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MEASUREMENT OF THE s-WAVE CONTRIBUTION TO 2p-LEVEL SHIFTS IN PIONIC ATOMS

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ABSTRACT

Energies and widths of pionic 3d-2p transitions of $_{30}Zn$, $_{32}Ge$, and $_{33}As$ have been measured with a Ge detector. The values of the 2p shifts obtained from the measurement $\varepsilon_{2p}(Zn) = 7.0 + 1.4$ keV, $\varepsilon_{2p}(Ge) = 5.5 +$ $+ 0.9$ keV, and $\varepsilon_{2p}(As) = 4.6 + 0.9$ keV show a decreasing behaviour for large Z, which is caused by an increasing s-wave contribution as predicted by theory.

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1. INTRODUCTION

The π-nucleus interaction is repulsive in the s-wave and attractive in the p-wave, resulting in energy shifts of opposite sign for s-levels and p-, d-, and higher levels in pionic atoms. Attractive 2p-level shifts had been observed in elements with $13 \leqq Z \leqq 30$ [1]. However, the experimental error of the shift ε increased with increasing Z ($\varepsilon = 8.5 \pm 3$ keV for Z = 30). This large error was caused by the rapidly decreasing line intensity due to increasing absorption from the 3d-level and the increasing line width of the 3d-2p transition, both of which make the determination of the line position more difficult, and above Z = 30 impossible. Since in a 2p-level also the s-wave contributes according to the overlaps of the pion wave function with the nucleus, one might expect increasing influence of the repulsive s-wave interaction with increasing Z, owing to the increasing overlap. From an optical potential model, Krell and Ericson[2] predicted a change from attraction to repulsion in 2p-levels for $Z \simeq 36$.

In contrast to Leon et al.[3], we have tried to observe this behaviour directly by measuring the 2p-level shift in pionic atoms. We have succeeded in taking measurements for elements with Z = 30, 32, and 33. This should show whether the attractive shift increases further beyond Z = 30, or whether a tendency towards smaller shifts appears as required if a change towards a repulsive interaction occurs. The progress in detector techniques, in particular the improved time resolution, has made such measurements possible.

2. EXPERIMENT

The experiment was performed at the muon channel of the 600 MeV CERN Synchrocyclotron. The experimental set-up was standard; it consisted of a scintillation counter telescope to define the incoming beam, which contained pions and muons from the forward decay. A Čerenkov counter reduced the electron background. Pions and muons were separated by their different ranges in a carbon absorber. A stop rate of 10^5 per second in targets of about 7.5 g/cm^2 thickness has been obtained, containing, besides pions, about 5% stopping muons. The X-ray transitions of the muonic atoms could be used as calibration lines. All targets used were of a metallic type: Zn was in plates, and Ge and As in powder, which was packed in a lucite container. The X-rays were detected in a semiplanar Ge(Li) detector with an area of 15 cm^2 and a thickness of 1 cm. The in-beam resolution was about 2 keV at 595 keV. The coincidence width between the Ge detector pulses and the π-stop trigger could be made 3.5 nsec wide without losing too many of the X-rays from the energy region of interest. This sharp timing condition eliminates mainly the neutron background by time of flight, and this was the main reason for the success in measuring these very weak transitions. Figure 1 shows the X-ray spectra of pionic Ge and As in the energy region of interest. Besides the broad 3d-2p transition line, a variety of lines are seen, which come partly from the inelastic neutron scattering in the Ge detector and from induced reactions in the targets.

3. EVALUATION AND RESULTS

The lines of the spectrum were fitted by means of a computer program[4]. They were assumed to have a Gaussian shape, which represented the experimental resolution. The 3d-2p transitions were fitted by folding a Gaussian shape with a Lorentzian shape. The energies of the pionic lines were calibrated with $3d_{5/2}$-$2p_{3/2}$ and $3d_{3/2}$-$2p_{1/2}$ muonic X-ray transitions, the e^+e^- annihilation radiation, and identified nuclear gamma-rays from Ge. The muonic calibration energies were calculated including finite size shift, vacuum polarization, and higher corrections. The energies of the identified nuclear gamma-rays were measured by Weishaupt et al.[5]. It was necessary to fit a 30 keV broad bump at 611 keV, which originated from inelastic scattered neutrons on the Ge of the detector. The experimental results are shown in Table 1.

Table 1

Pionic 3d-2p transitions

Z^N (1)	E_{exp} [keV] (2)	ΔE_{stat} [keV] (3)	ΔE_{tot} [keV] (4)	E_{el} [keV] (5)	Shift [keV] (6)	Γ^{exp}_{2p} [keV] (7)	$\Delta\Gamma^{stat}_{2p}$ [keV] (8)	$\Delta\Gamma^{tot}_{2p}$ [keV] (9)
$_{30}$Zn	476.8	±0.4	±1.4	469.805	7.0 ± 1.4	15.6	±1.4	±4
$_{32}$Ge	540.3	±0.4	±0.9	534.828	5.5 ± 0.9	18.5	±2.0	±2.5
$_{33}$As	573.5	±0.3	±0.9	568.849	4.6 ± 0.9	14.5	±1.7	±4.0

The total error in columns 4 and 9 contains, in addition to the statistical error and the error in calibration, the uncertainty due to the insensitive fit procedure for such broad lines. In Table 2 this point is demonstrated for the extreme situation of $_{33}$As. This effect was less for $_{30}$Zn and $_{32}$Ge.

Table 2

The variation of the strong interaction shifts and χ^2 by changing the width of the 3d-2p transition of pionic As.

Shift [keV]	Γ_{2p} [keV]	χ^2
4.5 ± 0.18	6.6	366
4.54 ± 0.2	8.8	342
4.59 ± 0.3	13.2	323
4.6 ± 0.3	14.5	321
4.67 ± 0.4	17.5	325
4.89 ± 0.5	21.9	339

The strong interaction shifts (Table 1, col. 6) are defined as the difference between the experimental energy and the energy calculated with pure electromagnetic interaction. The calculated energies include corrections for finite size shift, vacuum polarization, and higher-order corrections.

4. COMPARISON OF THE STRONG INTERACTION SHIFTS AND WIDTHS WITH THEORETICAL PREDICTION

The gross behaviour of the strong interaction effects, shifts of energy levels, as well as natural line widths and reductions of X-ray transition intensities as a consequence of the strong absorption of the pions by the nucleus, are well described by optical potential with a local part (s-wave interaction) and a non-local part (p-wave interaction), as derived by Ericson and Ericson[6]. We have used it in the following form:

$$-2\mu V(r) = 4\pi\left(\left\{p_1 b_0 \rho(r) + p_1 b_1\left[\rho_n(r) - \rho_p(r)\right] + p_2 \text{ Im } B_0 \rho^2(r)\right\} + \right.$$

$$\left. + \nabla \frac{q(r)}{1 + (4\pi/3)q(r)} \nabla + 0(1/A)\right\}\Bigg) ,$$

where $q(r)$ and $\rho(r)$ are given by

$$q(r) = p_1^{-1} c_0 \rho(r) + p_1^{-1} c_1\left[\rho_n(r) - \rho_p(r)\right] + p_2^{-1} \text{ Im } C_0 \rho^2(r)$$

$$\rho(r) = \rho_n(r) + \rho_p(r) ;$$

p_1 and p_2 are kinematical factors. $\rho_n(r)$ was assumed to be proportional to $\rho_p(r)$ as obtained by electron scattering, and the optical potential parameters were taken from a fit[7] to all then available data. This potential was inserted into the

Klein-Gordon equation, which was then solved in order to obtain shifts and widths of the 2p-levels of interest. These solutions together with earlier experimental results[1] are shown in Fig. 2a. The same is done in Fig. 2b for the 2p-level widths.

In conclusion, our data show clearly the predicted compensation of the attractive p-wave interaction by the repulsive s-wave pion-nucleon interaction.

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Figure captions

Fig. 1 : Pionic X-ray spectra of ${}_{32}Ge$ and ${}_{33}As$. Above the broad lines one sees some sharp lines. Possible interpretation for those indicated are:

Ge: (1) 531.5 keV nuclear gamma from ${}^{74}Ge$, ${}^{69}Ga$, ${}^{73}Ge$

(2) 544.0 keV and 554.2 keV μGe (4-2)

(3) 572 keV nuclear gamma from ${}^{71}Ge$, ${}^{69}Ga$

(4) 595.8 keV nuclear gamma from ${}^{74}Ge$, ${}^{71}Ga$, used for calibration

As: (1) 573.3 keV nuclear gamma of ${}^{71}Ge$ (571.5 keV)

${}^{71}Ge$ (574.2 keV)

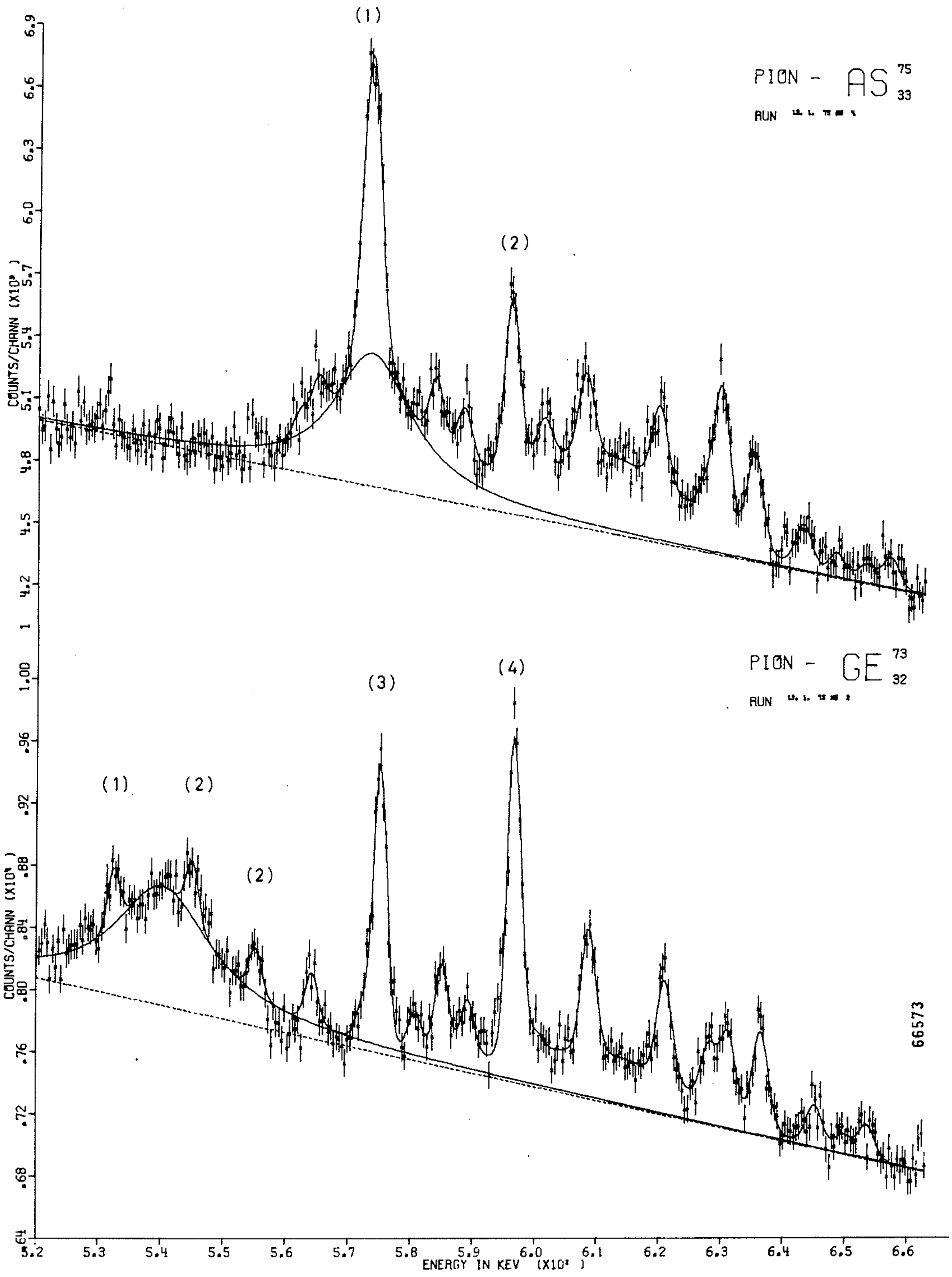
${}^{69}Ga$ (573.8 keV)

${}^{73}As$ (572.3 keV)

(2) as line (4) of Ge.

Fig. 2a : Strong interaction shifts of the 2p-state. The new measurements indicate a stronger decreasing behaviour than obtained by solving the Klein-Gordon equation using an optical potential ansatz with parameters fitted to previous data (solid line).

Fig. 2b : Strong interaction widths of the 2p-state. The solid line indicates solutions of the Klein-Gordon equations with an optical potential.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RUN
(1)
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COUNTS/CHANN
PION - GE 73 32
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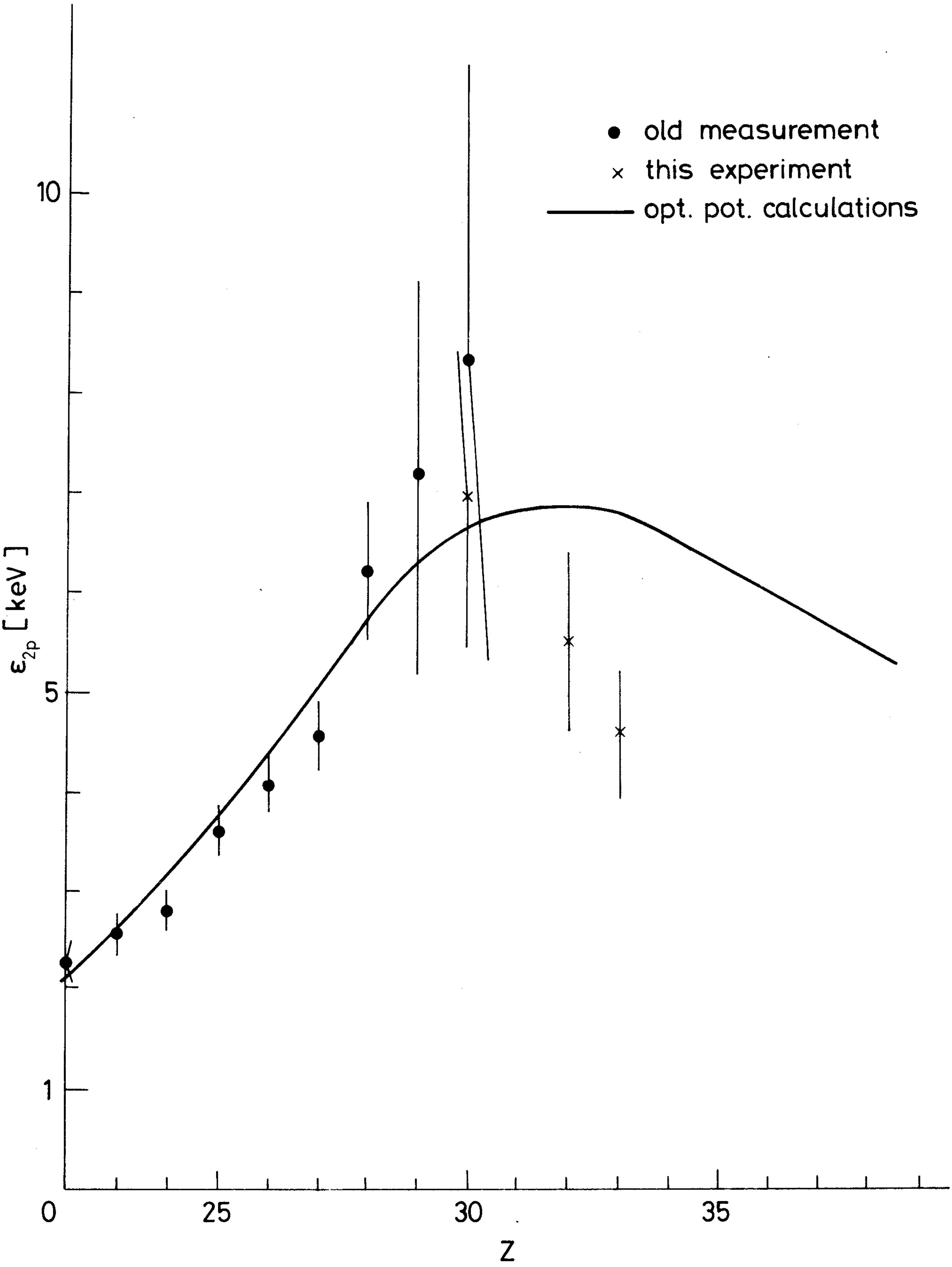
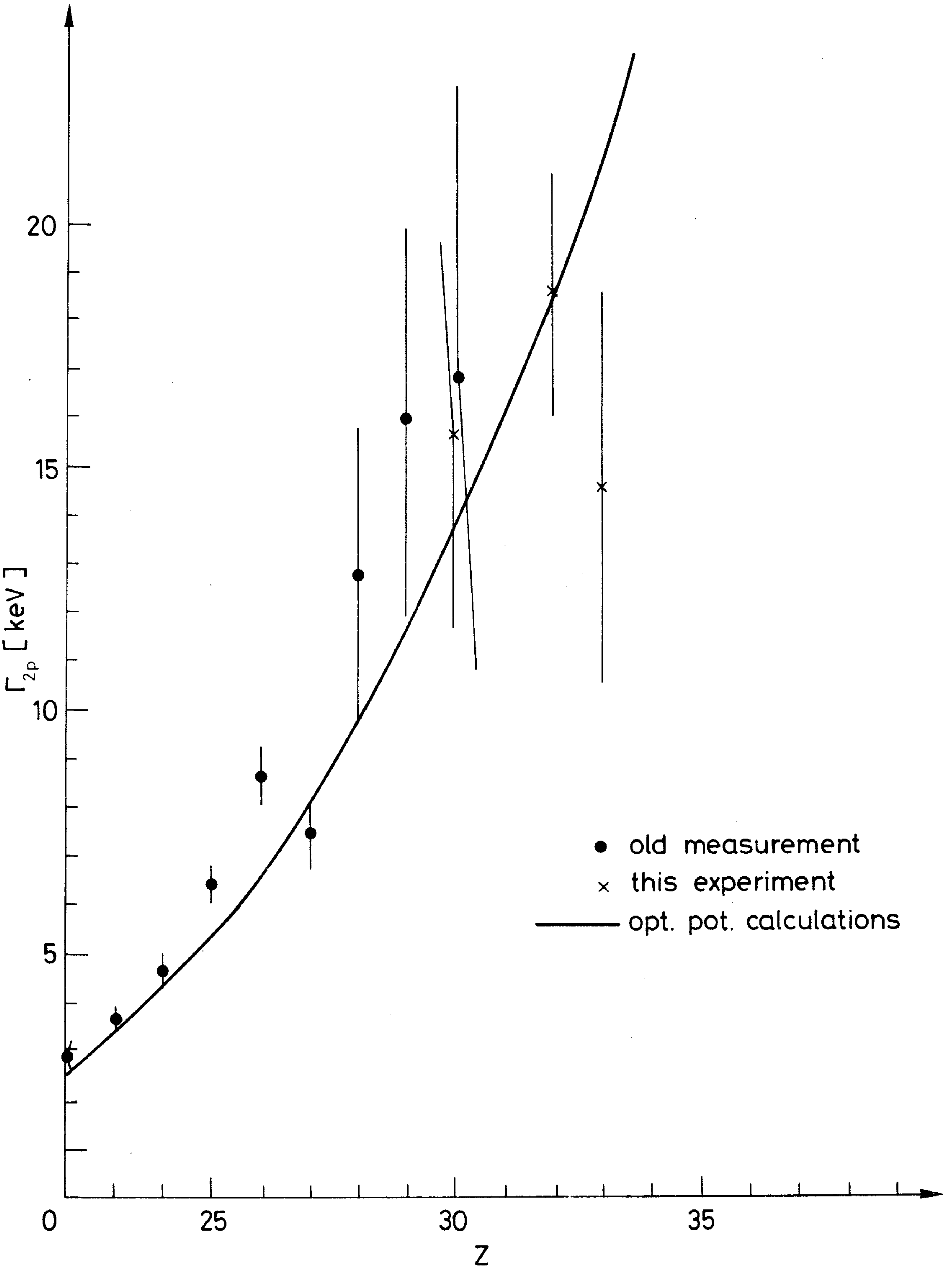
Fig. 1



old measurement
this experiment
opt. pot. calculations
10
5
1
ε2p [keV]
0
25
30
35
Z

Fig. 2a



Γ2p [keV]
20
15
10
5
0
25
30
35
Z
old measurement
this experiment
opt. pot. calculations

Fig. 2b