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Nucleon Scattering from Mo Isotopes and the Lane Model

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(Received 18 September 1978)

A unified optical-model analysis of neutron and proton elastic scattering from Mo isotopes reveals breakdowns of the Lane model of $\vec{t}\cdot\vec{T}$ interactions, most clearly evident as shell effects. The puzzle is that a coupled–reaction-channel reanalysis does not remove these.

Recent analyses of neutron elastic-scattering data[1,2] on Mo isotopes have revealed some inconsistencies with the Lane model of $\vec{t}\cdot\vec{T}$ interactions.[3] The $(N-Z)$ dependence of the imaginary potential was opposite to that of the real potential, in contrast to the usual expectations. Problems have also been noted in the application of the Lane model in (p,n) reactions on molybdenum.[4]

The recent availability of excellent neutron-scattering data, in conjunction with existing proton-scattering data, enables more sensitive analyses of small effects in the scattering mechanisms. The Mo isotopes are especially appropriate for these. The asymmetry $\epsilon = (N-Z)/A$ nearly doubles between ^{92}Mo and ^{100}Mo. Inelastic-scattering cross sections to the lowest 2^+ states also increase by about a factor of 5, yet this onset of collectivity does not entirely mask shell effects.

A study of the influence of nuclear structure on nucleon scattering, and the implications for the Lane model, is reported here. Both neutron and proton scattering from even Mo isotopes are analyzed consistently with common geometries for the potentials. The best optical-model (OM) results for the volume integrals are inconsistent in significant ways with the predictions of the Lane model. An important discrepancy is the evidence for pronounced shell effects in the scattering from ^{92,100}Mo, very prominent for protons but nearly absent for neutrons. Couplings with deuteron intermediate channels are suggested. Coupled–reaction-channel (CRC) calculations are made that include couplings to 2^+ and 3^- states via inelastic scattering and to deuteron intermediate channels via pickup reactions, and the elastic data are refitted. Somewhat better consistency with the Lane model is found, but the shell effects remain large.

Elastic-scattering cross sections for 11-MeV neutrons from ^{92,96,98,100}Mo were obtained from Rapaport *et al.* and are described elsewhere.[1] They are corrected for very small compound-nucleus contributions and have absolute scales known to within 5%. Cross sections for 15-MeV protons on ^{92,94,96,98,100}Mo were measured with a ruler from enlarged figures from Lutz, Heikkinen, and Bartonlini,[5] the numbers being no longer extant. Normalizations had originally been made to the optical model. Inspection of the forward angles indicated that some readjustments of about ± 10%, for ^{96,98,100}Mo might be in order, and were applied. This uncertainty does not appear to affect the conclusions significantly. These data were supplemented with 14.5-MeV proton analyzing-power data,[6] averaged over Zr isotopes. The energies of 11 and 15 MeV have the advantage of differing by the Coulomb correction energy $0.4Z/A^{1/3} \simeq 4$ MeV.

Analysis was made with the search program CUPID.[7] The potentials were similar to those of Ref. 1, consisting of a real volume and imaginary derivative Woods-Saxon central terms and a conventional real spin-orbit term. Each data set showed a preference for the geometry of the real-central and spin-orbit terms to be nearly the same and this constraint was adopted. The spin-orbit well depth was held constant at -24 MeV.[8]

Optical-model searches on the individual data sets revealed some possible systematics regarding the projectile and/or mass dependence of the parameters. These were generally smooth except for occasional irregularities for ^{92,100}Mo. However, the χ^2 fitting parameter was weakly dependent on these trends and it proved to be reasonable and convenient to adopt a common geometry for each data set ($r_0 = r_{\mathrm{s.o.}} = 1.20$, $a = a_{\mathrm{s.o.}}$

$=0.68$, $r_0' = 1.20$, and $a' = 0.60$ fm). The influence on the systematics of the real and imaginary volume integrals per nucleon was smaller. The fits to the data are very similar to those in Refs. 1 and 5.

The results for the volume integrals are shown as solid points in Fig. 1. The Lane model[3] predicts that the neutron potentials should decrease with ϵ, and the proton potentials should increase, the slopes having the same magnitude. Difficulties are clearly apparent for V_p and W_n'. Although V_p for $^{94-98}$Mo seem reasonable, the values for ^{92,100}Mo are quite out of line and go in the wrong direction. The W_n' also slope up when they should slope down. While there my be some irregularity in the neutron potentials for ^{92,100}Mo, it is clear that *proton* scattering from these isotopes has unusual behavior.

What is the role of nuclear structure in this behavior? Since couplings to inelastic-scattering states should affect neutron and proton elastic scattering similarly, another explanation must be sought. This is found in the coupling to deuteron intermediate channels via pickup reactions. In the simple shell-model scheme suggested by Fig. 2, (n,d) reactions will always pick up the same $g_{9/2}$, $p_{1/2}$ and $p_{3/2}$, protons from Mo isotopes. However, (p,d) reactions are isotope dependent. For $^{94-98}$Mo, the main contribution will be from $d_{5/2}$ neutrons, while for ^{92}Mo we must consider $g_{9/2}$ and p-shell neutrons and, for ^{100}Mo, $s_{1/2}$ and $d_{5/2}$ particles are most important.[9] Explicit calculations also show that the cross sections resulting from the back-coupling amplitudes in the elastic channel are an order-of-magnitude or more larger for the (N,d,N) couplings than for the (N,N',N) couplings, where N designates nucleon. Finite-range effects have been found[10] to reduce (p,d,n) cross sections by about a factor of 3 and may be equally important here, although programs were not available for this evaluation. Nevertheless, the (N,d,N) couplings would still be significant and, furthermore, could possibly be enhanced by additions of more channels.

Hence we are led to consider CRC calculations and to refit the elastic-scattering data in this environment. This was done by use of interated applications of programs CUPID[7] and the zero-range CRC program CHUCK2.[11] Inelastic couplings with the lowest 2^+ and 3^- states were included, with deformation parameters taken from Ref. 5, and with Coulomb-excitation terms added for proton scattering. The spectroscopic amplitudes for the pickup transitions cited above were calculated from the assumed simple shell model.

A choice had to be made for the deuteron optical potential in the CRC calculations. A potential that fits deuteron elastic-scattering data[12] near 6 MeV resulted in very poor nucleon elastic-scat-

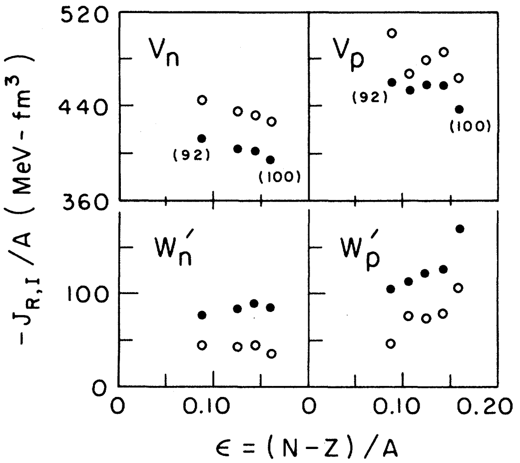

FIG. 1. Real and imaginary volume integrals per nucleon $J_{R,I}/A$ for nucleon scattering from Mo isotopes. Solid circles result from an optical-model analysis and open circles result from the CRC reanalysis. Each set is labeled by the potential used in the volume integral.

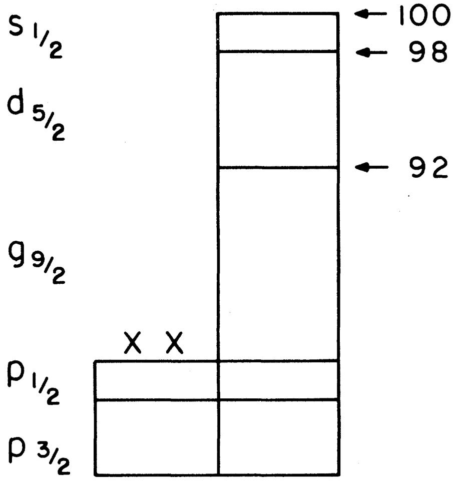

FIG. 2. Simple shell-model representation of the Mo isotopes. Neutrons fill the boxes on the right-hand side up to the levels marked by arrows for the labeled masses.

tering refits and anomalous parameters, a difficulty previously noted elsewhere.[13] A folded deuteron potential, evaluated in the Johnson-Soper method[14] from my own neutron and proton OM potentials extrapolated downward in energy, gave much better results. The refits are generally not quite as good as those with the optical model, but are very acceptable.

The importance of contributions from deuteron breakup and continuum p-n propagation in intermediate states has been receiving much attention recently.[13,15,16] The Johnson-Soper folding procedure[14] accounts for some of these. Only a few specilized programs can calculate some of the other effects.[15,16] The contributions are undoubtedly somewhat more important than is assumed here. Since the elastic-scattering data could be refitted reasonably well with the Johnson-Soper adiabatic potentials, it would seem that the remaining contributions were being simulated reasonably well in the final proton optical potential. More theoretical work on these problems is certainly needed.

Refitting the elastic-scattering data results, of course, in a new nucleon optical potential for use in the CRC calculations. It appeared that a geometry different from the original OM potential was preferred ($r_0 = r_{\rm s.o.} = 1.20$, $a = a_{\rm s.o.} = 0.62$, $r_0' = 1.22$, and $a' = 0.55$ fm). Again, this was taken to be common to all data sets. In fact, the trends referred to previously seemed to be reduced, suggesting that "best-fit" OM potentials might simulate some coupled-channel effects.

The volume integrals resulting from refitting the scattering data in the CRC environment are shown as open circles in Fig. 1. The channel couplings have a repulsive effect on the real well depths so that greater strength is needed in the CRC calculations. This is consistent with observations in other cases.[17,18] The imaginary well depths are reduced because account is made of some of the absorption processes.

There is some improvement in the systematics with regard to the Lane model. V_p for $^{94-98}$Mo have a very definite upward slope (perhaps too steep), although the presumed shell effects for ^{92,100}Mo are not eliminated. (They even appear to be enhanced.) Very significantly, the original upward slope for W_n' has now been changed to one that is approximately horizontal or slightly downward.

The calculations discussed here represent the beginnings of a new approach to the analysis of elastic-scattering data, particularly regarding the role of nuclear structure and neutron excess on the parametrizations. One may conclude that nuclear structure (i.e., shell-model effects) can have a very important influence on elastic-scattering data, and especially on the isospin-dependent parametrizations, in agreement with earlier suggestions.[19]

At this stage, the magnitude of the effect is not easy to ascertain. In the present case, there is a disturbing uncertainty about the proton-scattering cross sections. More important are finite-range effects and the treatment of the deuteron interactions in the intermediate channels. It was very apparent that a conventional optical potential that reproduces elastic-scattering data is very inadequate. A folded potential is needed,[12] but the precise form is not known.

It should be added that the present calculations have only dealt with the diagonal matrix elements of the Lane $\vec{t}\cdot\vec{T}$ interaction. A full approach that treats isospin consistently is inconvenient at this time. Auxilliary calculations show that it will have rather small effects on the *elastic* nucleon scattering. Extensions of these calculations to (p,n) reactions[4] would be interesting. Additional studies are planned at higher energies and on other elements.

This study was supported in part by the National Science Foundation. The author thanks the Ohio University group (Ref. 1) for providing their neutron data, as well as the numbers for the proton data. Special thanks are due to Mr. John Tender for carrying out the calculations.

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Fragmentations of ^{40}Ar at 213 MeV/Nucleon

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(Received 11 October 1978)

Energy and isotope distributions were measured for peripheral reactions induced by ^{40}Ar at 213 MeV/nucleon. The data are consistent with the predictions of abrasion-ablation models. The influence of correlations in the nuclear ground state is discussed.

The study of ^{40}Ar-induced reactions at energies below 10 MeV/nucleon has led to important advances in our knowledge of deeply inelastic scattering.[1] At these energies the reaction is believed to proceed by a diffusion mechanism, leading to the emission of fragments from an equilibrated dinuclear system. At much higher energies, it is unlikely that a dinuclear system can ever be formed and there is evidence from studies with light projectiles like ^{16}O that a fast abrasion mechanism[2] becomes the dominant peripheral process. However, projectile excitation followed by equilibration and decay can also explain many features of the results with ^{16}O.[3-5] Since the characteristic features of heavy-ion reactions at lower energies are much better developed with projectiles like ^{40}Ar, it is likely that a better understanding of the high-energy processes will come from studies on such heavy systems. Here we present the first measurements of energy and isotope distributions in this new energy region with an ^{40}Ar beam at 213 MeV/nucleon.

The experiment used the ^{40}Ar beam of 10^8 particles/sec from the Bevalac to bombard a carbon target of thickness of 400 mg/cm^2. Projectile fragments were detected at several laboratory angles in the range 0–4° in a telescope consisting of nine 5-mm-thick silicon detectors, which could stop fragments heavier than nitrogen. The particle identification technique used the algorithm[6] $(E+\Delta E)^n - E^n \propto TM^{n-1}Z^2$, where T is the thickness of the ΔE detector, M and Z are the mass and charge of the particle, and n was set equal to 1.78. This expression was modified for the case of a multielement detector telescope[7] to give several identifications. For each event the weighted mean and χ^2-consistency function were determined. Events arising from reactions in detectors and statistical fluctuations in energy loss were rejected by making cuts on the tail of the χ^2 distribution. The resulting mass spectra had a resolution varying from 0.2 amu for oxygen to 0.5 amu for sulfur.

For isotopes close to the valley of stability, which were produced with high yields, the total cross section was obtained by integrating the angular distributions. For low-yield isotopes far from stability, the cross sections were obtained by adding the yields of all angles and assuming that the angular distributions for these isotopes were the same as for the more-abundant