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P. Doll

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NUCLEAR HOLE STATES AS A PROBE OF THE NUCLEAR MANY BODY SYSTEM*

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ABSTRACT

Nuclear hole states studied in proton and neutron pick-up reactions on light and heavy target nuclei exhibit -- for deeply-bound shell model orbits -- properties, which are strongly affected by target nucleus collectivities. Quasiparticle-like holes in nuclei are formed showing features very similar to those of other highly excited modes e.g. giant quadrupole resonances.

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Introduction

One of the most striking features of finite nuclei is the validity of the shell model. The long mean free path of the nucleons implies that each of them feels independently a smoothly varying average potential. In case of rotational symmetry of the nuclear system single particle states in such a potential are well defined by their angular momentum quantum numbers ℓ,j and by their single particle energies $\varepsilon_{\ell,j}$. In the past, [1,2] one nucleon transfer reactions into orbits above and out of orbits below the Fermi surface have given valuable information concerning the central shell model potential that the nucleons feel, and about the spatial, spin and isospin dependent terms in the residual interaction with neighbouring nucleons.

When one comes to study deeply-bound hole states well below the Fermi surface, one can expect interesting features showing deviations from bare single-particle properties. The hole is surrounded by many nucleons and interacts with them through a highly non-local potential[3]. For deeply-bound hole states the energy of the hole becomes comparable with or larger than the excitation energy of collective modes in the same nucleus. The long range part of the residual interaction will then couple[4] the hole-state to these collective degrees of freedom. In this way a deeply-bound hole state becomes a sensitive probe of the nuclear many body system and a specific tool

for investigating the spreading mechanism which "dissolves" the single-particle modes as they are buried below the Fermi surface[5].

The hole-vibration coupling in the nucleus is analogous to the displacement potentials employed in the analysis of various condensed atomic systems. Fröhlich[6] has derived the Hamiltonian which describes the coupling of an electron wave function $|k\rangle$ to the lattice vibrations ω_q giving rise to superconducting electron pairs.

$$H^{(k)}_{coupl} \propto \sum_q |q| (2\rho\omega_q)^{-\frac{1}{2}} \; C^+_{k+q} \; C_k (a_q - a^+_{-q})$$

The operators C_k and a_q are acting in the electron and phonon space, respectively. As result of this coupling, the single-particle states are clothed in a cloud of vibrational quanta. The electron kinetic energy is lowered while its effective mass m^* increases. Similarly, the phonon energy and phonon strength are expected to become renormalized through this interaction. It can be shown that it is not the elementary electron moving in a continuous translationally invariant ion potential, but rather the quasi-electron surrounded by its phonon cloud that represents an eigenstate of the solid state system.

The microscopic analogy in a nuclear system means that the removal of a nucleon from an inner shell model orbit does not lead directly to a stationary state of the residual nucleus - rather, a quasihole[7,8] is

formed, characterized by parameters which differ from elementary single-particle properties. Therefore, in the excitation spectrum of the residual nucleus we can not expect a single isolated hole state, but rather a "distorted" state consisting of a bulk of levels with fixed spin j and parity $(-)^{\ell}$.

The ^{39}Ca spectrum (see fig. 1) investigated in the $^{40}Ca(d,t)^{39}Ca$ neutron pick-up reaction[9] at 52 MeV incident energy may serve as an example which I want to discuss briefly: The ground state belongs to pick-up from the outer $1d_{3/2}$ shell and the 2.47 MeV state to that of the inner $2s_{1/2}$ shell. Nearly all levels observed between 4.5 MeV and 9 MeV of excitation show an angular distribution characteristic of $\ell = 2$ transfer and are attributed to pick-up from the deeply-bound $1d_{5/2}$ shell. Angular momenta ℓ and spin j were assigned to the isolated levels by measuring their angular distributions and vector analyzing powers iT_{11} as shown in figure 2. Similar energy spectra have been obtained for all proton and neutron pick-up reactions measured on Argon[10], Calcium[9] and Titanium[11] target nuclei. In all the spectra we observed a large fragmentation of the $1d_{5/2}$ hole strength. While the DWBA analysis for the low-lying $1d_{3/2}$ and $2s_{1/2}$ levels nearly gives the full shell model strength of 2j+1 nucleons - up to 40% of the summed $1d_{5/2}$ strength is missing, depending on the excitation energy limit (e.g. $E_x \leq E_o \cong 9$ MeV in fig. 1) up to which the spectra of the residual nuclei could be evaluated.

Quasihole Model

Since we are dealing with a discrete strength distribution, it is trivial to ask for the short-time behaviour of the hole created within a system of interacting Fermi particles. By analogy with the optical model the quasihole features are obtained[12] by averaging the strength distribution in an energy interval large compared to the average spacing of the levels. So called intermediate structures become visible, revealing the location of doorway states through which the primarily created hole propagates into the complicated eigenstates.

Our aim was to understand these intermediate structures in a hole-phonon coupling approach[12,13]. For that purpose we calculated the decay of the "unperturbed" $1d_{5/2}$ hole state into a limited number of doorway states. These doorway states consist of holes in outer shells coupled to low-lying collective target states. We used the usual hole-phonon interaction[4], linear[13] in the vibrational coordinates $\alpha_{\lambda\mu}$

$$H^{(\lambda)}_{coupl} \propto \sum_{\mu} \beta_{\lambda} (2\lambda+1)^{-1/2} \, Y^{+}_{\lambda\mu} (\alpha_{\lambda\mu} + (-)^{\mu} \alpha^{+}_{\lambda-\mu}),$$

and which is completely determined by the collective strength β_{λ} of the corresponding target state. The calculated $1d_{5/2}$ spectroscopic factors for the collective doorway states were again folded with a normalized Gaussian to account for their further decay into non collective background states. In fig. 3 we compare for all residual nuclei which were studied, the

experimental distributions (solid curves) with the calculated ones (dashed curves).

To make a quantitative comparison between the experimental and model distributions, we have calculated their lowest energy moments from the solid and dashed curves. The first moment defines the mean removal or binding energy of the $1d_{5/2}$ quasihole:

$$\varepsilon = \int_0^\infty E\, S_{5/2}(E)dE$$

The center part of fig. 4 shows the result of the integration. The experimental mean removal energies given by squares are quite well reproduced by the model (open circles) where integration up to the same excitation energy limit E_o (indicated by arrows in fig. 3.) was applied. This means that the model accounts for the energy shift [14] from the unperturbed $1d_{5/2}$ single-particle energies $\varepsilon_{5/2}$ (full circles in fig. 4), which were used as input parameters in the calculations, to the measured quasihole energies. As known from the theory of superconductivity[15], hole-phonon coupling leads to a closer spacing of the single-particle levels near the Fermi energy. The same behaviour is found in the center part of fig. 4 where the Fermi energy for each nucleus is quoted as $\varepsilon_{3/2}$. Figure 4 also shows the energy $\varepsilon(2^+) = \hbar\omega_2 + E^{sep}(g.s.)$ of the lowest 2^+ target state (triangles) to demonstrate its dominant role in renormalizing single-particle energies.

Also, other energy moments are well reproduced by the model as shown in

the top and bottom part of fig. 4. The spreading width Γ e.g., defined in the following way

$$\Gamma^2 = \int_0^\infty (E - \varepsilon)^2 \, S_{5/2}(E) dE$$

determines the life-time of quasihole, while it decays through collisions with surrounding nucleons. This second energy moment is finite under the present considerations and proportional[16] to the strength of the phonon modes. Therefore, we may add also in the figure the β_2 values of the lowest 2^+ target state (triangles), to demonstrate the intimate role it plays in determining the life time of deeply-bound quasihole states.

In the framework of the solid state formalism[6] the following interesting equation is quoted

$$\frac{\hbar}{\tau} = \frac{16}{45\pi} \cdot \frac{\varepsilon_F^3 \; m^{*2}}{\hbar^3 \; \rho \; c_\ell}$$

relating the life time τ of a quasiparticle state to the longitudinal velocity of sound c_ℓ in the Fermi system under consideration. Taking an average $\hbar/\tau$ value of about 6 MeV ($\sim 2.35 \cdot \Gamma$, valid for a Gaussian line shape) and an effective mass $m^* \simeq 0.6 \; m_o$, which can be estimated[14,17] from the variation of th $1d_{5/2}$ single-particle strengths in the s,d and f,p shell nuclei under consideration, we obtain the longitudinal velocity of sound c_ℓ to be ~ 0.26 c for the nuclear Fermi system. From that value follows directly[18] the nuclear compressibility factor $k \cong 370$ MeV. This

factor is larger than recent findings from the frequency of the breathing mode in ^{208}Pb and ^{144}Sm (k $\sim$ 200 MeV)[19]. However both methods of extracting the nuclear compressibility factor k, require a more careful discussion of the parameters involved. At least the values are typical of those obtained with density dependent Skyrme-type forces (k $\sim$ 300 MeV).

"Giant-resonance-like" aspects

Studies of deeply-bound hole states for a long time were thought to be limited to light nuclear systems due to the rapid increase of the level density in heavy nuclei. It was only through recent work at Tokyo[20] and Groningen[21] that it was shown that pick-up from inner shells in heavy nuclei does occur and is present in the continuous part of the pick-up spectra. S. Y. van der Werf and coworkers[21] studied the $1g_{9/2}$ neutron hole structure in a series of Tin and Palladium isotopes. They observed gross structure peaks riding on a continuous background which they could unfold into a narrow peak characteristic of pick-up from the $1g_{9/2}$ subshell and a broad side peak characteristic of pick-up from the next inner 2p shell. They also observed an increasing fragmentation of the $1g_{9/2}$ hole strength when going from ^{102}Pd to ^{110}Pd. These results were used to ask the question, whether this behaviour can be quantitatively linked to the collectivity of low lying target states in the Palladium nuclei.

To investigate this behaviour we looked for a nuclear system which shows a stronger variation of its collective properties with the mass number than the Paladium nuclei. We found that the even-even Samarium nuclei[22] besides showing a strong variation in the frequencies and transition strengths of the lowest 2^+ state, also have the property that their collective modes vary from vibrations around the spherical shape of ^{144}Sm rotational band sequences in ^{152}Sm. From this behaviour we expected a systematic renormalization of the $1g_{9/2}$ single-particle properties through coupling to these collective fields. In the proton pick-up reaction on ^{144}, ^{148}, ^{152}Sm[23] we observed indeed (see Fig. 5) "giant-resonance-like" gross structures standing out from an extremely low background and showing a strong variation of their centroid excitation energy (5 MeV, 4 MeV and 2.7 MeV for ^{144}Sm, ^{150}Sm and ^{152}Sm, respectively). Typical angular distributions from the ^{144}Sm(d,^{3}He)^{143}Pm reaction are shown in fig. 6. The occupation probability found in the region indicated by arrows in the energy spectra varies from 60% over 50% to about 40% of the $1g_{9/2}$ shell model occupation number when going from ^{144}Sm over ^{148}Sm to ^{152}Sm, respectively. Similar variations of the $1d_{5/2}$ occupation numbers in the light s,d and f,p shell nuclei are understood in terms of target dependent renormalization effects (see fig. 4).

With the observation of deeply-bound hole states in the region of high level densities in nuclei a comparison with a similar complicated excitation mode in the same target nucleus, e.g. a giant multipole

resonance can be drawn. Inelastic α-scattering data on $^{144,\ 148}Sm$ and ^{154}Sm[24], reveal a line shape of the giant quadrupole resonance (see fig. 7) which is very similar to that of the $1g_{9/2}$ hole state. The centroid excitation energy of the giant quadrupole resonance (13.0, 12.5, and 12.4 MeV for ^{144}Sm, ^{148}Sm, and ^{154}Sm, respectively) shows a similar mass dependence as the $1g_{9/2}$ quasihole energies. Also the spreading widths of the collective excitations increase in the same way as the hole widths with the mass number (see fig. 8). However, the collective mode properties show a weaker mass dependence than the hole properties, because the former are already embedded in higher level densities which is due to their higher excitation energy

Very recently available systematic ^{6}Li scattering data on various Ca nuclei[25] allow a similar comparison between giant quadrupole resonance properties and $1d_{5/2}$ quasihole properties: the giant quadrupole resonance centroid excitation energy decreases much more quickly from ^{40}Ca (17.9 MeV) to ^{44}Ca (16.8 MeV) than expected ($\sim A^{-1/3}$) and the width increases from 3.4 MeV to about 4.2 MeV. In ^{48}Ca, however, the centroid energy and the width are nearly identical with those in ^{40}Ca. This behaviour is very reminiscent (see fig. 4) of the variation of the energy and width of the $1d_{5/2}$ quasihole states we found in the same target nuclei.

Summary and Outlook

The similarity between these two complicated modes of excitation in light and heavy nuclei asks for a detailed theoretical interpretation. Both modes

are built up by a bulk of levels with fixed spin and parity in the continuum region of nuclei. Deeply bound hole states may, like giant multipole resonances, be interpreted as collective phenomena and, therefore, can represent a new tool for investigating the nuclear many body system. γ-decay measurements of these complicated modes, or nuclear photoeffect measurements of quasiholes, would provide the most direct access to their collective structure. However, such experiments are difficult to perform. On the other hand, light particle decay studies for the systems discussed here,will surely help to clarify their common microscopic features.

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Figure Captions

Fig. 1 Energy spectrum of the $^{40}Ca(d,t)^{39}Ca$ reaction.

Fig. 2 Angular distributions from the $^{40}Ca(d,t)^{39}Ca$ reaction (left hand side) and vector analyzing powers iT_{11} from the $^{40}C(d,^{3}He)\ ^{39}K$ reaction (right hand side in units of 0.1). Mirror relations between both residual nuclei allow to make identical spin assignments for corresponding mirror levels.

Fig. 3 Experimental (solid curve) and model (dashed curve) $1d_{5/2}$ proton-hole strength distributions versus excitation energy in the residual nucleus. Measured and calculated $1d_{3/2}$ spectroscopic factors are denoted by solid and dashed bars, respectively. The arrows indicate experimental energy limits.

Fig. 4 Experimental (squares) occupation numbers N, single-particle energies ε and spreading widths Γ for the $1d_{5/2}$ proton hole strength distributions in the residual nuclei. Corresponding model quantities are given by points (unrenormalized) and open circles (renormalized). The $1d_{3/2}$ single single-particle energies are also given as $\varepsilon_{3/2}$. Dominant collectivities are indicated by triangles.

Fig. 5 Energy spectra of ^{3}He particles resulting from the $(d,^{3}He)$ reaction on $^{144,\ 148,\ 152}Sm$, respectively.

Fig. 6 Angular distributions from the $^{144}Sm(d,^{3}He)^{143}Pm$ reaction. The solid curves represent DWBA calculations assuming quantum numbers as given

in the figure.

Fig. 7 Energy spectra of inelastically scattered α-particles from $^{144,\ 148,\ 154}Sm^{24)}$.

Fig. 8 Measured spreading widths of the $1g_{9/2}$hole state (full circles) and of the giant quadrupole resonance (open circles) in the nuclei $^{144,\ 148,\ 152,\ 154}Sm$. β_2 values for the lowest 2^+ state in the same target nuclei are indicated by triangles.

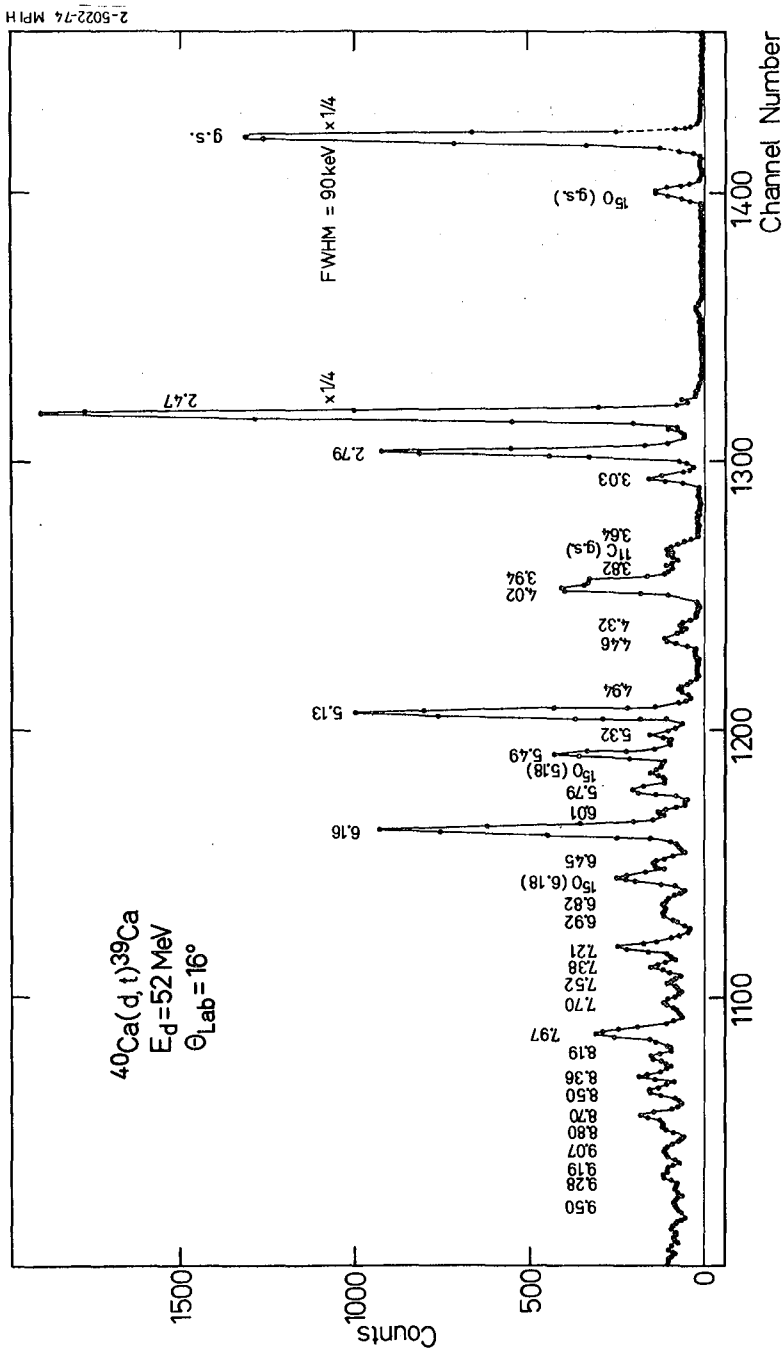

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Fig. 1

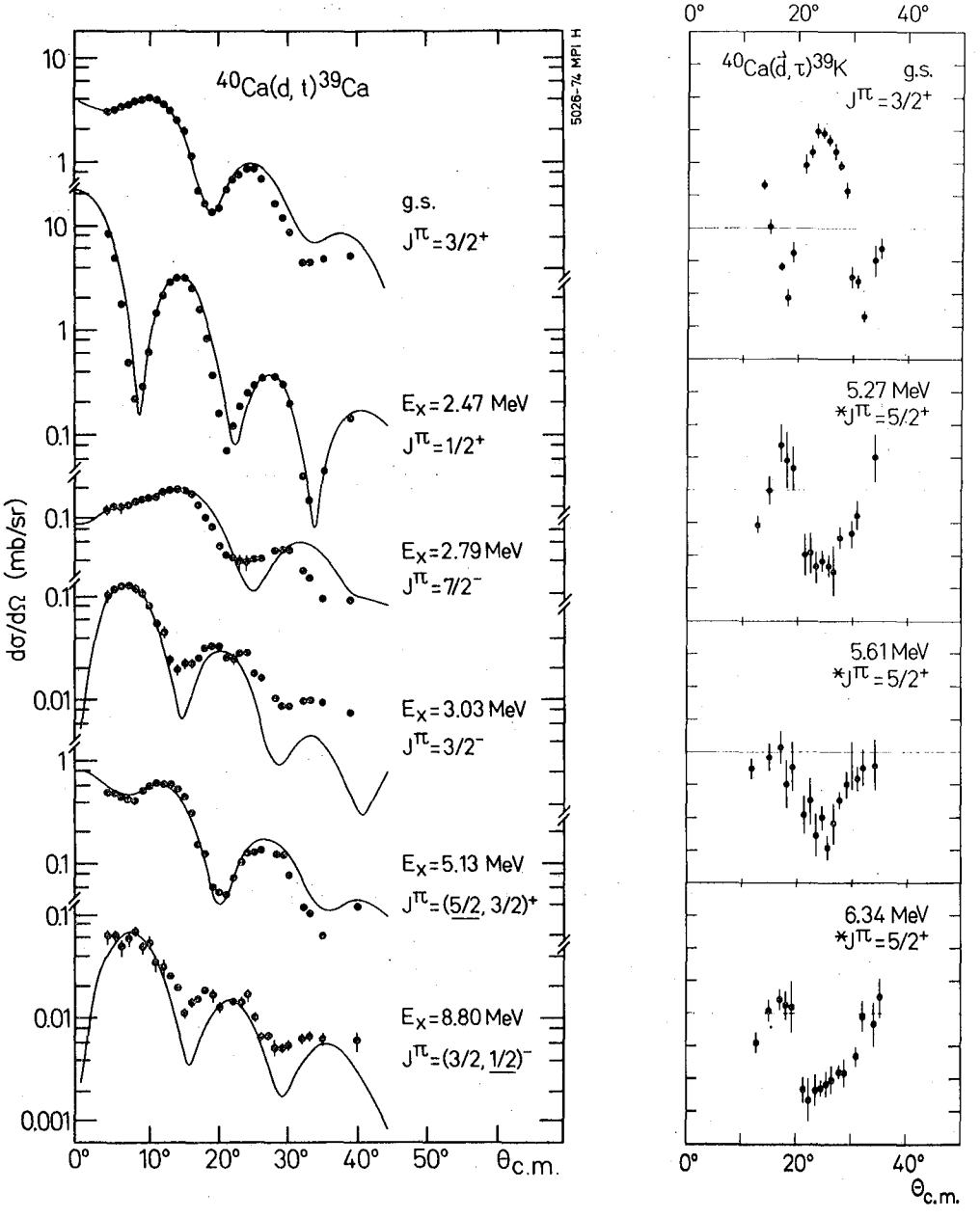

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Fig. 2

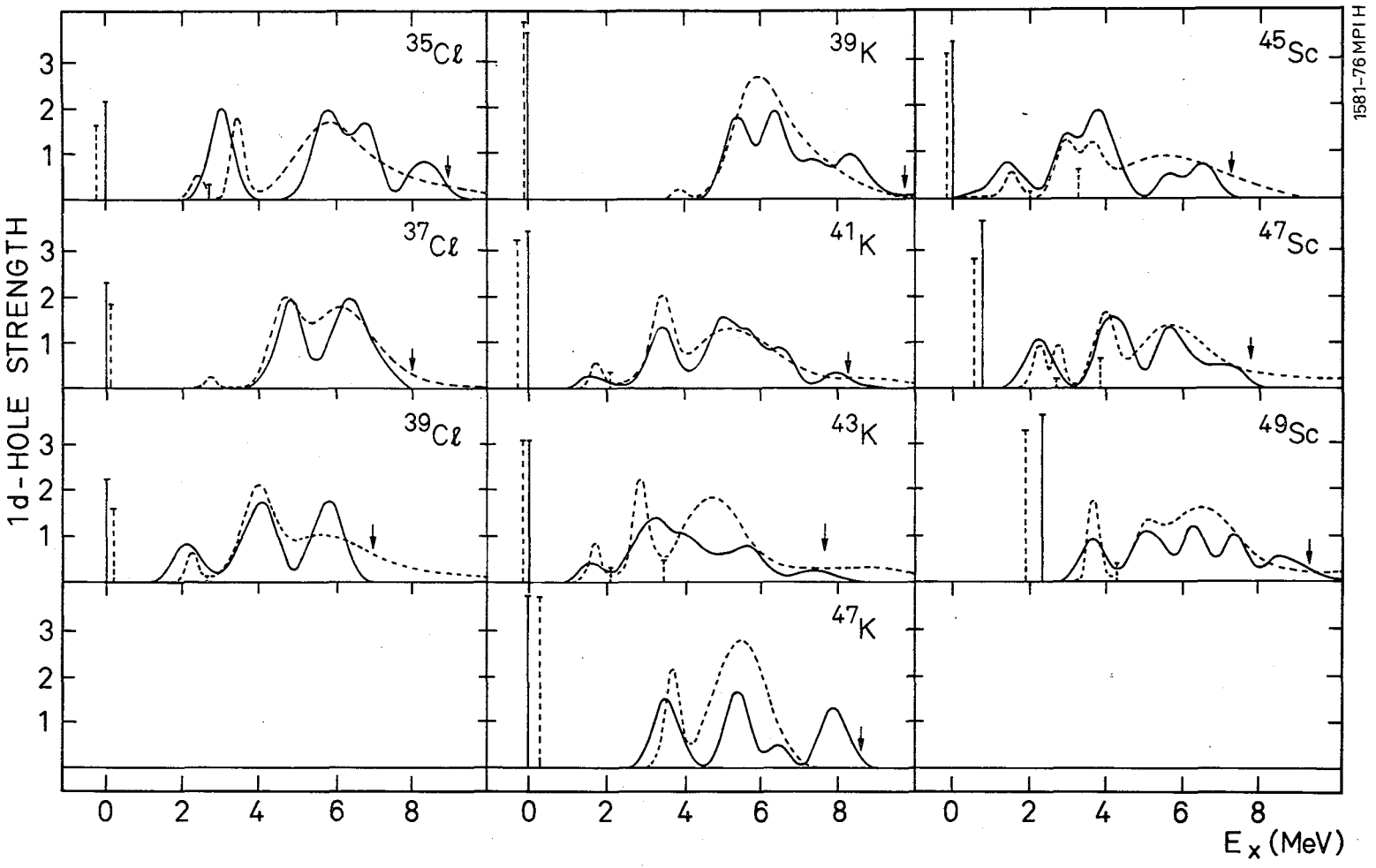

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Fig. 3

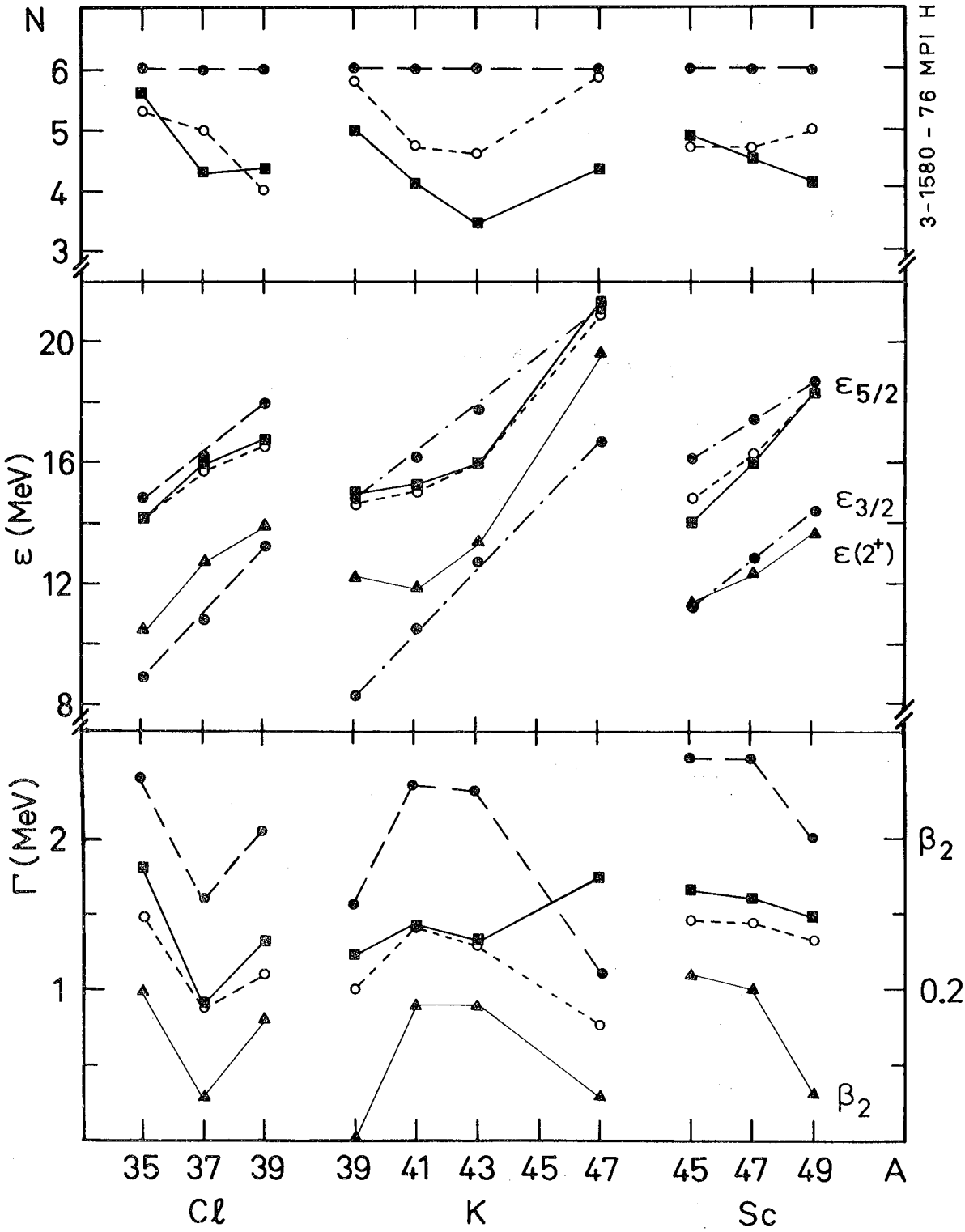

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Fig. 4

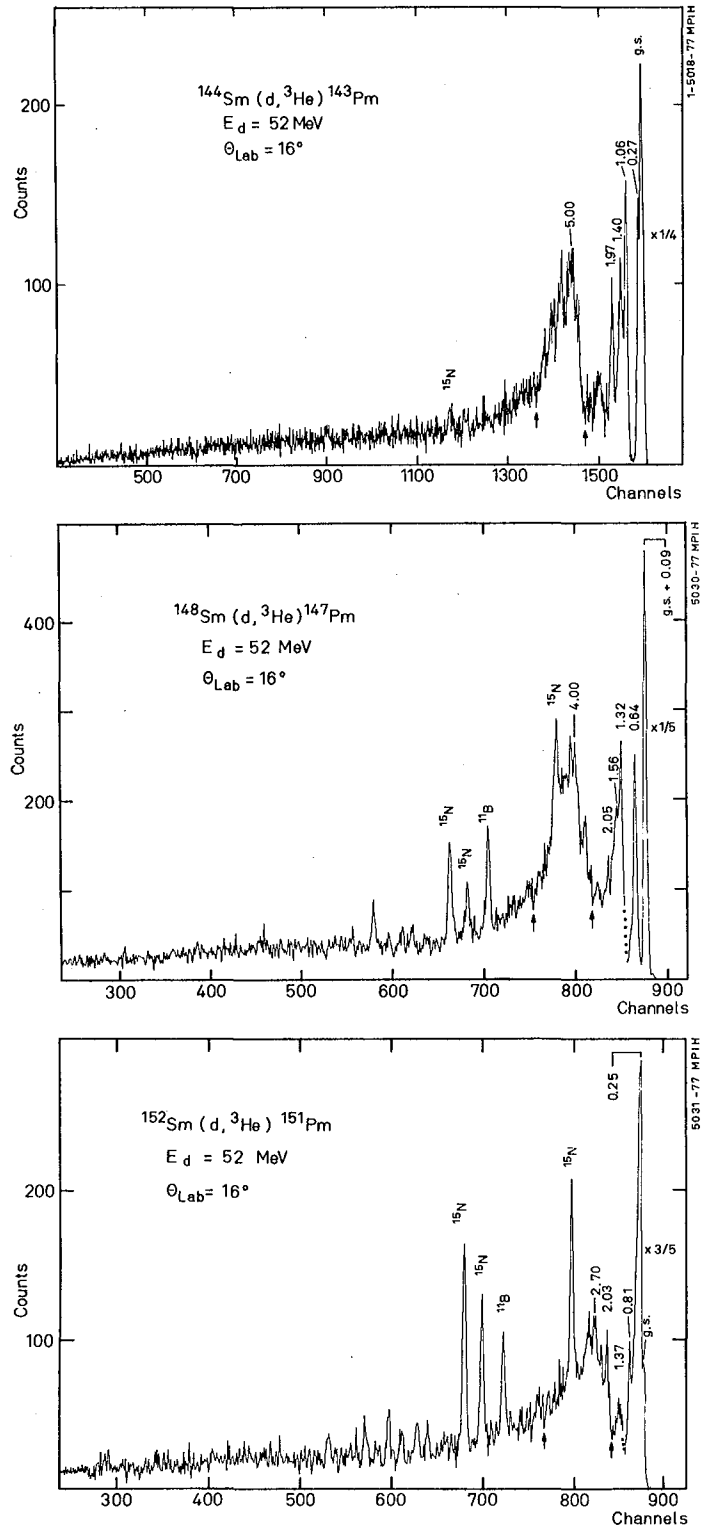

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Fig. 5

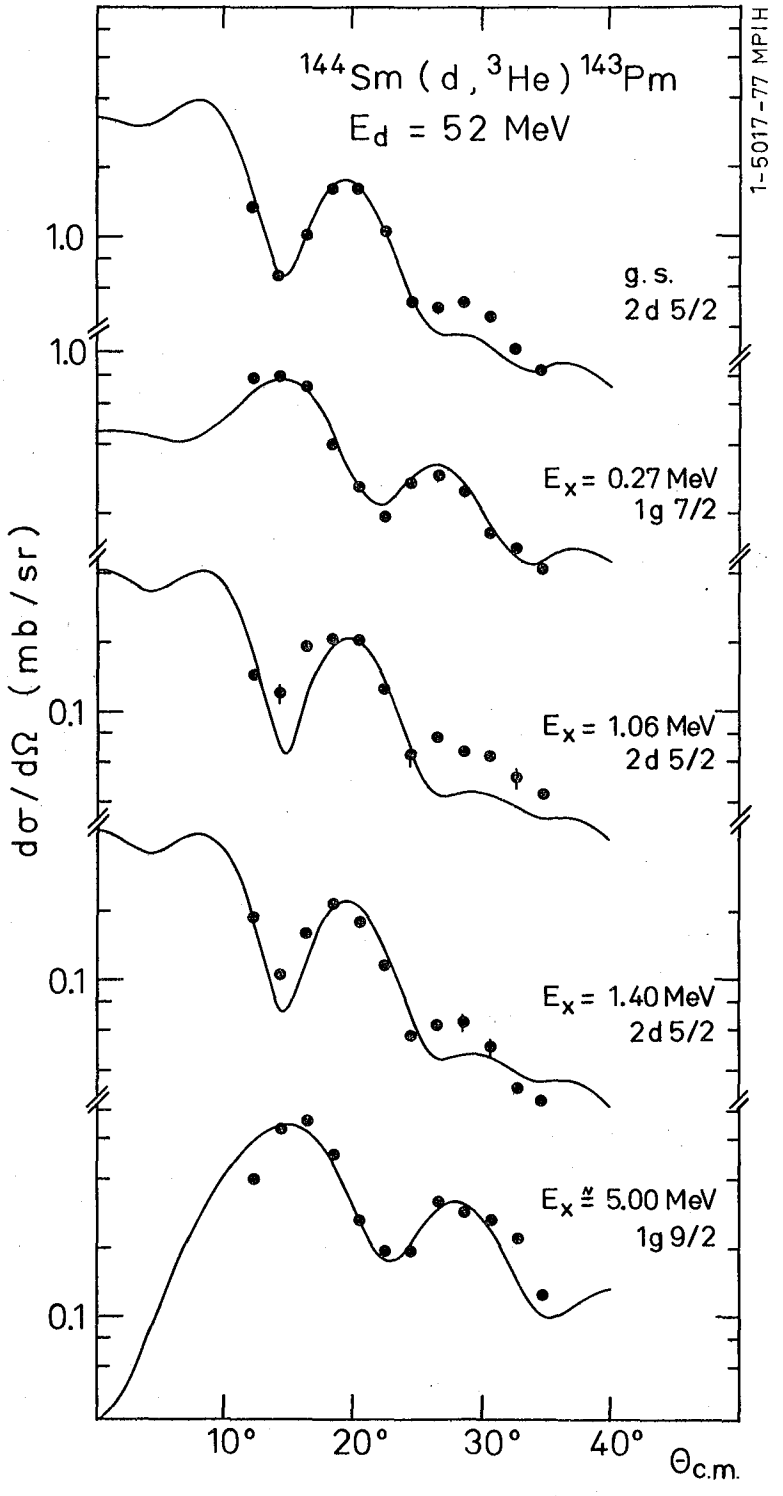

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Fig. 6

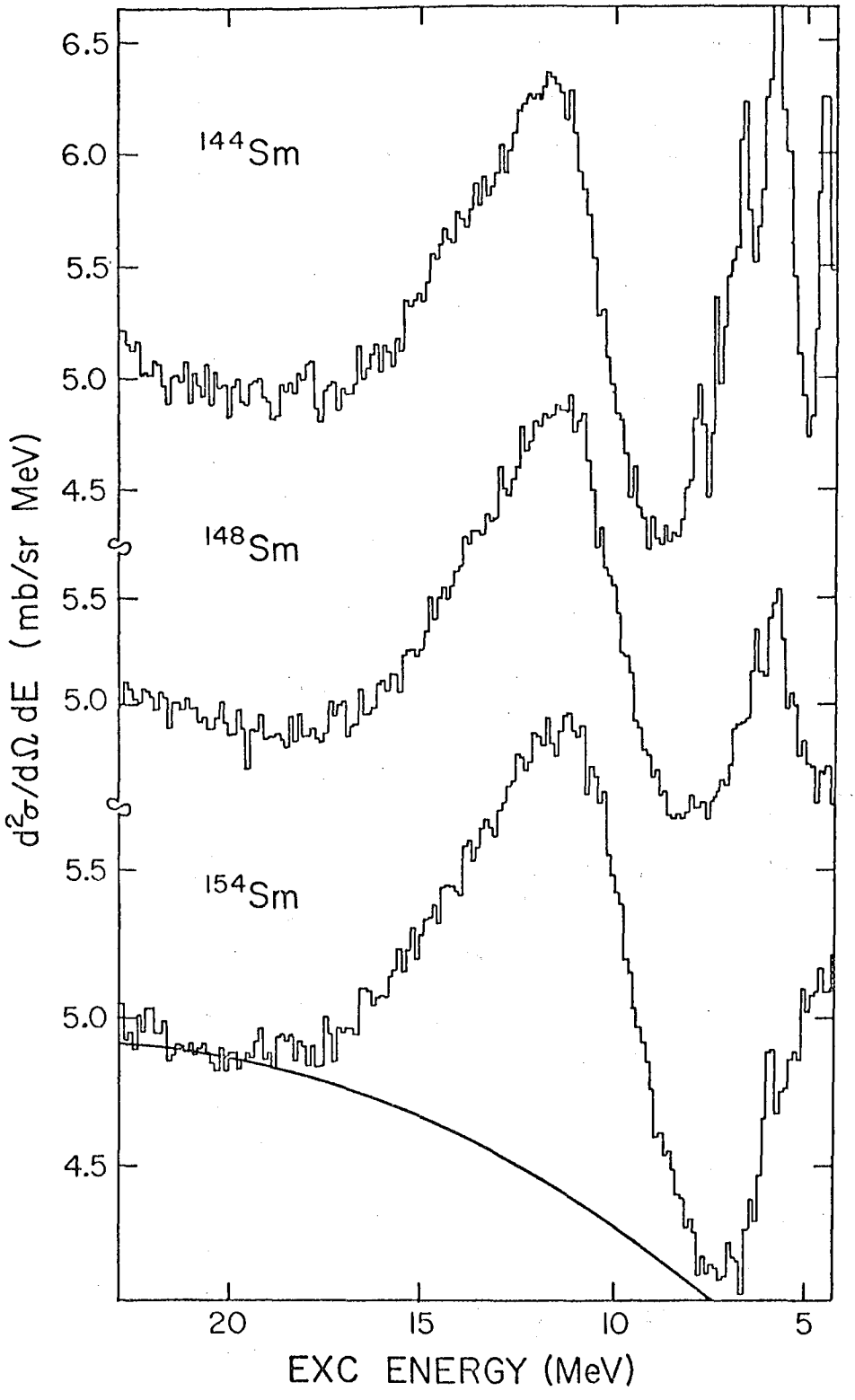

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Fig. 7

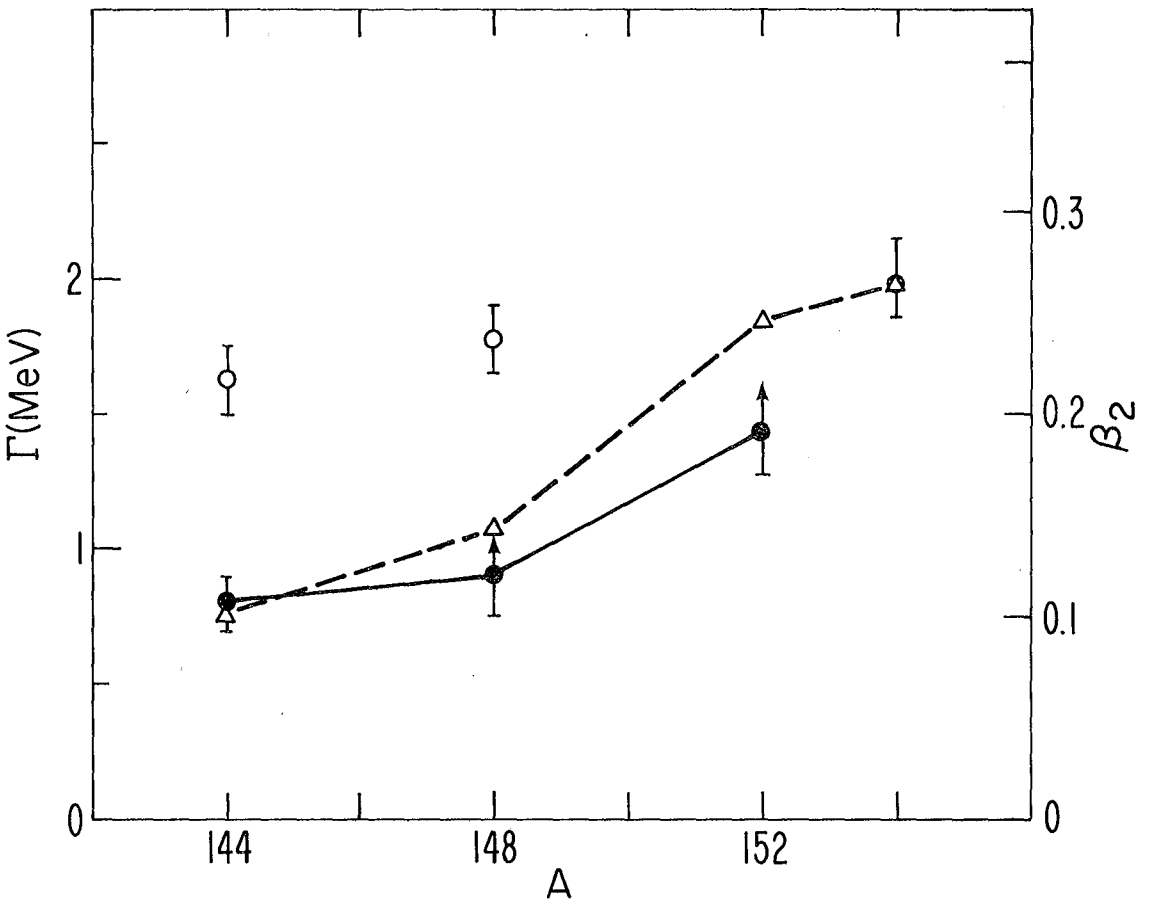

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Fig. 8

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