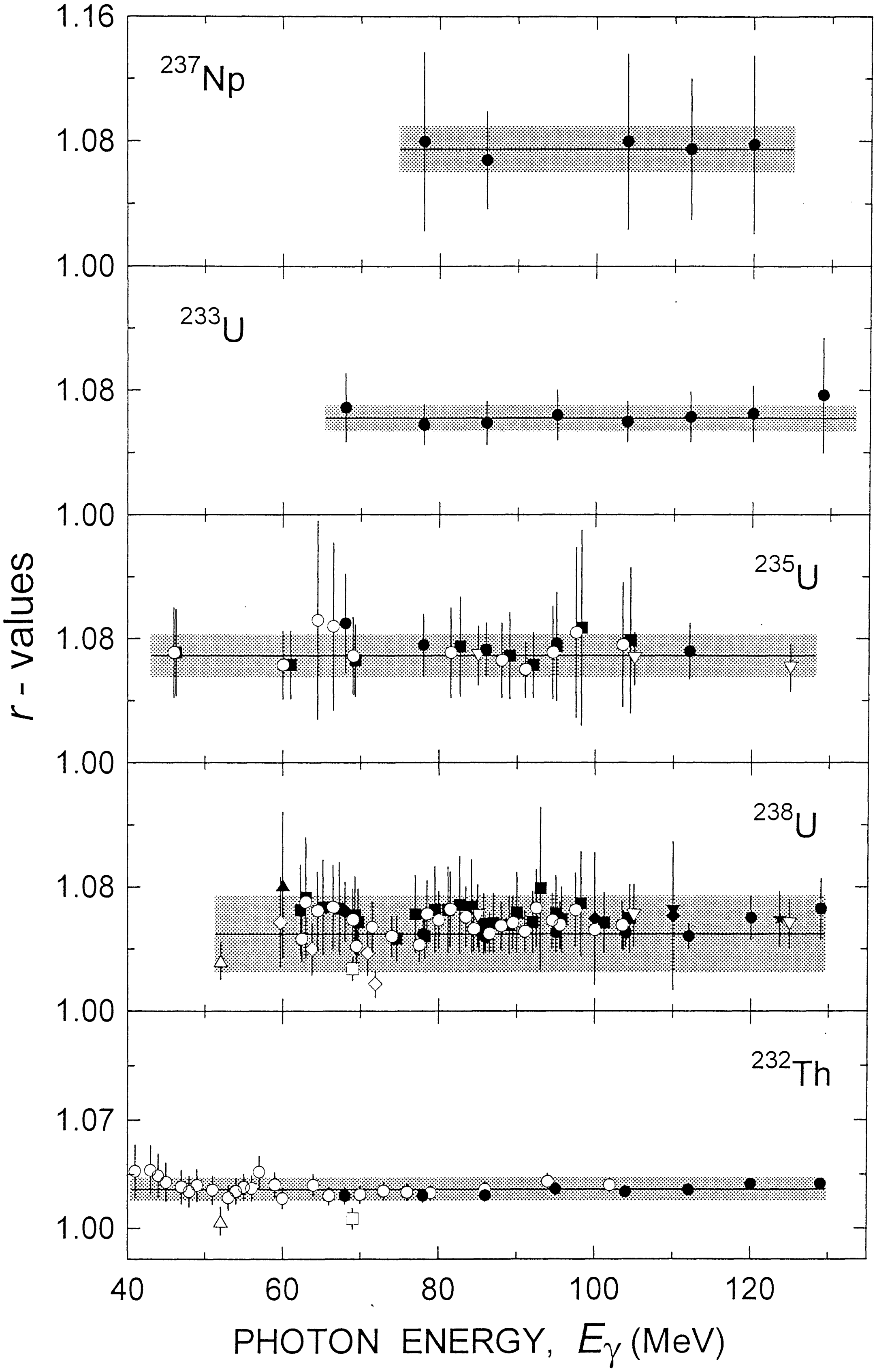
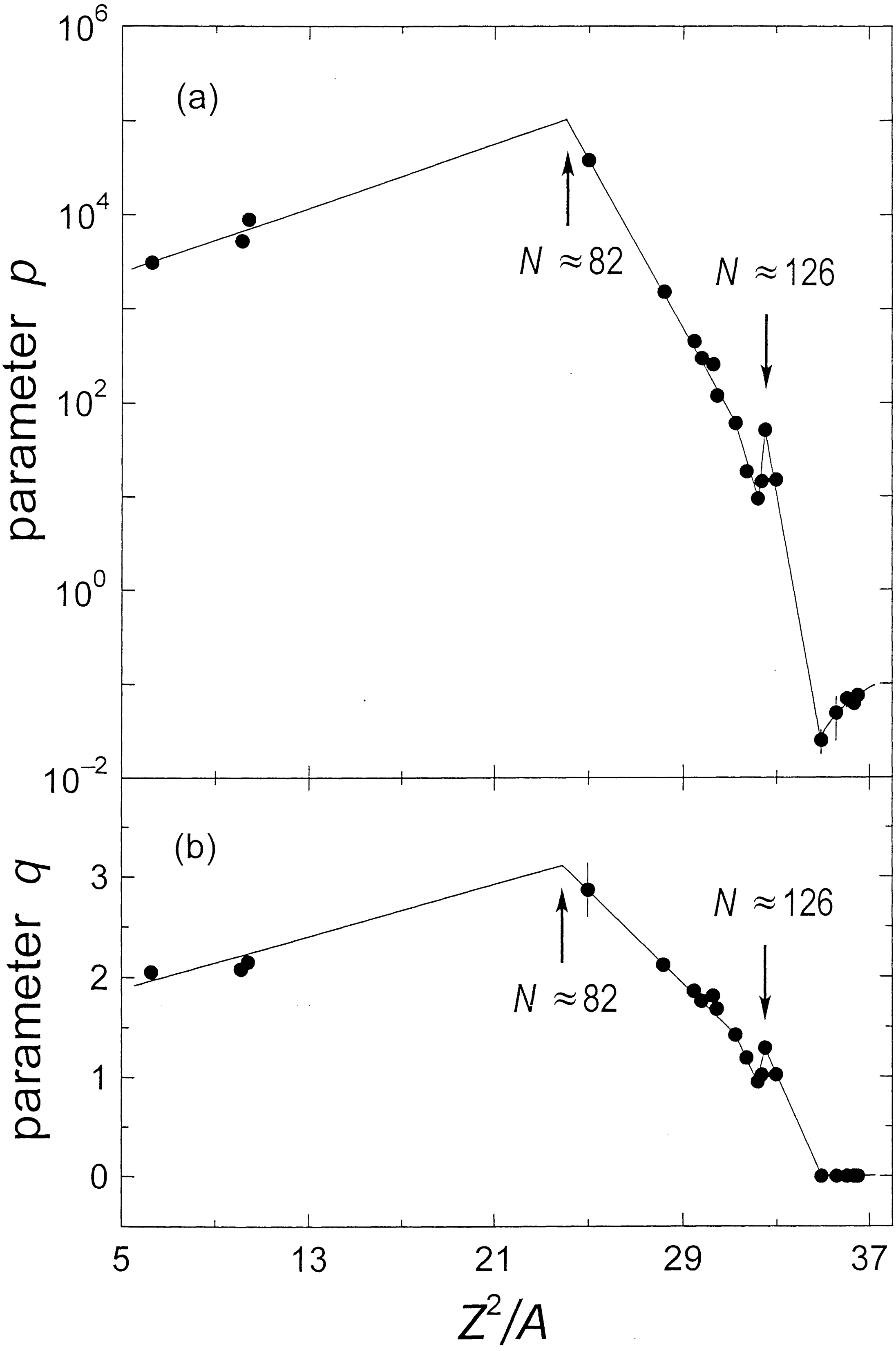

3.0
1.0
0.3
0.1
(a)
^{51}V
p = (8.90 ± 0.37)×10^3
q = 2.15 ± 0.04
(b)
^{174}Yb
0.30
0.10
0.03
p = (1.51 ± 0.14)×10^3
q = 2.12 ± 0.05
(c)
^{181}Ta
p = (4.46 ± 0.36)×10^2
q = 1.86 ± 0.05
(d)
^{209}Bi
p = 15.0 ± 1.2
q = 1.02 ± 0.02
r - 1 values
20
50
100
200
EXCITATION ENERGY, E* (MeV)

Fig. 2



1.16
1.08
1.00
1.08
1.00
1.08
1.00
1.08
1.00
1.07
1.00
^{237}Np
^{233}U
^{235}U
^{238}U
^{232}Th
r - values
40
60
80
100
120
PHOTON ENERGY, E_γ (MeV)

Fig. 3



(a)
parameter p
10^6
10^4
10^2
10^0
10^{-2}
N ≈ 82
N ≈ 126
(b)
parameter q
3
2
1
0
5
13
21
29
37
Z^2/A

Fig. 4