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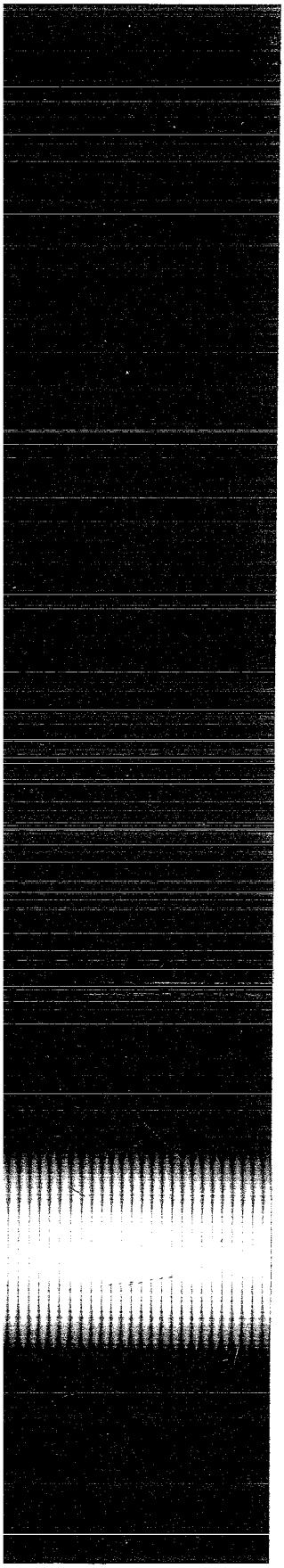

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FLUCTUATION ANALYSIS OF TOTAL NEUTRON CROSS SECTIONS*

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1. INTRODUCTION

The cross section fluctuations occurring in the excitation functions of nuclear reactions have been investigated in several experimental and theoretical studies to determine average level densities and level widths. In addition, some experimental data have been the subject of a search for intermediate structure. However, many of these previous studies were restricted to narrow energy intervals in a few nuclei and gave partially inconclusive results.

The large set of neutron total cross sections measured with the Karlsruhe time-of-flight spectrometer was therefore considered as a favorable case for such study, because the data have high statistical accuracy and extend over the entire energy range in which significant fluctuations occur.

2. EXPERIMENTAL

The total neutron cross sections of the elements F, Na, Al, Si, S, K, Ca, V, Cr, Mn, Fe, Co and Ni have been measured during the last three years with the time-of-flight facility at the Karlsruhe isochronous cyclotron. This facility combines a 20 kHz pulsed neutron source of ~ 1,5 ns burst width, a 57 m flight path and a proton recoil counter as the neutron detector. Operational details of the facility have been described elsewhere [1].

The cross sections of the 13 elements were measured in the energy range 0.5 - 32 MeV by transmission experiments. Standard time-of-flight techniques were applied for the neutron energy determination. All transmission samples, except F, were in solid elemen-

tal form. For fluorine a sample of $(CF_2)_n$ was used. In this case a carefully matched carbon sample was used for the sample-out measurement.

Sample thicknesses generally were chosen to give approximately 40 % - 70 % transmission in most of the time channels. Data collection in the typically 8000 time channels was accomplished with a digital time analyzer LABEN UC-KB and a CDC 3100 on-line computer.

The total neutron cross sections were calculated off-line by combining sample-in, sample-out and background measurements. Corrections for dead-time losses were applied using an analytical equation which has been experimentally verified for the applied conditions. The measurements were carried out with an energy resolution of typically 1 keV at 0.5 MeV increasing as $E^{3/2}$ to 70 keV at 32 MeV. With the exception of the lowest and highest portions of the excitation functions the measurements were performed with a statistical uncertainty of ≤ 2 %. In fig. 1 the total neutron cross sections of vanadium and chromium, which may serve as characteristic examples of our results, are shown on a double logarithmic scale.

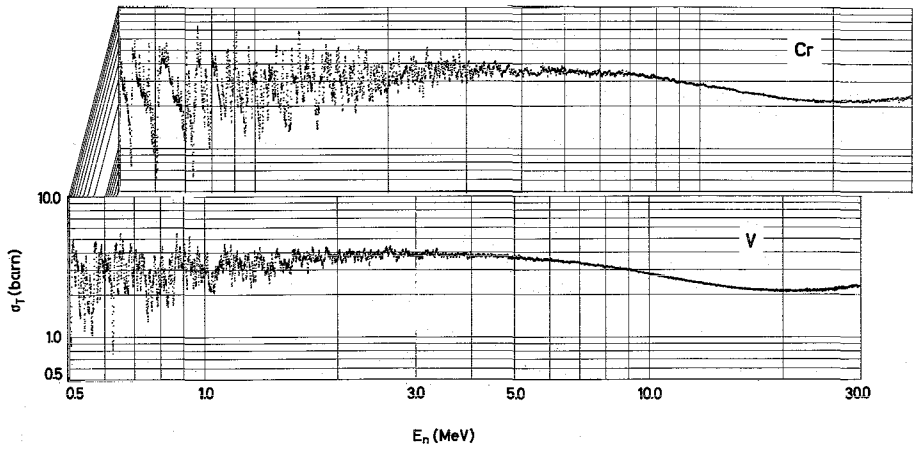

Fig. 1 Total neutron cross section of vanadium and chromium

3. ANALYSIS

Fluctuation analyses of the cross sections were carried out in the energy region between 0.8 and 14 MeV. Above 14 MeV none of the nuclei investigated here exhibited significant fluctuations. The motivation for the analyses was threefold: (i) to determine average level densities, (ii) to deduce mean level widths and (iii) to search for intermediate structure.

Determination of average level densities: The determination of average level densities was accomplished by the method adopted by Carlson and Barshall [2]. Considering statistical fluctuations in

spacings as well as in widths of compound-nucleus levels, these authors have shown that the variance of the compound-nucleus formation cross section can be expressed by

$$F=(\pi\lambda^2)^2\cdot\frac{1}{\omega(E)\cdot\Delta_n}\sum_{J\pi}\frac{g^2(J)}{H(J\pi)}\left[k_W\sum_{l,s}(T_{l,s}^J)^2+k_n\Big(\sum_{l,s}T_{l,s}^J\Big)^2\right] \qquad (1)$$

with the abreviations:

$$k_W=\frac{var[\Gamma_i(ls,J\pi)]}{\langle\Gamma_i(ls,J\pi)\rangle^2}\ \text{and}\ k_n=\frac{var[N_{J\pi}^{(n)}]}{\langle N_{J\pi}^{(n)}\rangle} \qquad (2)$$

Here λ is the reduced wave length, $\omega(E)\cdot H(J,\pi)=N_{J\pi}$ is the level density split into an energy dependent and a spin dependent part, g is the spin weighting factor and T is the transmission coefficient. The quantities k_W and k_n can be calculated from the standard width and spacing distributions, respectively.

From the experiments we calculated the variances

$$F=\langle(\sigma_n-\bar{\sigma})^2\rangle \qquad (3)$$

where σ_n is the average cross section in Δ_n and $\bar{\sigma}$ means the average compound nucleus formation cross section. The latter was obtained by subtracting the optical potential scattering cross section from the measured total cross section. For $H(J,\pi)$ the formula given by Gilbert and Cameron [3] and for T-values those calculated by Mani, Melkanoff and Iori [4] were used in our analysis.

For all 13 elements, analyses were carried out in 2 MeV wide subintervals extending to high energies until no fluctuations were observable. With the exception of F, Al, Si and S, reasonable agreement was found between the deduced energy dependence of the level density and the theoretical predictions.
Fig. 2 shows the results of Na, Ca and Co as typical examples. In

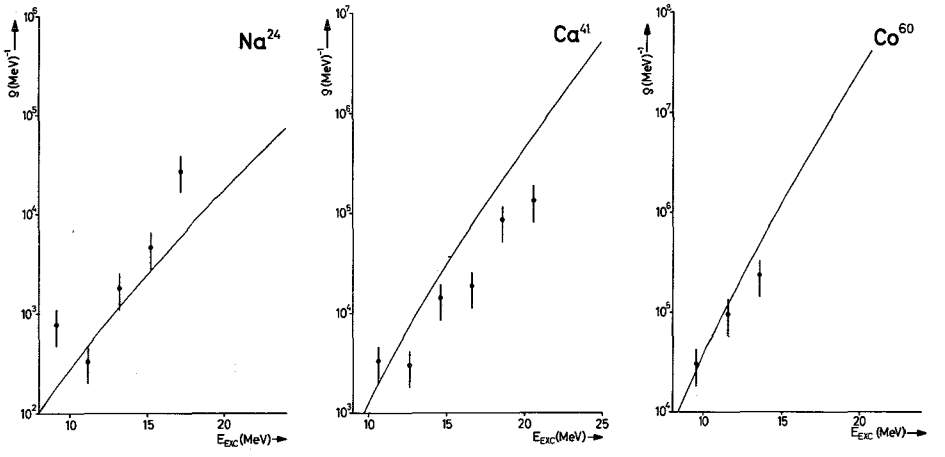

Fig. 2 Level densities of ^{24}Na, ^{41}Ca and ^{60}Co

this figure the solid circles are the results of the present analysis, the solid lines are those of a calculation using the Gilbert and Cameron formula.

Deduction of average level widths. For the deduction of average level widths the theory developed by Ericson [3] was applied. In this theory it is assumed that all levels have the same total width Γ and that the effect of fluctuations in level spacings may be neglected. At energies at which a large number of levels overlap the following dependence of the self-correlation function on the energy increment ε was deduced:

$$C(\varepsilon) = C(0) \cdot 1/\left[1 + (\varepsilon/\Gamma)^2\right] \qquad (4)$$

i.e. a Lorentzian form factor times the mean square deviation of the average cross section $C(0)$. Γ therefore can be obtained from the width (FWHM) of the autocorrelation function.

In the present analysis we calculated the self-correlation function in the form modified by Pappalardo [6], as

$$C(\varepsilon, I) = \langle (\sigma(E) - \sigma_I(E))\,(\sigma(E+\varepsilon) - \sigma_I(E+\varepsilon)) \rangle \qquad (5)$$

Here the quantities $\sigma_I(E)$ and $\sigma_I(E+\varepsilon)$ mean average cross sections in a sliding energy interval smaller than the total analyzing interval. This is done to account for a slowly varying mean value.

Although the conditions for the Ericson theory may not be satisfied for all measurements we have calculated the correlation widths for all elements from 0.8 MeV to the highest energies at which fluctuations occur. In all cases a nearly Lorentzian shape of the self-correlation function was obtained.

Fig. 3 shows as a typical example the self-correlation function of vanadium calculated for the energy region between 2 and 4 MeV.

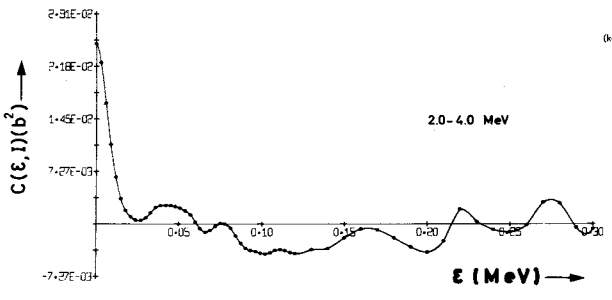

Fig. 3 Correlation function $C(\varepsilon, I_f)$ of vanadium

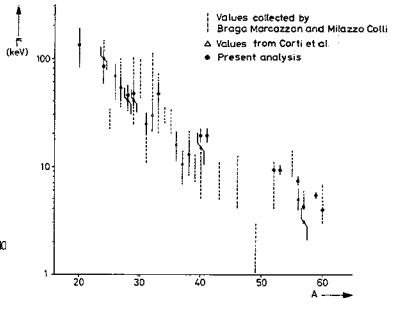

Fig. 4 Mass dependence of average level widths

The Γ values obtained from the analysis have been corrected for the effects of counting statistics and the energy resolution. The latter corrections were performed using the method proposed by Lang [7].

In Fig. 4 the mass dependence of the deduced average level widths is compared with recent results from (d,p) and (d,α) reaction measurements [8] at about 20 MeV excitation energy. In this figure our results are those for the highest energy subintervals. With the exception of the mass region near A = 40 there is agreement within the stated errors.

Search for intermediate structure: An investigation of the evidence of structure with intermediate widths, i.e. widths between approximately 50 and some hundred keV was performed following the procedure proposed by Pappalardo [9]. The occurrence of a second rise in the correlation function C(0,I) given in eqn. 5 and the occurrence of two correlations with largely different widths in $C(\epsilon,I_f)$ (where f stands for "fixed") was taken as evidence that such intermediate structure exists. For all nuclei with the exception of Si, Mn and Co evidence was found in part of the investigated energy regions. No interpretation in terms of doorway states was tried. We hope to investigate this question by the inclusion of partial cross sections and a search for correlations in scattering angle as well as in reaction channels in a future study [10].

*Paper presented by G. Kirouac of Knolls Atomic Power Laboratory

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DISCUSSION

SCHRACK (National Bureau of Standards)

We have measured total cross sections also at the same energy region and for seven elements in which the level spacing and frequency was adequate to make a correlation analysis. The conclusions that one has about intermediate structure are dependent, I think, on what one wants to look for. I'm sorry he didn't show the actual correlation analysis curves. That actual Papalardo effect that you indicated on the top graph, the plateau effect, is very seldom seen. I think a more realistic thing to look for is a delayed rise. If you have no delayed rise, then there is no second width. With that criteria you can see a distribution in what you might call intermediate structure, strong cases, and weak cases and the distribution of seeing intermediate structure is approximately equivalent to a Monte Carlo mock-up that we've done; so one can make any conclusion one wants to from this whether these are purely statistical appearances or whether they have some real door-way state meaning.

KIROUAC

If I may, I'd like to make a couple of comments and then, if I might turn things about, I'd like to ask you two questions. First of all, when I say there was some evidence, that varied from very strong in some cases to rather weak in others, and for three materials there was absolutely no evidence whatsoever for intermediate structure. No interpretation was made obviously in terms of doorway states. These are simply intermediate structures in correlation functions. Now I did read your contribution and I have two questions. First of all, I wonder if you could tell me what your energy interval was and how high you did go.

SCHRACK

The energy interval over which the correlation analysis was made varied upon the structure change in the cross-section. We did two types of analysis. Once we just went through all the data and tried to pick out groupings of energy that had fairly similar structure and did correlation analysis on those. Those varied in widths from 1 MeV, 2 MeV to 10 MeV, depending on whether it was a low energy or a high energy. Then we went back and we said that we felt that the correlation analysis was really not very meaningful when the level overlap was high because there are two effects coming in: one, the statistical fluctuation type effect; two, you have many channels contributing and so really any significant intermediate structure would have to lie in one spin channel so that when you have many spin channels contributing, the theoretical significance of the fluctuation is not clear. So we went back and only did it from a half MeV to 1 MeV of where the levels could be easily identified and we felt there was some significance.

KIROUAC

Most of the intermediate structure observed in the present work was observed above 1.5 MeV, usually above 2.0 MeV.

SCHRACK

There was a particular case that I saw that was printed in an earlier report at 2.7 MeV in aluminum. There is a very nice plateau there. We examined that in some detail because we thought it was so high up in excitation that we didn't think it could have significance from the standard doorway state analysis. If you look at it closely you find that this is actually based on an interference type of shape in the fluctuation, and I'm not sure what the significance is of it.

VONACH (Technische Universitat Munchen)

From your slide on the gamma values, I noticed in the region of high A 40-60 your gammas were quite a bit larger than those for particle reactions. Might this be due to experimental resolution or do you think this is a real effect.

KIROUAC

I'm afraid I can't comment on that beyond the error bars that have been put on the points.