FR 82 o 1696

Université Scientifique et Médicale de Grenoble

INSTITUT DES SCIENCES NUCLÉAIRES DE GRENOBLE

53, avenue des Martyrs – GRENOBLE

ISN 81.47

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Invited talk presented at the international symposium on "Nuclear fission and related collective phenomena and properties of heavy nuclei", Bad Honnef, october 26-29, 1981.

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ISOTOPIC EFFECT ON GIANT RESONANCES

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Abstract. - The systematics of the excitation energy of the giant dipole, monopole, and quadrupole resonances are shown to exhibit an isotopic effect. For a given element, the excitation energy of the transition decreases faster with the increasing neutron number than the empirical laws fitting the overall data. This effect is discussed in terms of the available models.

The giant resonances (GR) are normal modes of nuclear vibrations. As such, they exist or are expected to exist in all nuclei, provided they have a number of nucleons large enough to develop a coherent collective motion. These modes of vibration are quasi-hydrodynamical and their frequency varies smoothly with the mass of the nucleus. This feature may be (loosely) considered as arising from the boundary condition set on the equation of motion governing the oscillation of the nuclear fluid. This condition in turn, sets a dependence of the oscillation frequency on the nuclear size and then on the nuclear mass. Experimentally, the GR's exhibit approximately an $A^{-1/3}$ dependence in heavy nuclei. However we shall see that one observes systematic departures from the empirical laws along families of isotopes. Indeed, the frequencies of giant vibrations are found to exhibit different variation laws along families of isotopes when compared to the empirical laws fitting the data through the mass table. In the following we discuss these isotopic effect for the three giant modes for which enough data are available to make the effect clearly show up. The modes are the giant (compressionnal) monopole resonance (GMR), the giant (isovector) dipole resonance (GDR), and the giant (surface) quadrupole resonance (GQR).

I - THE GIANT MONOPOLE RESONANCE.

The recent systematic study of the giant monopole resonance (GMR) has permitted the observation of an isotopic effect on the GMR excitation energy. This may be interpreted as an evidence for an asymmetry dependence of the nuclear compressibility, and it allows to isolate the corresponding contribution to the nuclear compression modulus. A detailed discussion of the results has been reported in ref. 1. (see also refs.2,3). The part of these results relevant to the subject treated here is summarized in the following for the sake of completeness.

The frequency ω_M of the monopole mode of nuclear compressionnal vibration is related to the compression modulus of the nucleus K_A by the relation [4]:

$$\omega_M = \left[\frac{K_A}{m \langle r^2 \rangle} \right]^{1/2} \qquad (1)$$

m being the nucleon mass and $\langle r^2 \rangle$ the mean square (ms) radius of the nucleus. In the hydrodynamic model K_A is related to the second derivative of the nuclear binding energy with respect to the nuclear radius, and then it can be related to the volume, surface, asymmetry and coulomb energies of the nucleus. This approach leads to

$$K_A = K_\infty + K_s A^{-1/3} + K_\tau \left(\frac{N - Z}{A}\right)^2 + K_c Z^2 A^{-4/3} \qquad (2)$$

(see ref. 1, relation (5)).

The asymmetry term in this relation is always small and a reliable determination of K_τ requires to be based on a large number of data points with a nuclear asymmetry $\delta = (N - Z) / A$ as different as possible.

The experimental study has been performed at Grenoble ISN using the 110 MeV ^{3}He beam from the variable energy cyclotron. Experimental details have been reported in refs. 5. Inelastic spectra were measured at very small scattering angles including zero degree. The angular distributions have been investigated up to 8°.

Figure 1a shows the measured GMR excitation energy, plotted as a function of the nuclear mass for nuclei with $89 \leq A \leq 144$, so as to emphasized the asymmetry effect, better observed experimentally in this region of mass. If the monopole frequency would depend only on the geometrical features of the nucleus, it should have a smooth dependence on A. Instead of that, a different and rather systematic trend is observed. On fig. 1a, the values of E_x (GMR) for the various families of isotopes studied, are lying approximately along lines with a roughly constant negative slope, each line making on angle with the overall systematic dependence on A given by the dotted line. This curve corresponds to the prediction of relation (1), (2) with the ki's parameters fitted to the overall data (K_∞ = 261,5 Me, K_s = -552 MeV, K_τ = -420 MeV), for nuclei lying along the stability line defined as $Z = A(1.98 + 0.0155\ A^{2/3})^{-1}$. Figure 1b shows the same GMR excitation energy plotted versus the squared nuclear asymmetry for the studied Zr, Mo, Pd, Cd and Sn isotopes. It shows the same consistent trend of decreasing E_x with increasing asymmetry, with a roughly constant average slope. A few nuclei such as ^{92}Mo and ^{116}Cd do not follow the general trend. These discrepancies are not quite understood, although some possible explanation may be speculated. Indeed, it has been shown recently that there is a dependence of the GMR excitation energy and transition strength on the static quadrupole deformation of the nucleus. Such an effect has been observed both in the actinides [6] and in the region A ~ 90 - 110 (réf. 1) which is of interest here. One may tentatively understand the lack of continuity in Mo and Cd isotopes as coming from that deformation effect. This is consistent with the fact that for the spherical Sn isotopes, such a discrepancy is not observed.

The dotted line on fig. 1b for Sn isotopes has been obtained with the best fit parameters given above (full square symbols), whereas the dashed line corresponds to K_{δ} = -700 MeV (see ref. 1,2 for a discussion of these values). This shows that the isotopic effect on the GMR excitation energy can be understood in terms of the asymmetry dependence of the nuclear compression modulus.

II - THE GIANT DIPOLE RESONANCE.

Next, it is interesting to wonder whether such an isotopic effect is observed for the GMR only. A close look at the experimental values of the excitation energies of the other two extensively studied GR's, the GDR and the GQR, show that they also exhibit some isotopic effect. The origin of the effect can be rather well understood in one case (GDR) but it is much more measy to account for it in the other case (GQR). Figure 2 and 3 display samples of values illustrating the subject.

Let us examine first the case of the giant dipole resonance. Figure 2 displays the excitation energy, width (FWHM), and deduced asymmetry energy for the chosen set of nuclei (refs. 7,9,10). Also shown on the upper graph is the empirical law $E_x(GDR) = 76\ A^{-1/3}$ (MeV), fitting the data on heavy nuclei. It is seen on this plot that E_x (GDR) exhibits a strong isotopic effect for the Z_r and M_o isotopes. Indeed, the corresponding isotopes are lying along lines making an angle with the curve from the empirical law. This is strikingly similar to the effect observed on the GMR. However, the Sn isotopes surprisingly show no isotopic effect. To understand this paradox, it is necessary to consider the width of the GDR shown on the middle graph. It can be seen there that E_x and are clearly correlated : the sharp decrease of E_x for M_o and Z_r isotopes takes place along with a sharp increase of the width (due to the increasing ground state deformation [8]), whereas a constant width is associated with a steady behaviour of E_x along the empirical law for the Sn isotopes. This can be understood in terms of the Jensen-Steinwedel (JS) model of the giant dipole oscillation. In this model, the frequency ω_D is related to the width through the relation given by Danos [9] :

$$\omega_D = \frac{2.082}{R} \left[\frac{8\,NZ}{m\,A^2}\, K \left(1 - \frac{\Gamma}{2\pi\omega_D} \right)^2 \right]^{1/2} \qquad (3)$$

one see that to any increase of Γ, this relation associates a corresponding decrease of ω_D. Note that the term NZ/A also introduces differences between the frequencies of the isotopes of a given element. Formula (3) allows to extract the experimental values of the symmetry energy K shown on the lower graph of figure 2. If formula (3) would perfectly account for the experimental correlation between E_x(GDR) and Γ, it would lead to a constant value of K. Instead of that, the deduced value of K fluctuates around an average, but one can consider that this model reasonably account for the observed isotopic effect. The small average increase of K between Z_r-M_o and S_n is understood as arising from the surface symmetry-energy [10].

III - THE GIANT QUADRUPOLE RESONANCE.

The GQR experimental values on the same sample of nuclei as for the GDR are displayed on figure 3. The quadrupole frequencies do exhibit an isotopic effect as well as the GDR and GMR frequencies with an amplitude quite similar to that exhibited by the monopole resonance. This is illustrated on figure 4 which shows the difference spectra measured on the Sn isotopes in the Grenoble study [1,3]. The figure also shows the unfolding of the GR peak into quadrupole (lower Ex) and monopole (upper Ex) components. Both components exhibit an appreciable isotopic shift which can be traced from ^{112}Sn to ^{124}Sn. The total shift amounts to around 1.3 MeV between these isotopes. Note that such a shift had been noted previously in ref. 11 for Mo isotopes. The data points on figure 3 are only illustrative of a more widely observed trend. Indeed, this effect is also observed for Ni, Zn, Pd and Cd isotopes with only one exception for ^{110}Cd .(see numerical values in refs. 1,3).

A stimulating aspect of such observation is that the available macroscopic models of nuclear vibration do not seem to be able to account for this effect as will be going to see in the following. It is well known that the liquid drop model [12] predicts an $A^{-1/2}$ dependence for the quadrupole frequency instead of the $A^{-1/3}$ observed empirically. This failure is now understood and related to the dynamical assumptions (classical hydrodynamics, local quilibrium) underlying the model [13]. This problem has stimulated a considerable amount of theoretical investigations and it has been established in the recent years that the experimental GQR frequency can be accounted for by collective macroscopic models, provided the dynamics are suitably treated [14 - 17]. The theories developped in refs. 14, 16, predict the quadrupole frequency to be given by the following relation

$$\omega_Q = \left[\alpha \, \frac{< t >}{m < r^2 >} \right]^{\frac{1}{2}} \qquad (4)$$

where α is a constant, and m is taken as the effective mass [14] , or the free nucleon mass [16] , $\langle t \rangle$ is the nucleon average kinetic energy, $\langle r^2 \rangle$ in the ms radius of the nucleus. One can expect the observed isotopic effect to be originated by either one of these two latter quantities. If we consider first the effect of $\langle t \rangle$, an asymmetry dependence can indeed be incorporated in this term using a fermi gas model, following the lines of ref. 18. This leads to $\langle t \rangle = \frac{3}{5} t_f \, (1 + \frac{5}{9} \delta^2)$, where t_f is the nucleon fermi energy in symmetric nuclear matter and δ is the nuclear asymmetry. This dependence on δ is very weak and moreover goes just the opposite way to that observed experimentally.

One can then turn to $\langle r^2 \rangle$ to account for the observed effect. Indeed, it is not unlikely that the ms radius exhibit local variations departing from the $A^{1/3}$ law along lines of isotopes. Although the matter radius is the relevant quantity in our case, we can have a first indication on the trends by considering the evolution of the charge radius which is a quantity very well known experimentally. Figure 5 shows the evolution of the charge radius along Zr, Mo and Sn isotopes as a function of the neutron number (open symbols). The y axis gives the ratio of the experimental value of the rms radius to a theoretical value given by a formula fitting the overall data [19] :

$$\langle r^2 \rangle^{1/2} = \frac{3}{5} A^{1/3} \, (1.15 + 1.8 \, A^{-2/3} - 1.2 \, A^{-4/3}) \, \mathrm{fm} \qquad (5)$$

It is seen that the experimental rms radii show only very slight departures ($\sim$ 1%) from the empirical law. The theoretical predictions of the droplet model [20] for the matter radii do not predict any departure from the empirical law either (full symbols connected by dotted lines). Note the larger average values for matter radii than for change radii. The full symbols connected by solid lines show the change of radii which would account for the observed isotopic effect. Since for these points only the variations are significant, the absolute value has been normalized on the droplet model value of the lightest isotope for each element. One observes a sharp disagreement between the theoretical variations closely following the empirical law given by relation (5) (constant value on the graph), and the variations required by the isotopic shift. The radius difference is predicted to be 0.16 fm by the droplet model whereas a difference of 0.45 fm is required to account for the GQR frequency shift between ^{112}Sn and ^{124}Sn. This required difference is also in disagreement with the recent determination of the matter radii in ^{116}Sn and ^{124}Sn from the analysis of 800 MeV proton scattering [21] : the experimental matter radius difference between ^{116}Sn and ^{124}Sn is 0.12 fm to be compared to 0.28 fm to account for the GQR excitation energy shift. Here again the disagreement is severe.

Finally it appears that the isotopic effect observed on the quadrupole frequency cannot be simply accounted for by the fluid dynamical model(s) [14, 16] . One must keep in mind that macroscopic models are expected to describe properly the quantities characterizing the GR'S (Ex, FWHM, strength) only on the average. In particular, the excitation energy in neighbouring nuclei is expected to fluctuate around the average value predicted by collective models because of local shell-effects. However what is observed here is not an erratic fluctuation but a clearly correlated departure from the average value which is observed in Ni, Zn, Zr, Mo, Pd, Cd and Sn isotopes with only a few exceptions [1, 2] . This effect is bound to have a specific physical origin and we believe that a theoritical interpretation of it is required and would bring about new information on the dynamic of the giant surface modes.

In conclusion we have seen that isotopic effect on the GR frequencies has been observed experimentally for a polarisation mode (GDR), a compression mode (GMR), and a surface mode (GQR). Although this effect can be interpreted in the first two cases, a theoretical interpretation is lacking for the GQR.

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Figure Captions

Fig. 1 - GMR Excitation energy versus the nuclear mass in the range $89 \leq A \leq 141$ (upper) or versus the squared nuclear asymmetry (lower). The dotted lines are the best fit predictions of the hydrodynamic formula with $K_{\tau} = -420$ MeV along the stability line (upper) or restricted to the Sn isotopes (lower). Adjusting K to fit the Sn isotope experimental values only leads to the dashed curve, with $K_{\tau} = -700$ MeV.

Fig. 2 - Experimental values in MeV of the excitation energy (upper) and width (middle) of the GDR, for an illustrative set of isotopes. The lower graph gives the asymmetry energy (in MeV) obtained from the experimental data using relation (3). The dashed lines are to guide the eye.

Fig. 3 - Experimental excitation energies of the GQR for some Zr, Mo and Sn isotopes showing a clear isotopic effect. The solid line is the empirical law fitting the data through the mass table. The dashed lines are only to guide the eye.

Fig. 4 - Inelastic spectra (background subtracted) measured with 110 MeV ^{3}He on Sn isotopes (réf. 3). The unfolding of the bump into GMR and GQR components is shown. Both peaks are shifting towards lower E_x between ^{112}Sn and ^{124}Sn. The solid lines on the figure connect the abscissas of the peak centroids.

Fig. 5 - Ratio of radii to calculated values of the charge radii given by relation (5). Open symbols : experimental charge radii. Full symbols connected by dashed lines : droplet model matter radii (réf. 20). Full symbols connected by solid lines : relative radii as required to account for the observed GQR excitation energy differences, using relation (4).

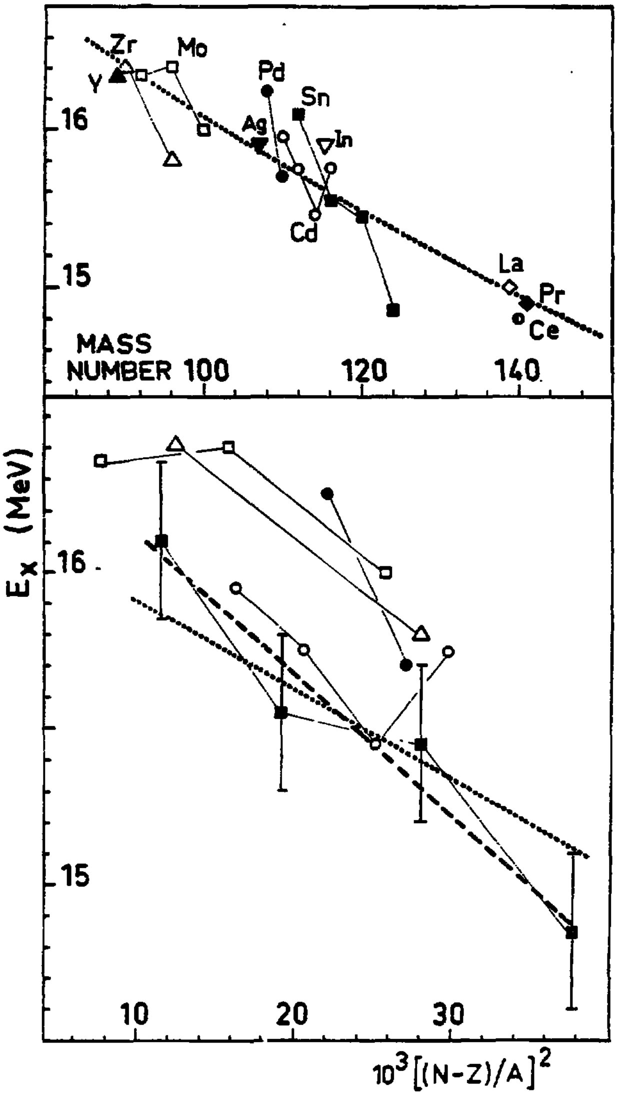

Zr
Mo
Y
Pd
Sn
Ag
In
Cd
La
Pr
Ce
16
15
MASS
NUMBER 100
120
140
E_x (MeV)
16
15
10
20
30
$10^3[(N-Z)/A]^2$

Fig 1

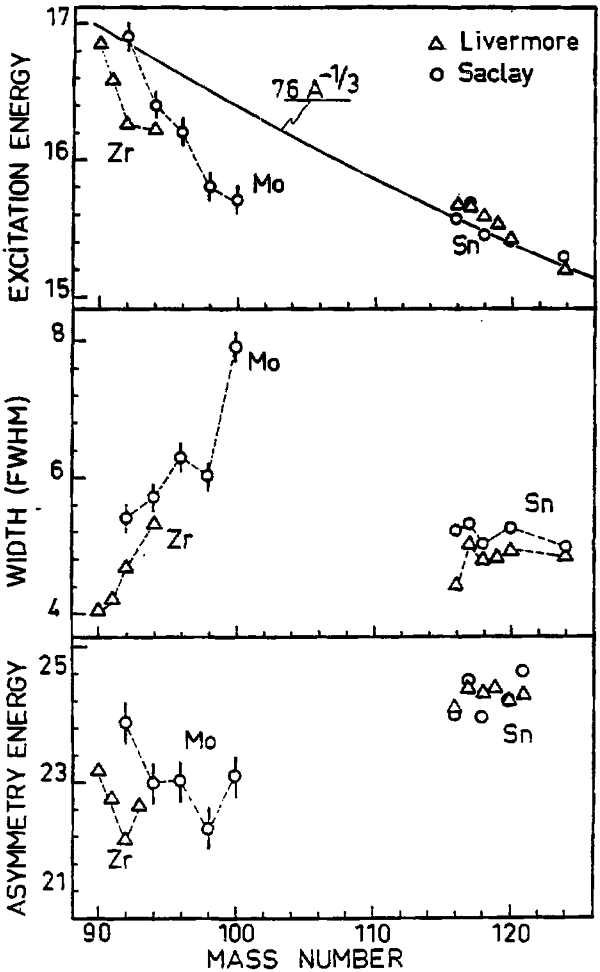
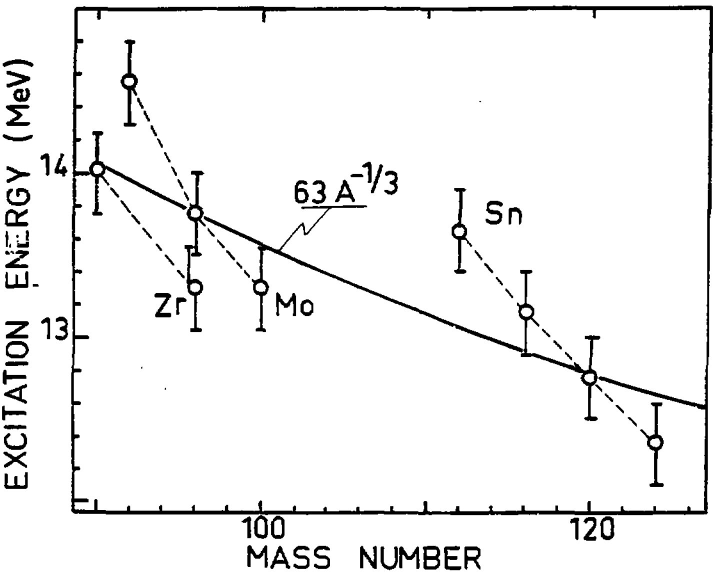

EXCITATION ENERGY
17
16
15
Livermore
Saclay
76 A^-1/3
Zr
Mo
Sn
WIDTH (FWHM)
8
6
4
Mo
Zr
Sn
ASYMMETRY ENERGY
25
23
21
Mo
Zr
Sn
90
100
110
120
MASS NUMBER

Fig 2



EXCITATION ENERGY (MeV)
14
13
100
120
MASS NUMBER
$63\,A^{-1/3}$
Zr
Mo
Sn

Fig 3

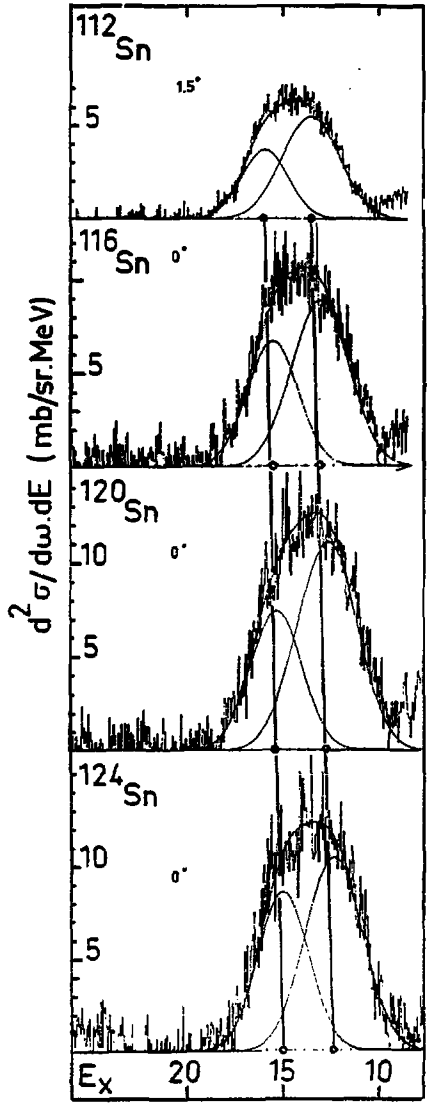
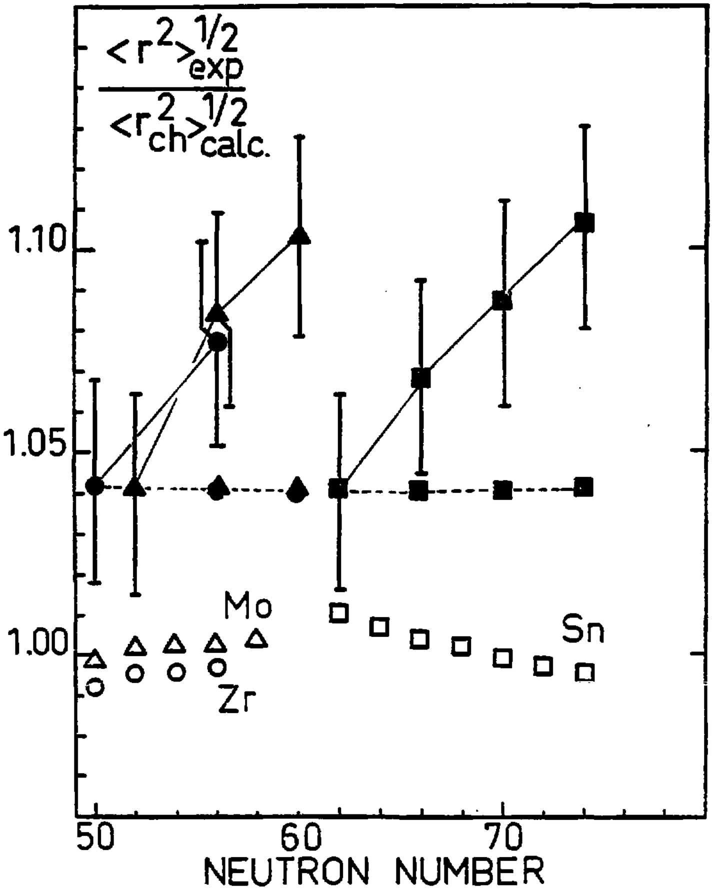

112Sn
1.5°
5
116Sn
0°
5
120Sn
0°
10
5
124Sn
0°
10
5
d2σ/dω.dE (mb/sr.MeV)
Ex
20
15
10

Fig 4



$\frac{\langle r^2 \rangle^{1/2}_{exp}}{\langle r^2_{ch} \rangle^{1/2}_{calc.}}$
1.10
1.05
1.00
Mo
Zr
Sn
50
60
70
NEUTRON NUMBER

Fig 5