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# Light Ion Reaction Mechanisms and Nuclear Structure

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## §1 Introduction

Of the many fine contributions to the subject 'Light ion reaction mechanism and nuclear structure', I have with some difficulty selected a few, which I believe highlight the present state of the field. On the experimental side there is a tendency firstly to obtain a more complete set of data and secondly to employ higher bombarding energies, which sometimes improve a particular theoretical assumption or increase the effect of a particular spin-dependent interaction. On the theoretical side, the current trend is to use more arbitrary phenomenological interactions, which can be compared with microscopic model potentials and also to employ relations between polarization observables to place constraints on the reaction mechanism. I shall show examples of polarization measurements which yield information about nuclear interactions, reaction mechanisms and nuclear structure.

## §2 Nuclear interactions

The TUNL group of Murphy et al.[1)] have investigated the isovector potential for the $^{9}$Be + nucleon system. Using the Lane model they have analyzed the complete set of

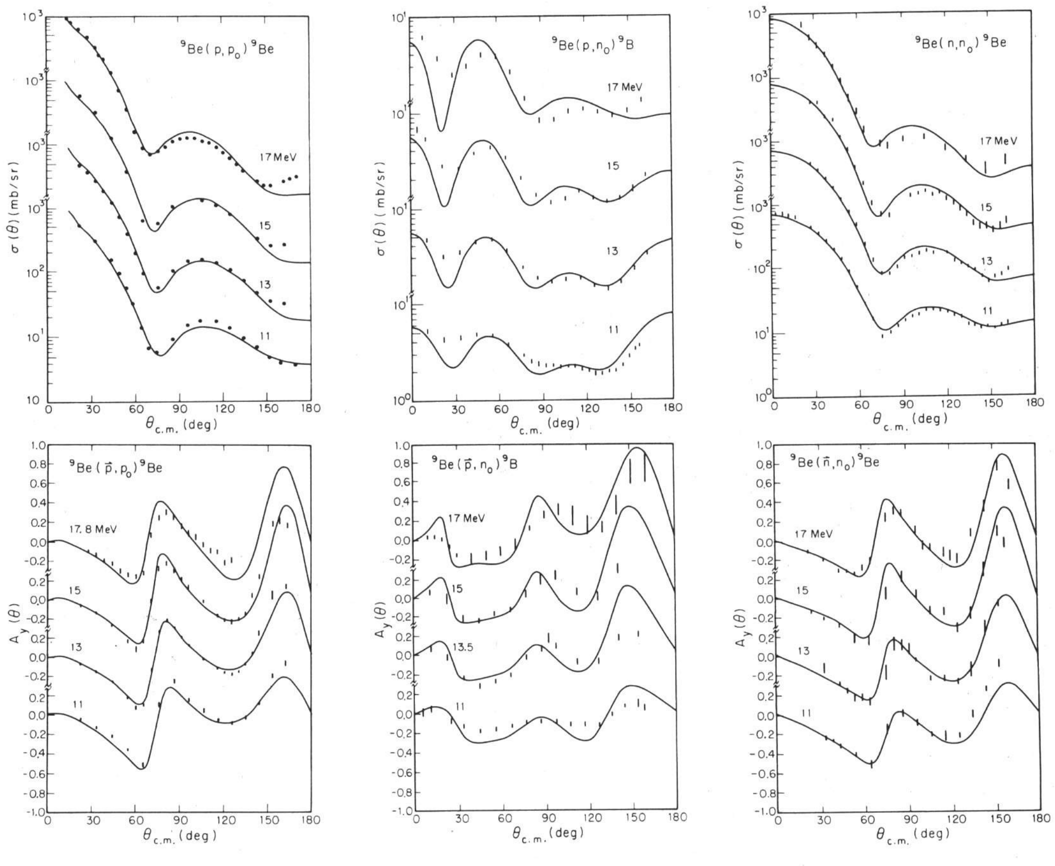


Fig. 1. Comparison of Lane model calculations to data for $^{9}$Be.

(p,p), (p,n) and (n,n) cross section and analyzing power data and have obtained a satisfactory description of the data (see Fig. 1). In this way, Murphy et al. have found strong confirmatory evidence for a complex isovector potential.

Fig. 2 shows the complete scattering data of Yosoi et al.[2] for p - $^{40}$Ca elastic scattering at 65 MeV: the cross section, analyzing power and spin-rotation or Wolfenstein R-parameter. The use of an energy in the intermediate energy range and the measurement of the spin-rotation parameter allows one to gain more information about the spin-orbit interaction. In this case, the Kyoto group found that the spin-rotation parameter is particularly sensitive to the imaginary part of the spin-orbit potential.

Fig.3 shows the real central potential for the d + $^{32}$S system at 52 MeV extracted by Clement et al.[3] from cross section and vector analyzing power measurements of the angular distributions. The inclusion of the analyzing power data is essential to allow one to separate out the real spin-orbit interaction. Their result is shown by the solid curve. Also shown by the dotted curve is the double-folding model potential in the frozen density approximation. It is seen that this curve is considerably more diffuse than the

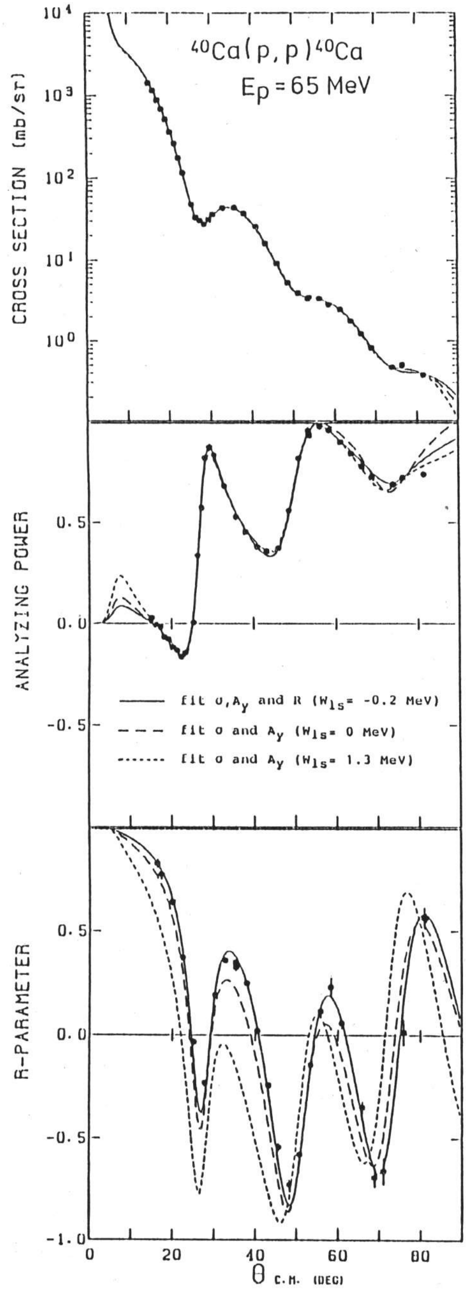


Fig. 2. Angular distributions of the cross sections, the analyzing powers and the spin-rotation parameters (R) for p - $^{40}$Ca.

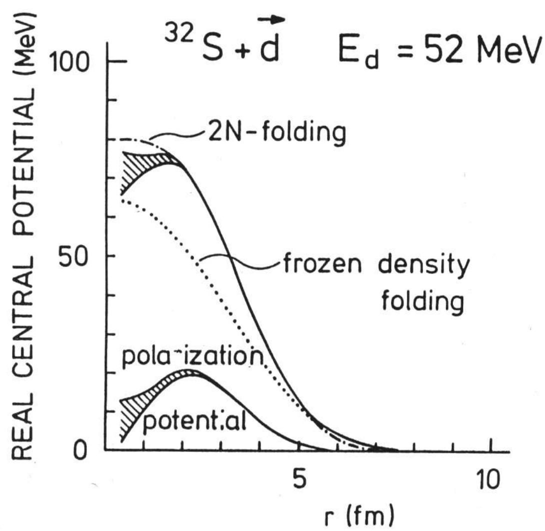


Fig. 3. Real central potential for d + $^{32}$S resulting from the FB-analysis compared with frozen density folding (dotted line) and δ-function folding (dash-dot line).

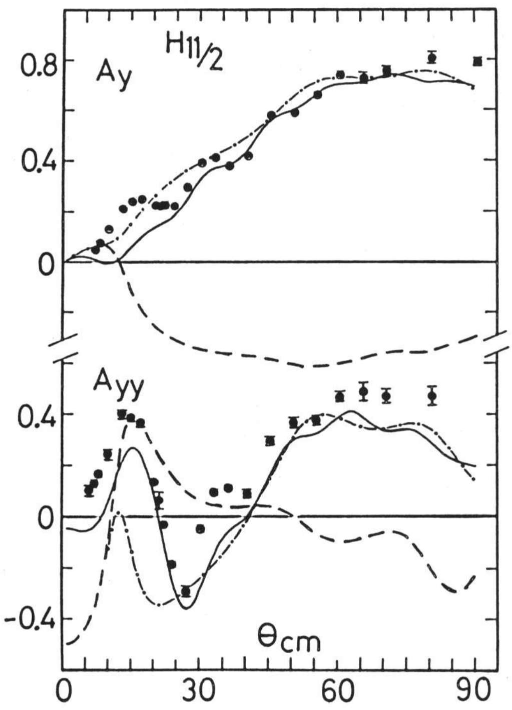


Fig. 4. Near-side (dash curve) and far-side (dash-dot curve) contributions to the calculated analyzing powers in the $^{116}Sn(d,p)^{117}Sn$ ($11/2^-$) transition.

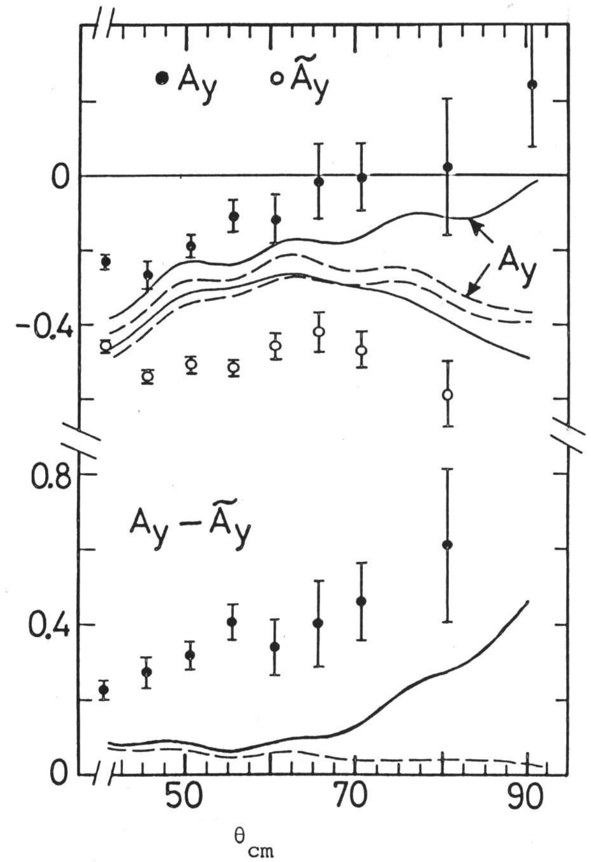


Fig. 5. Calculated and experimental $A_y$, $\tilde{A}_y$ and their difference for $^{116}Sn(d,p)^{117}Sn(7/2^+$, 0.71 MeV) at 79 MeV.

phenomenological potential parametrized in terms of a Woods-Saxon form-factor plus Fourier-Bessel type terms. Clement et al. attribute the difference in the potentials, which is measured by the effective dynamical polarization potential, as arising from the neglect of deuteron breakup effects. Assuming a $\delta$-function for the effective deuteron point density, they obtain the dash-dot curve which agrees closely with the solid curve. Thus Clement et al. conclude that the effective size of deuterons in nuclear matter is very small.

§3 Reaction mechanism

The Indiana-Surrey collaboration has studied the $^{116}Sn(d,p)^{117}Sn$ reaction at 79 MeV in order to test the accuracy of the DWBA at higher energies. In particular, the $\ell=0$ ground state transition, which is highly momentum mismatched at this energy, provides a good test of the one-step approximation. Stephenson et al.[4] found that the DWBA provided qualitative agreement with the data, which included $A_y$, $p_y$ and $A_{yy}$ polarization observables. For large orbital angular momentum transfer, very marked j-dependences at large angles were found for both the vector ($A_y$) and tensor ($A_{yy}$) analyzing powers. Tostevin et al.[5] show that these effects arise from the dominance of the far-side reaction amplitude (see Fig. 4). In another contribution, Johnson et al.[6] show that such a mechanism implies strong constraints upon the polarization observables. In particular, the vector ($A_y$) and tensor ($A_{yy}$) analyzing powers and proton polarization ($p_y$) are no longer independent for $j=\ell-1/2$ transitions:

(neglecting deuteron spin-flip terms)

$$A_{yy} + 3A_y + 2 = 0 \quad (1)$$

$$2p_y + A_{yy} - A_y = 0 \quad (2)$$

$$3p_y + 2A_{yy} + 1 = 0. \quad (3)$$

Such relations are very useful for testing the underlying reaction mechanism. Fig. 5 shows the results of Stephenson et al.[7] for the transition to the $7/2^+$ 0.71 MeV state. The dashed curves neglect the deuteron D-state and in this case $\tilde{A}_y = -(A_{yy}+2)/3 \simeq A_y$. However, the data differ significantly from these predictions. Inclusion of the D-state (solid curves) improves the agreement with experiment but the $A_y - \tilde{A}_y$ difference is still underestimated by a factor of about two. It remains to be seen whether a more sophisticated treatment of deuteron breakup effects can account for this discrepancy.

Sakai et al.[8] have measured the cross sections and analyzing powers of the continuum energy spectra for the $^{58}$Ni(p,p'X) reaction for a wide range of bombarding energies (35-80 MeV). They found that one-step DWBA calculations reproduce the differential cross sections but do not describe the analyzing powers very well (see dash curves of Fig. 6). The Osaka group also found the very interesting result (see Fig. 7) that if the analyzing powers are plotted as a function of the transferred momentum $q = |k_p - k_{p'}|$, the analyzing powers show a peak at $q \sim 2\ \text{fm}^{-1}$ independent of bombarding energy. This q-scaling which is not predicted by the DWBA calculations is unexpected and its origin needs to be investigated. It remains to be seen whether

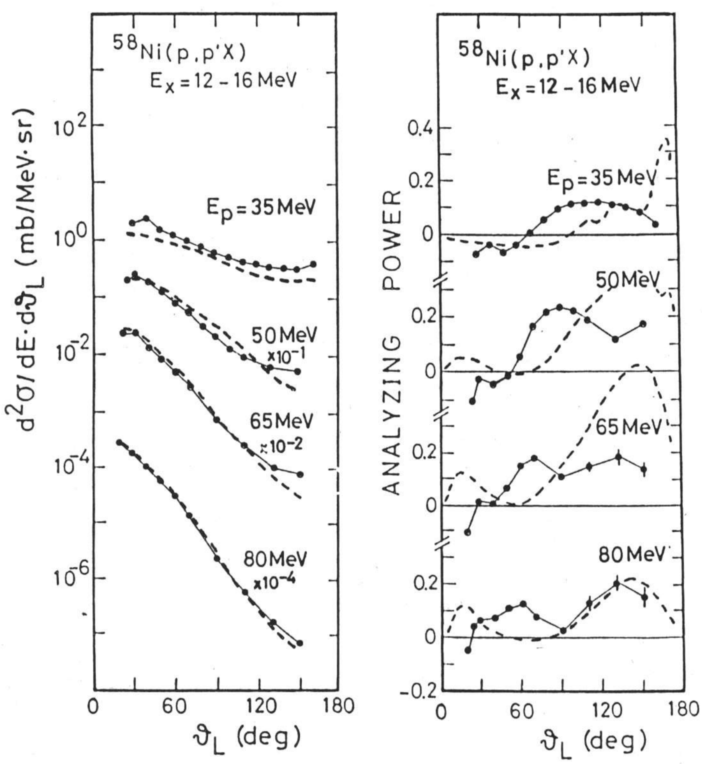


Fig. 6. $d^2\sigma/d\Omega dE$ and $A_y$ vs. $\theta_{lab}$ for the continuum region of $E_x$=12-16 MeV.

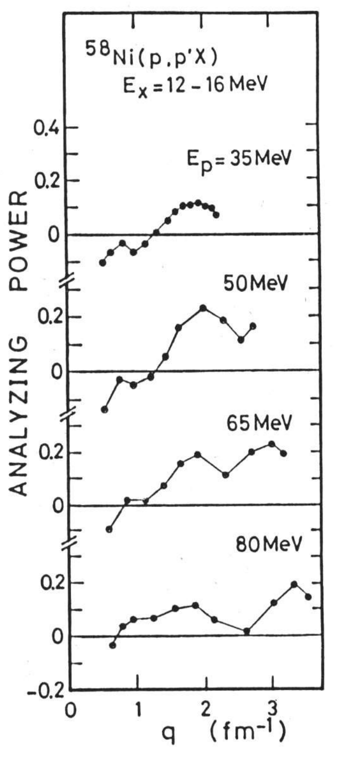


Fig. 7. $A_y$ vs. q (momentum transfer).

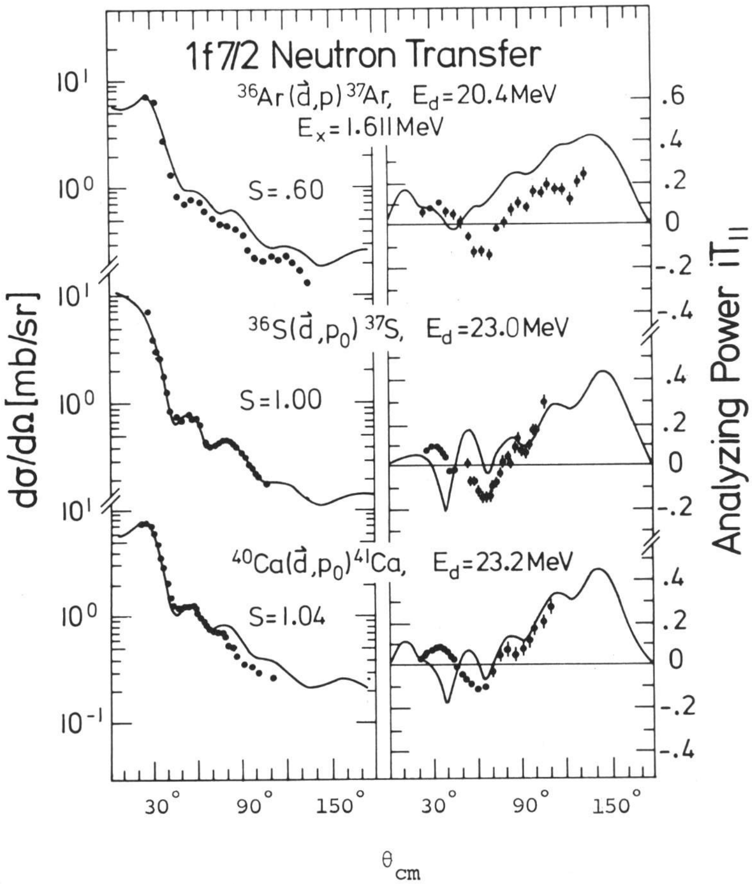


Fig. 8. Transfer data with DWBA curves.

more sophisticated multi-step theories can describe these novel results or whether they represent some structure effects or nuclear dynamics in the continuum reaction process.

The Munich group of Seichert et al.[9] in their systematic studies of (d,p) reactions have also discovered an anomalous result. Fig. 8 shows the cross section and analyzing power data for three 1f7/2 transitions involving $^{36}Ar$, $^{36}S$ and $^{40}Ca$ targets near 23 MeV bombarding energy. While standard DWBA calculations using global optical model parameters give a good description of the cross sections and analyzing powers for most of the observed transitions, they provide a poor description of the analyzing powers for $20^\circ \leq \theta_{cm} \leq 70^\circ$ for the 1f7/2 transitions. The origin of this discrepancy is still an open question.

§4 Nuclear structure

Kurokawa et al.[10] from Tsukuba have measured the cross section and analyzing power at 22 MeV for the reaction $^{208}Pb(p,t)^{206}Pb(3_2^+)$ and compare them with those for the $3_1^+$ transition. Fig. 9 shows that the analyzing powers for the two transitions are of opposite signs. These transitions to unnatural parity states are completely forbidden within the framework of a one-step zero-range DWBA approach. However, the reactions can proceed by a one-step process if a more sophisticated finite-range DWBA method is used or alternatively via the sequential (p,d), (d,t) two-step process. In an earlier analysis, Igarashi and Kubo[11] show that such data can tell us a good deal about the one-step and two-step contributions to the reaction mechanism in addition to the two-neutron hole configuration of the $^{206}$Pb states. This is because at forward angles, the analyzing powers for the one-step and two-step processes tend to have opposite signs and both depend strongly on the j-configuration of the nuclear wave function.

A different example is the work of Matsuki et al.[12)] who have investigated the structure of nuclei from Ge to Sr with valence neutrons in the 1g9/2 shell. This Kyoto group measured cross sections and analyzing powers for inelastic proton scattering from the first $4^+$ states. These are particularly sensitive to the sign of the $\beta_4$ deformation. Using coupled-channels techniques they have extracted a comprehensive set of hexadecapole moments, which are shown in Fig. 10. Such systematic data are very useful for understanding the structure of these nuclei.

## §5 Conclusion

The above examples show that polarization measurements are crucial for extracting important information about nuclear interactions, reaction mechanisms and nuclear structure.

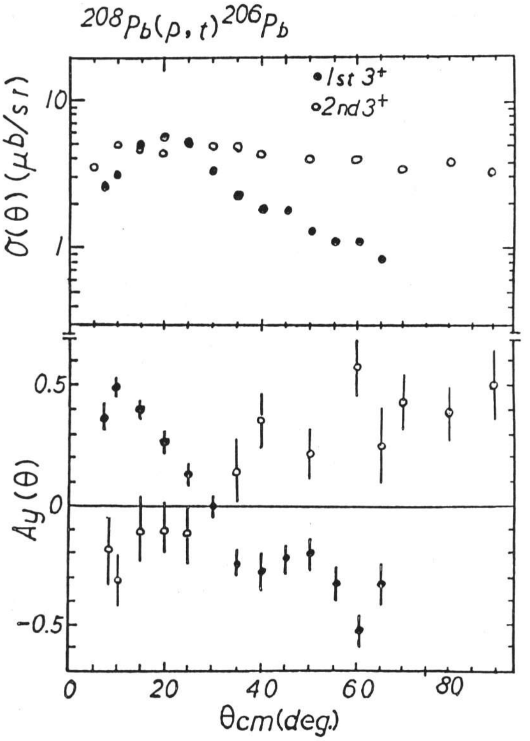


Fig. 9. Cross sections and analyzing powers for the $^{208}$Pb(p,t)$^{206}$Pb($3_1^+$,$3_2^+$) reaction at $E_p$=22 MeV.

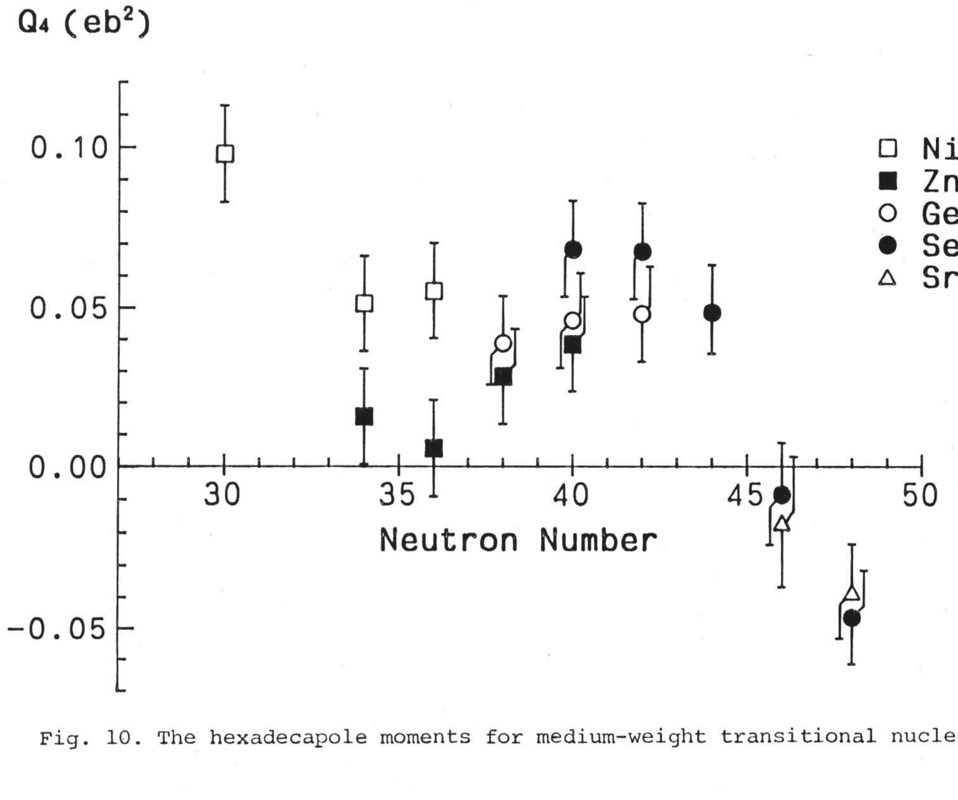


Fig. 10. The hexadecapole moments for medium-weight transitional nuclei.

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