Anomalous Behavior of the (p,n) Analog Reaction on the Molybdenum Isotopes*

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Differential cross sections of the (p,n) reaction to the ground-state analogs of the stable Mo isotopes have been measured for proton energies between 16 and 26 MeV. The integrated cross sections deviate strongly from the linear dependence on $N-Z$ predicted by the $\vec{t}\cdot\vec{T}$ form of the isovector interaction commonly used to describe quasielastic scattering.

The excitation of isobaric analog states in (p,n) reactions[1] has generally been interpreted in terms of a direct charge-exchange process. This quasielastic scattering may be described by an isospin-dependent optical model in which the potential is assumed to include a term proportional to $\vec{t}\cdot\vec{T}$, the scalar product of the isospin operator of the incident nucleon and that of the target.[2] By solving the scattering problem with the use of either coupled-channel calculations[3] or the distorted-wave Born approximation,[4] this isovector interaction has yielded reasonable agreement with measured (p,n) analog differential cross sections. However, several authors[5,6] report being unable to reproduce the energy dependence of the (p,n) analog cross section by using standard optical-model potentials.[7]

An important test of the model may be made by examining the dependence of the cross section on the neutron excess, $N-Z$. Naively, one would expect the cross section to be proportional to the number of neutrons which could participate in the reaction. For the (p,n) analog reaction this is just those neutrons whose corresponding proton orbit is unfilled, that is $N-Z$. The prediction that the cross section be proportional to $N-Z$ is also correct quantum mechanically for the $\vec{t}\cdot\vec{T}$ interaction. In this Letter we present data which disagree strongly with this prediction and which clearly exhibit the anomalous energy dependence.

Differential cross sections for the (p,n) reaction to the isobaric analogs of the ground states of ^{92,94,95,96,97,98,100}Mo were measured by bombarding energies from 16 to 26 MeV in 2-MeV steps. Protons were accelerated by the Lawrence Livermore Laboratory cycloGraaff accelerator and pulsed-beam time-of-flight spectrometry was used to obtain the energy spectra of the emitted neutrons. The number of protons incident on the target was measured by integrating the current in a Faraday cup. Targets, in the form of rolled foils, were supplied by the Isotopes Division of Oak Ridge National Laboratory, and areal densities determined by weighing the foils and measuring their areas agreed to within 2%

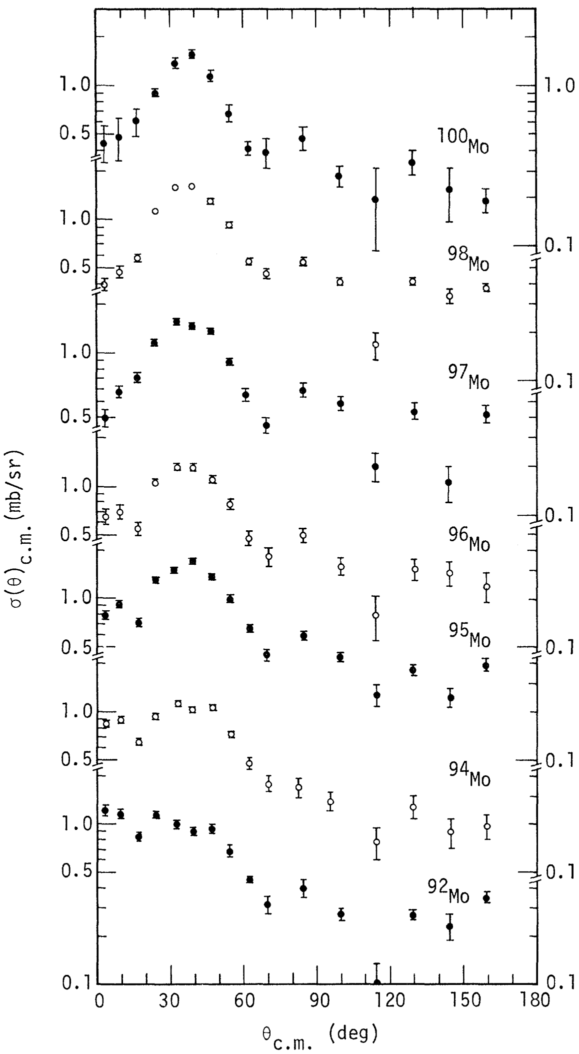

FIG. 1. 18-MeV c.m. differential cross sections for the (p,n) ground-state analog reactions on the Mo isotopes.

of the values quoted by Oak Ridge National Laboratory. In all cases, isotopic enrichment of the targets was greater than 93% and no evidence of target nonuniformities was observed. Figure 1 illustrates the data for each isotope at a bombarding energy of 18 MeV. The error bars include statistics and peak-separation errors only. Data taken on widely separated dates using the same target and energy were found to reproduce within these errors.

Each of the angular distributions was fitted with a series of Legendre polynomials in order to determine the integrated (p, n) ground-state analog cross section as a function of energy. The results for ^{95}Mo are shown in Fig. 2 where the error bars reflect statistical and peak-separation errors only—there is, in addition, a 7% scale error because of uncertainty in the absolute efficiency of the neutron detectors. Figure 2 also shows some of the lower-energy data of Miller and Garvey[8] obtained by detecting the proton decays ($\tilde{p}$) of the analog state and the higher-energy $\tilde{p}$ data from the University of California at Los Angeles.[9] (The latter data were arbitrarily increased by 30% in order to obtain agreement with the present data in the region of overlap.) The solid curve is the prediction of the isovector $\vec{t}\cdot\vec{T}$ model using a coupled-channel calculation.[3]

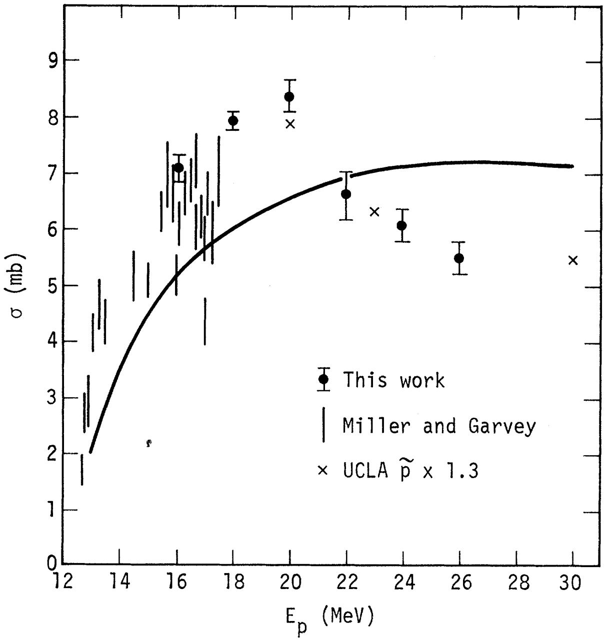

FIG. 2. Integrated cross section for the (p,n) ground-state analog reaction on ^{95}Mo as a function of proton bombarding energy. For clarity, not all of the data of Ref. 8 are shown.

The optical-model parameters for the entrance channel were those proposed by Becchetti and Greenlees[7] from their global fit of elastic scattering data, while the strength and form factor for the isovector interaction were chosen to correspond to the real and imaginary symmetry terms in their proton potential, thereby explicitly conserving isospin. This prediction increases smoothly from threshold to 26 MeV and does not reproduce the peak in the data at 20 MeV. Cross sections for the other isotopes are similar to that of ^{95}Mo, each exhibiting a maximum near 20 MeV, and, with the exception of ^{100}Mo, the rapid falloff at higher energies.

In order to study the dependence of the cross section on $N - Z$ and to attempt to remove the effect of the energy dependence the following procedure was adopted: The cross section for each isotope at a given energy was divided by the corresponding value of $N - Z$ and then normalized to the value for ^{96}Mo at that energy. According to the theory, this ratio should be close to unity.[10] Figure 3 illustrates the results plotted as a function of $N - Z$. For a given isotope the ratios obtained at different energies tend to cluster together and significant deviations from unity are seen. Because the average error for points in Fig. 3 is about ±0.09, agreement between measurements at different energies is within the errors, with the possible exception that the cross section for ^{100}Mo is increasing at the higher energies and does not have the same general shape

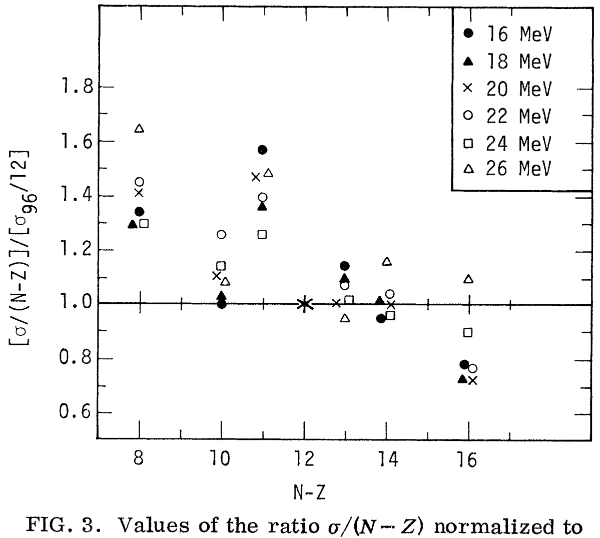

FIG. 3. Values of the ratio $\sigma/(N-Z)$ normalized to that of ^{96}Mo as a function of neutron excess. The different symbols identify the proton energy at which the cross section was measured. Some of the points have been displaced horizontally for clarity.

TABLE I. Average value of the ratio of integrated cross section to $N-Z$ normalized to the value for ^{96}Mo.

Isotope	$N-Z$	Ratio
^{92}Mo	8	1.36
^{94}Mo	10	1.07
^{95}Mo	11	1.41
^{96}Mo	12	1
^{97}Mo	13	1.06
^{98}Mo	14	1.01
^{100}Mo	16	0.79

as for the other isotopes. The ratios obtained at different energies were then averaged together and the results for each isotope are presented in Table I.

Although the ratios for the ^{94}Mo, ^{97}Mo, and ^{98}Mo cross sections are reasonably close to unity, it is seen that those for ^{92}Mo and ^{95}Mo are 40% too large, whereas that for ^{100}Mo is about 20% too low. Substantially the same results are found if the differential cross section at a maximum is studied—for example, the peak near 40° at 18 MeV shows ^{95}Mo to be about 44% high, whereas ^{92}Mo and ^{100}Mo are too high and too low, respectively, but the deviations are not as great as in the integrated cross section. Because ^{95}Mo is odd-A and has spin $\frac{5}{2}$ it is possible that even multipoles with $l=2$ and 4 may also contribute to the cross section,[11] which would suggest that the angular distribution for this isotope should be different from the others. Inspection of the data in Fig. 1 shows this not to be the case. Furthermore, ^{97}Mo also has spin $\frac{5}{2}$, but does not show an anomalously large relative cross section. Another process which might enhance the cross section for the odd-A nuclei is spin-flip, arising from terms in the two-body potential of the form $(\vec{s}_i\cdot\vec{s}_j)\times(\vec{t}_i\cdot\vec{t}_j)$. However, this process should only enhance the cross section by about 1%[12] and should be about the same for ^{95}Mo and ^{97}Mo.

The anomalous behavior of the cross sections for the even isotopes ^{92}Mo and ^{100}Mo cannot be explained by either the contribution of higher multipoles or by spin-flip because their spins are zero. One would expect their cross sections to differ by a factor of 2, the ratio of their neutron excesses; however, ^{100}Mo has a cross section which averages only about 16% greater than that for ^{92}Mo. Perhaps the explanation is associated with the fact that ^{92}Mo has a closed neutron shell, $1g_{9/2}$, while in ^{100}Mo the $1g_{7/2}$ shell is being filled. Both of these nuclei comprise different shells than the remaining isotopes in which the $2d_{5/2}$ shell is filling. However, while it is possible that the isospin potential strength and form factor may be shell dependent, one would still expect the cross section to increase monotonically with $N-Z$ within a given shell. For the $2d_{5/2}$ shell this is clearly violated by ^{95}Mo. Furthermore, the cross section decreases in going from the $1g_{9/2}$ to the $2d_{5/2}$ shell (^{92}Mo to ^{94}Mo) and from the $2d_{5/2}$ to the $1g_{7/2}$ shell (^{98}Mo to ^{100}Mo) whereas, if the ^{92}Mo or ^{98}Mo core is unaltered by adding two valence neutrons to form ^{94}Mo or ^{100}Mo, one would expect the cross section to increase.

In summary, the measured cross sections for the (p,n) analog reaction on the Mo isotopes are not, in general, proportional to $N-Z$ and the deviations cannot be accounted for in terms of refinements to the model such as spin-flip, the presence of higher multipoles, or simple shell effects. Furthermore, although the presence of exchange forces in microscopic calculations is known to be important,[13] their effect on the $N-Z$ dependence is not expected to vary in a discontinuous way within a given shell-model configuration.[14] The presence of the peak in the excitation function (Fig. 2) strongly suggests the effects of a single-particle resonance or perhaps even a giant multipole resonance,[15] but efforts to fit the data by including a resonance of given J in the coupled-channel calculations have so far been unsuccessful.

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[15] Y. Torizuka *et al.*, in *Proceedings of the International Conference on Photonuclear Reactions and Applications, Pacific Grove, California, 1973,* edited by B. L. Berman (Lawrence Livermore Laboratory, Livermore, Calif., 1973), p. 675. This reference reports evidence for an $E2$ isovector giant resonance whose excitation energy varies as (120 MeV)/$A^{1/3}$. For the Mo isotopes this corresponds to an incident proton energy of about 20 MeV.

Delayed-Neutron Spectra Following Decay of ^{85}As and ^{135}Sb

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The delayed-neutron spectra following decay of 2.05-sec ^{85}As and 1.7-sec ^{135}Sb are found to consist of a small number of discrete lines and the fluctuations in the experimental spectra differ significantly from those calculated with a statistical model. The data indicate that the β-strength function for these decays contains narrow resonances in the energy range 5–8 MeV.

The phenomenon of β-delayed–neutron emission provides an interesting tool for studying nuclear properties at intermediate excitation energies in nuclei far off the stability line. Most of the delayed-neutron precursors so far known have been found among the fission products. Since in such nuclei the neutrons are emitted from regions of high level density, it has been assumed in the past that the delayed-neutron spectra should have a continuous shape.[1,2]

Because of experimental difficulties, high-resolution neutron spectra of individual neutron emitters in the fission-product region were not known until recently.[3,4] Of particular interest are the neutron spectra of nuclei having a large energy window ($Q_\beta - B_n$) for neutron emission; Q_β is the β-decay energy of the precursor nuclide (e.g., ^{85}As) and B_n the neutron binding energy of the emitter nuclide (e.g., ^{85}Se). In such cases the properties governing this decay mode should be revealed most clearly.

We have investigated the delayed-neutron emission of two nuclides with large energy windows, 2.05-sec ^{85}As and 1.7-sec ^{135}Sb. According to mass formulas,[5] their Q_β values are estimated to amount to 9.1 and 7.5 MeV, respectively, and the B_n values to 4.1 and 3.9 MeV. These nuclides were obtained from thermal-neutron–induced fission by radiochemical separations based on hydride volatilization and purification through selective absorption.[6] The whole separation procedures were performed automatically and provided counting samples within 2.5 sec after the end of irradiation.

Delayed-neutron spectra were measured with commercially available ^{3}He-ionization chambers[7] which exhibited a resolution of 22 keV for 1.0-MeV neutrons in these experiments. Detector resolutions, response functions, and efficiencies were measured with monoenergetic neutrons from the reaction ^{7}Li$(p,n)^7$Be. The contribution of scattered neutrons was checked via the neutron spectrum of ^{17}N, and was found to be less than 4% beyond 100 keV. Singles and coincidence