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AUSTRALIAN ATOMIC ENERGY COMMISSION
RESEARCH ESTABLISHMENT
LUCAS HEIGHTS

NEUTRON RESONANCE PARAMETERS OF ^{96}Zr BELOW 100 keV**

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**Research sponsored in part by ERDA under contract to Union Carbide Corporation

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ABSTRACT

Transmission data taken at the 80 m station of the Oak Ridge Electron Linear Accelerator have provided resonance parameters for ^{96}Zr to 100 keV. The average level spacing and neutron strength function for s-wave neutrons were as follows: $\langle D \rangle = 8 \pm 2$ keV and $S_0 = (0.21 \pm 0.10) \times 10^{-4}$. The average p-wave neutron strength function was $S_1 = (7.4 \pm 2.0) \times 10^{-4}$.

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P WAVES; NEUTRONS; ORELA; ZIRCONIUM 96; keV RANGE 10-100;
keV RANGE 01-10; S WAVES; DATA

CONTENTS

1. INTRODUCTION

In recent publications average neutron resonance parameters for the isotopes of zirconium and molybdenum, which occur near the maximum of the p-wave neutron strength function at mass number A ~ 95, have been studied [Boldeman et al. 1975, 1976; Musgrove et al. 1976, 1977; Musgrove, Good & Harvey 1977]. High resolution neutron transmission measurements are performed at the Oak Ridge Electron Linear Accelerator (ORELA) and analysed at the AAEC in a collaborative project to provide neutron resonance data across the entire periodic table.

The present report concludes our study of the Zr isotopes by giving resonance parameters for ^{96}Zr below 100 keV bombarding energy. Although resonances have previously been reported to ~16 keV [Moskalev, Muradyan & Adamchuk 1964] and subsequently to ~60 keV by Good & Kim [1968], the absence of spin assignments made the estimation of average resonance parameters impossible. Also, from the present experiment, it appears that many of the previously reported resonances above 30 keV are spurious. The present data were obtained with a resolution which was an order of magnitude better than the earlier measurements and estimates for both s- and p-wave neutron strength functions were obtained.

2. EXPERIMENT AND DATA ANALYSIS

Two transmission runs were performed at the 80 m station of ORELA using respectively a ^{6}Li glass scintillator and an NE110 proton recoil counter as detectors. Details of these detectors have been given by Hill et al. [1971]. Above a few kilovolts the NE110 plastic scintillator is superior in efficiency to ^{6}Li glass by as much as an order of magnitude. The first run provided data to about 20 keV bombarding energy, while the second extended the range of useful data to ~100 keV. The target consisted of a zirconium oxide sample enriched to 58.42% in ^{96}Zr with isotopic thickness 0.02055 atom b^{-1}. For both measurements the neutron burst width was 30 ns which gave an energy resolution $\Delta E/E \lesssim 0.2\%$. Beam filters of 0.45 g cm^{-2} of ^{10}B eliminated overlap neutrons from the beam. Time-of-flight dependent backgrounds were determined using blacked out resonances in Cu and Fe. A standard Oak Ridge code was used [see, for example, Larson et al. 1976] to reduce the raw data to transmission form with appropriate background corrections, and to calculate dead time corrections and errors. The area and shape of the transmission dip were then analysed with a non-linear least squares fitting routine which employed single-level Doppler broadened resonance theory. The high resolution of the present data allowed g values for the larger p-wave resonances to be determined from the shape analysis. The s-wave resonances were identified by the characteristic asymmetry caused by resonance-potential interference.

The transmission data (averaged over many channels) between 0 and 100 keV appear in Fig. 1, while Fig. 2 gives an example of a fit to the data. The many isotopic impurities were readily identified by a comparison with our data for the other zirconium isotopes.

3. RESULTS

Table 1 lists the resonances observed in the present data and compares their neutron widths with those of the previous measurements as recommended by Mughabghab & Garber [1973]. The reduced neutron widths were obtained from

$$\Gamma_n^\ell = \Gamma_n/(P_\ell\sqrt{E})$$

where the ℓ-wave neutron penetrability is given by

$$P_0 = 1 \quad ,$$

$$P_1 = (kR)^2/(1+(kR)^2) \quad ,$$

and k denotes the neutron wave number and R the penetrability radius. For our calculations we use $R = 1.35\ A^{1/3}$ fm (=6.20 fm). A staircase plot of the cumulative level count below energy E is shown in Fig. 3 while Fig. 4 gives the cumulative sum of s- and p-wave reduced neutron widths versus energy. It is clear from Fig. 3 that resonances are increasingly missed above ~ 20 keV which is confirmed by fitting the observed distribution of reduced neutron widths with the expected Porter-Thomas distribution. This test indicates that about 4 s-wave and perhaps 10 p-wave resonances have not been detected to 100 keV. The average resonance parameters derived from the best straight line fits to the data, as shown in Figs. 3 and 4, are given in Table 2 and are compared in Table 3 with parameters of other nuclei in this mass region.

The average s-wave level spacing is an important parameter in cross section calculations. The systematics have been studied using a modified free-gas model approach by Gilbert & Cameron [1965] who found that the level density parameter a, which relates to the density of single-particle states near the Fermi energy, was closely proportional to the shell energy found in semi-empirical mass laws.

In Fig. 5, the quantity a/A is plotted versus the Cameron [1958] shell correction energy along with the Gilbert & Cameron [1965] universal fit for undeformed nuclei. Since neither the zirconium nor the molybdenum isotopes are described satisfactorily by the early fit, considerable adjustment to the semi-empirical shell function is required to account for the systematic variation in level density near the N=50 magic number.

The s-wave neutron strength function determined for ^{96}Zr confirms the deep minimum in this quantity over this mass region. The much larger values reported by Good & Kim [1968] ($S_0 \sim 1.2 \times 10^{-4}$) are now seen to be a result of a number of wrongly assigned p-wave resonances.

4. CONCLUSIONS

The neutron transmission through ^{96}Zr was measured at the 80 m station of ORELA and resonance parameters were obtained to 100 keV bombarding energy. Many new resonances were observed and several spin assignments were made which permit average ℓ-wave resonance parameters for this nucleus to be estimated for the first time.

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Musgrove, A.R. de L., Good, W.M. & Harvey, J.A. [1977] - Aust. J. Phys. (in press) (^{90}Zr)

TABLE 1

^{96}Zr RESONANCE PARAMETERS

E (eV) ±0.1%	ℓ	g	Γ_n (eV)	$g\Gamma_n$ (eV)	$g\Gamma_n$† (eV)
301.0	1	(1)[a]	0.141±0.015[b]	0.141	0.19±0.03
(869.5)[c]	(1)			0.0022±0.0010	
3818	1	1	2.85 ±0.25	2.85	6±2
4130	1	2	5.9 ±0.5	11.8	13±1
5437	0		17.4 ±0.9	17.4	15.7±3.0
5970	1	(2)	3.76 ±0.50	7.5	4
9004	1	(2)	4.4 ±0.7	8.8	-
13278	1			3.4±0.6	-
15140	1			3.9±0.8	-
15409	0		39±2	39	-
17778	1	2	6.2±1.0	12.4	-
24678	0		7.3±1.0	7.3	-
29830	1	1	304±20	304	402
35157	0		31±3	31	
35860	1			14±4	
36656	1	(2)	40±5	80	
41510	1			36±14	
53980	0		120±14	120	
55201	1	1	430±35	430	
59336	1			228±25	
63699	1			29±6	
73958	1			15±5	
75451	0		158±16	158	
80866	1	1	945±75	945	
82547	1			52±10	
84474	(0)		50±10	50	
84986	1			53±12	

TABLE 1 (cont'd)

E (eV) ±0.1%	ℓ	g	Γ_n (eV)	$g\Gamma_n$ (eV)	$g\Gamma_n$ [†] (eV)
87297	1	2	880±50	1760	
95236	1			240±25	
95927	0		720±60	720	

[†] Mughabghab & Garber [1973].

[a] Assumed

[b] Γ_γ assumed = 0.25 eV from Mughabghab & Garber [1973].

In all other cases we assumed $<\Gamma_\gamma>_p = 0.175$ eV and $<\Gamma_\gamma>_s = 0.13$ eV in accordance with systematic trends.

[c] Does not correspond with any known Zr impurity.

TABLE 2

AVERAGE NEUTRON RESONANCE PARAMETERS FOR ^{96}Zr

	$\ell=0$	$\ell=1$
<D> (keV)	8±2	2.6±0.6
$10^4 S_\ell$	0.21±0.10	7.4±2.0

TABLE 3

AVERAGE RESONANCE PARAMETERS FOR NUCLEI IN THE 3p REGION

Nuclide	<D> (keV)	a (MeV)$^{-1}$	$10^4 S_0$	$10^4 S_1$
^{90}Zr	8.6±1.6	9.39	0.54±0.14	4.2±0.7
^{91}Zr	0.64±0.12	10.04	0.36±0.10	5.7±1.0
^{92}Zr	4.0 ±1.0	11.28	0.76±0.28	8.3±1.4
^{94}Zr	4.5 ±1.0	11.63	0.55±0.16	9.6±2.2
^{96}Zr	8±2	12.55	0.21±0.10	7.4±2.0
^{92}Mo	2.40±0.65	10.20	0.65±0.25	3.7±1.0
^{94}Mo	1.15±0.35	12.39	0.45±0.25	7.5±2.5
^{95}Mo	0.080±0.025	13.03	0.48±0.10	7.5±2.5
^{96}Mo	0.95±0.22	13.84	0.54±0.20	8.0±2.5
^{97}Mo	0.042±0.015	15.46	0.37±0.15	3.5±2.0
^{98}Mo	0.95±0.15	16.16	0.44±0.12	3.3±0.7
^{100}Mo	0.42±0.10	20.00	0.51±0.18	3.5±1.0

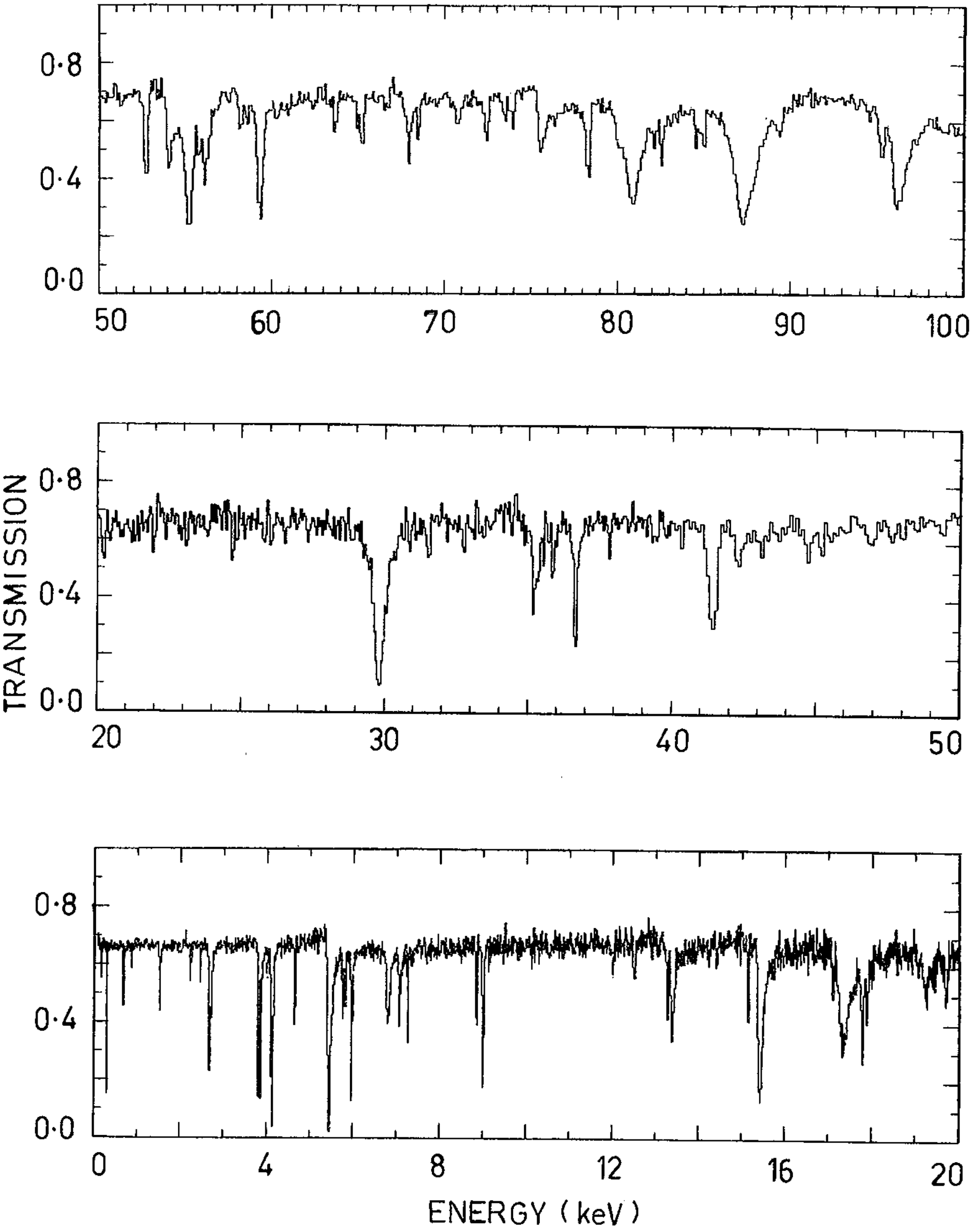

FIGURE 1. NEUTRON TRANSMISSION DATA FOR ^{96}Zr BELOW 100 keV

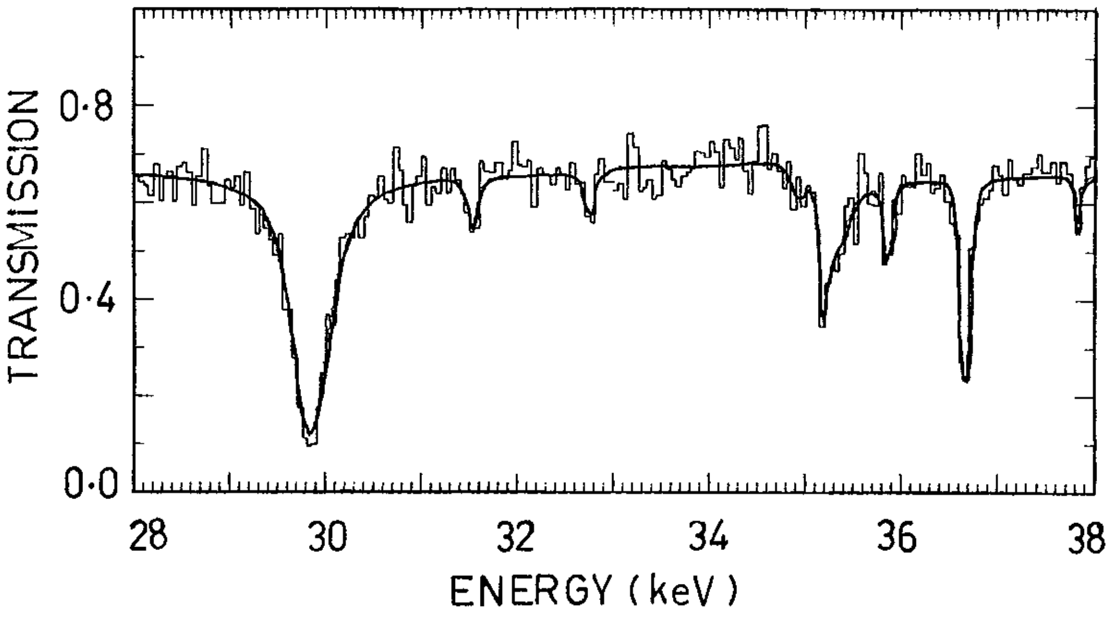

FIGURE 2. FIT TO PORTION OF THE DATA

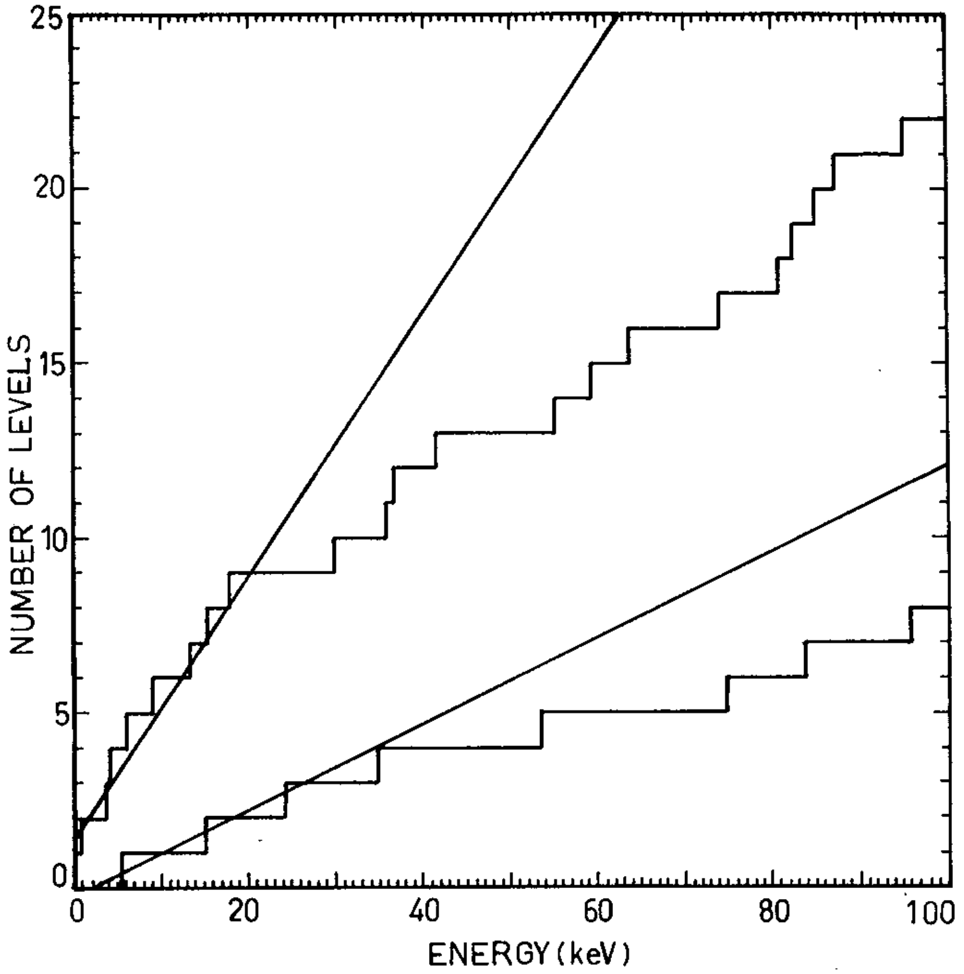

FIGURE 3. CUMULATIVE LEVEL COUNT BELOW ENERGY E FOR S-WAVES (BELOW) AND P-WAVES (ABOVE)

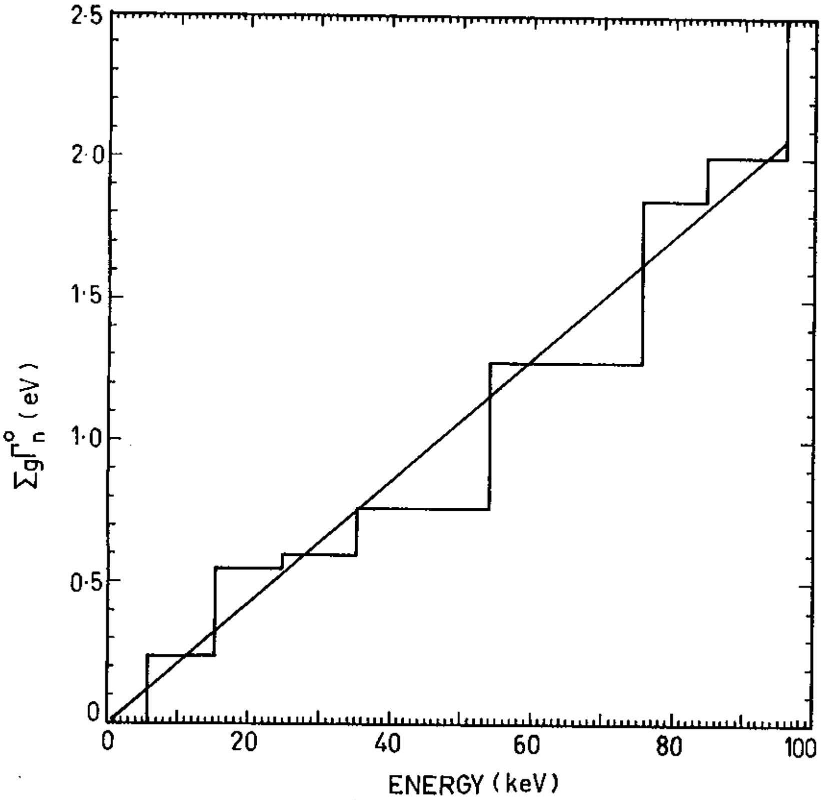

FIGURE 4a. CUMULATIVE SUM OF $g\Gamma_n^o$ FOR S-WAVE RESONANCES BELOW ENERGY E
S_0 = (0.21 ± 0.10) × 10^{-4}

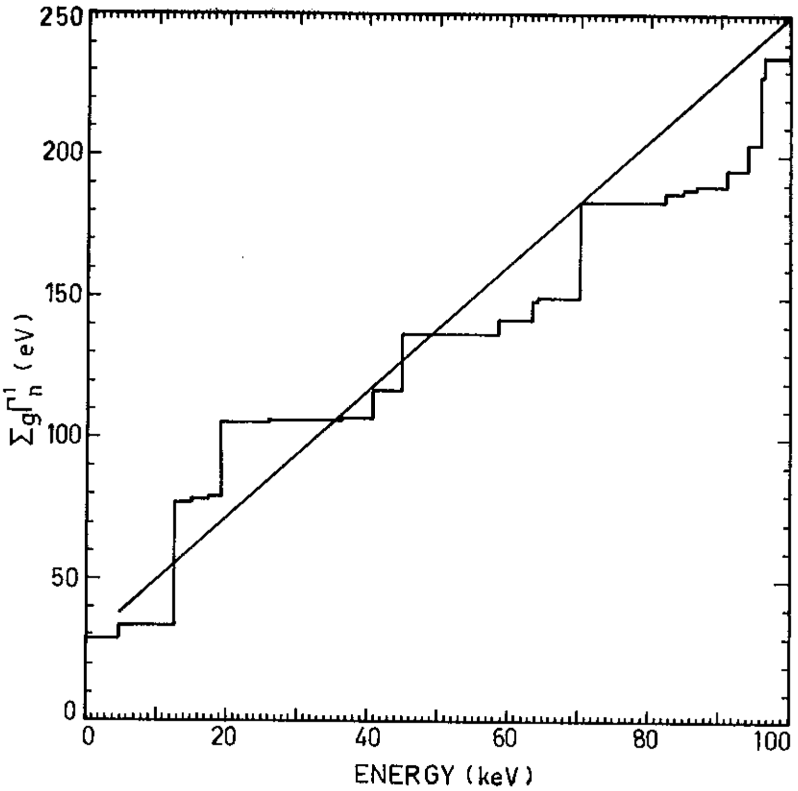

FIGURE 4b. CUMULATIVE SUM OF $g\Gamma_n^1$ FOR P-WAVE RESONANCES BELOW ENERGY E
S_1 = (7.4 ± 2.0) × 10^{-4}

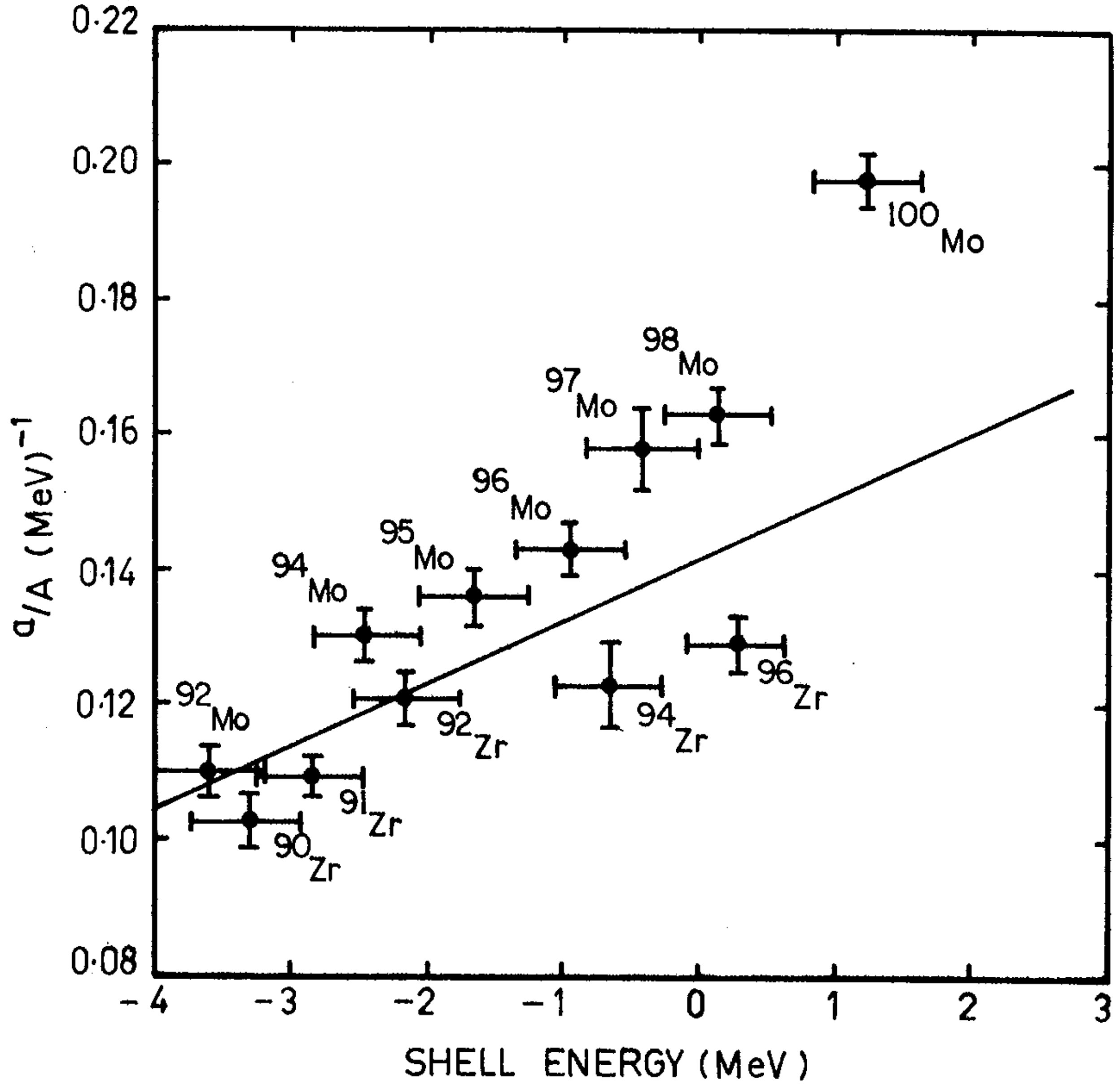

FIGURE 5. THE QUANTITY a/A v. THE SHELL CORRECTION ENERGY. THE GILBERT AND CAMERON UNIVERSAL FIT FOR UNDEFORMED NUCLEI IS ALSO SHOWN