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Sub-barrier one- and two-neutron pickup measurements in ^{32}S+^{93}Nb, ^{98,100}Mo reactions at 180°

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Excitation functions for sub-barrier one- and two-neutron pickup reactions were measured for $E_{\mathrm{lab}} \leq 106$ MeV in ^{32}S+^{93}Nb, ^{98,100}Mo systems by detecting targetlike recoils at 0° using a recoil mass spectrometer. The slopes of transfer probability vs distance of closest approach are in good agreement with binding energies, indicating the absence of a "slope anomaly." Angle-integrated transfer cross sections derived from measured 180° yields are consistent with enhancements in previously measured fusion yields for the ^{32}S+^{98,100}Mo systems.

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In the past several years considerable attention has been focused on the connection between sub-barrier transfer and sub-barrier fusion [1–3]. One outstanding question is whether sub-barrier transfer might serve as a "doorway" to fusion [4]. Sub-barrier fusion yields have been observed to fall off in an anomalously slow fashion (compared to one-dimensional barrier-penetration models) with decreasing bombarding energy. Recently, coupled-channels calculations that incorporate quasielastic, transfer, and fusion channels, and which use real potentials similar to those derived from microscopic models, have been successful in reproducing this trend [5]. However, the number of systems for which complete data (quasielastic, transfer, and fusion) is available is limited. Since fusion data does exist for ^{32}S on various molybdenum isotopes [6], we set out to measure the sub-barrier transfer yields for one- and two-nucleon pickup in the ^{32}S+^{98,100}Mo reactions.

A separate question of interest pertains to "slope anomalies" [2,7]. Sub-barrier transfer probabilities show an exponential dependence on distance of closest approach, $P_{\mathrm{tr}} \propto \exp(-2\kappa D_0)$, where D_0 is the distance of closest approach and κ is a slope parameter [2]. From binding energies, two-nucleon transfer slopes should be approximately twice those of one-nucleon transfer. The observed decrease in the two-nucleon transfer slope, compared to scaling from one-nucleon transfer, is referred to as a two-nucleon (or pair) transfer slope anomaly. To investigate this systematically, a ^{93}Nb target was also selected, providing a comparison among nuclei with two, six, and eight valence neutrons, respectively, above the $N = 50$ neutron shell. Additionally, since ^{93}Nb is a hard, spherical nucleus while ^{98}Mo and ^{100}Mo are soft vibrators, comparison of slope trends might reveal a dependence on collective excitations.

We used the Rochester Recoil Mass Spectrometer (RMS) [8] to measure targetlike products at 0° resulting from 180° scattering. Use of the RMS technique [9] eliminates the problem of diffractive scattering. Quantum diffractive effects have been shown in some cases to be a possible source of the spurious two-neutron slope anomaly [10]. These effects can be suppressed by going to lower bombarding energies and more backward angles to reduce the influence of the nuclear potential.

In order to separate the recoils entering the RMS from scattered beam, a ΔE-E detector was used at the focal plane, consisting of an isobutane-filled proportional counter for ΔE and a position-sensitive silicon detector (PSD) for residual energy measurement. Gating on the targetlike recoils, we obtain a mass spectrum like that shown in Fig. 1. As can be seen, individual masses are cleanly resolved. The RMS mass resolution is typically $\approx$ 1:400 FWHM, and $\approx$ 1:150 full-width at one-hundredth maximum. Transfer excitation functions were measured for $E_{\mathrm{lab}} \leq 106$ MeV. The Z resolution was insufficient to distinguish proton transfer from neutron transfer. Furthermore, energy resolution was inadequate to identify transfer to particular states, or to distinguish between transfer and elastic scattering off isotopic target contaminants.

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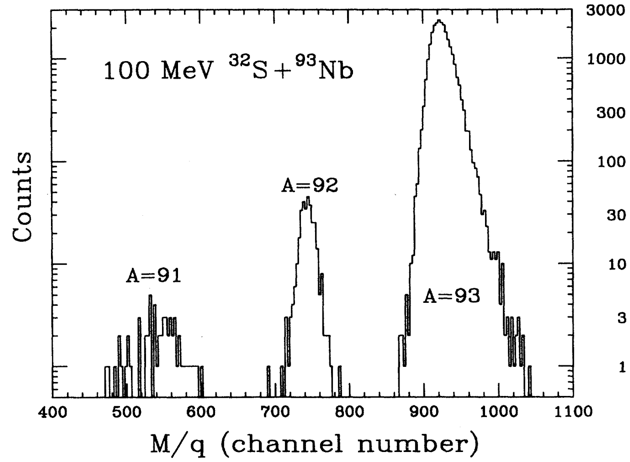

FIG. 1. Mass spectrum of targetlike recoils through the RMS for the 100-MeV ^{32}S+^{93}Nb reaction. The mass resolution of the RMS is typically $\approx$ 1:400 (FWHM) and $\approx$ 1:150 (full-width at one-hundredth maximum). No correction has been made in this figure for the RMS focal-plane efficiency.

Target thicknesses were 150 μg/cm^2 with a 95 μg/cm^2 carbon backing for ^{98}Mo, and 110 μg/cm^2 with a 20 μg/cm^2 carbon backing for ^{100}Mo. The ^{93}Nb target was 110 μg/cm^2 and self-supporting. The isotopically enriched molybdenum targets contain 0.1–1.0 % contamination from each of the other stable isotopes. Measurements of background levels at lab energies of 80 MeV were generally consistent with the stated assay values. This isotopic contamination was the dominant limitation on how low in bombarding energy we could measure transfer yields for the molybdenum targets. In contrast, beam-tail background was the dominant limitation for the ^{93}Nb target. Our procedure was to measure the transfer yield for each system at decreasing lab energies until the measured yield leveled off. This level was used as our experimental background and has been subtracted in the data shown.

We collected data one mass at a time (elastics+inelastics, one-nucleon and two-nucleon pickup), and used two monitor detectors in the scattering chamber at ±20° to normalize our focal-plane measurement to integrated beam flux. Each mass was focused to the same focal-plane position. This procedure simplified analysis by implicitly removing the RMS efficiency dependence on focal-plane position. The ratio of the monitor-normalized yield for each mass to the sum of all three normalized yields was then taken as the transfer probability. Inclusion of additional reaction channels would increase this sum and hence decrease the calculated transfer probability. However, the dominant contribution to such a correction should be one-nucleon stripping, and preliminary analysis of a just-completed stripping-yield measurement [11] indicates that there is at most a 10% correction to this sum at the highest energy measured (106 MeV).

For each system, data was taken using a single recoil charge state (chosen to achieve the best balance of yield and beam rejection). Implicit in this approach is the assumption that the charge-state distributions for the elastics and transfer products are the same. It has been previously noted [12] that charge-state distributions may be strongly shifted as a result of internal conversion, followed by the emission of Auger electrons. However, for the relatively light nuclei studied in the present work, such processes have been calculated to be of negligible effect. As a further check, transfer probabilites at selected energies were measured using several different charge states, and the results were found to agree within ±10%.

By scaling the measured transfer probabilities by the 180° Rutherford cross section, we obtain differential transfer cross sections, shown in Fig. 2. For comparison, DWBA calculations using the code PTOLEMY [13] are shown for the same systems. Since spectroscopic factors have been measured for several states in all of the product nuclei, it was possible to do a fairly complete calculation. Inclusion of additional states in the calculation is not expected to change the results shown by more than about 10%. The calculation result was scaled down by

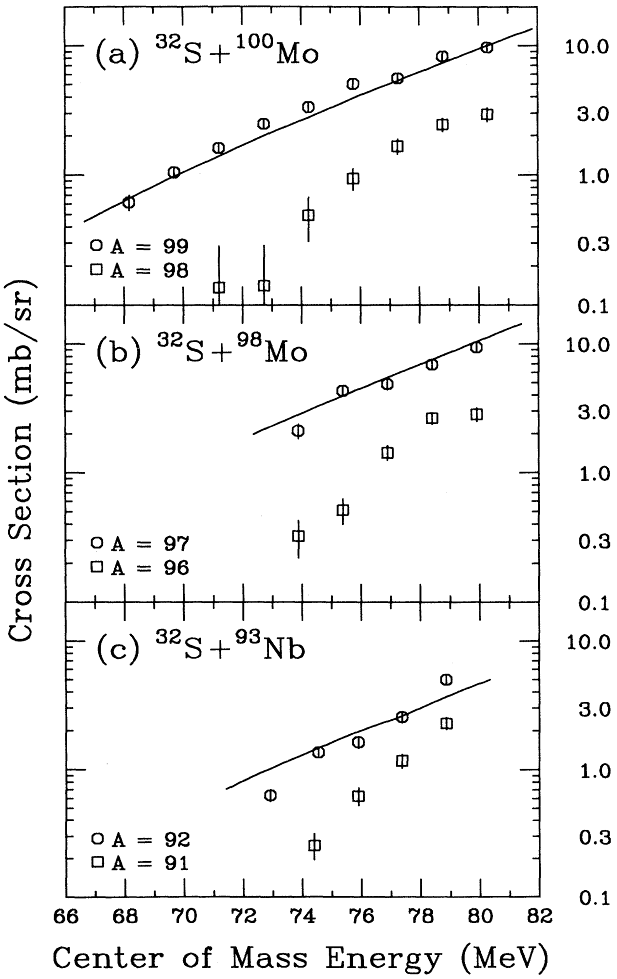

FIG. 2. Differential cross sections at 180° for one- and two-neutron pickup. The solid lines are calculations using the DWBA code PTOLEMY. The PTOLEMY yields have been scaled down by a factor of 3 for the molybdenum cases, and by a factor of 2 for the niobium case.

a factor of 3 for the molybdenum cases, and by a factor of 2 for niobium, suggesting that some additional physics needs to be incorporated into the calculation. However, DWBA calculations have long been known to have difficulties in reproducing absolute yields to better than a factor of 2 or 3 for heavy-ion reactions.

The PTOLEMY calculations shown include only neutron pickup since the predicted proton pickup was down by several orders of magnitude, consistent with simple Q-value considerations. Furthermore, measurements done at Stony Brook [14] of the scattered sulfur at near-barrier energies indicate that the pickup yields are, indeed, dominated by neutron transfer.

In Fig. 3 we show the measured pickup probabilities vs reduced distance of closest approach,

$$d_0 = D_0/(A_T^{\frac{1}{3}} + A_P^{\frac{1}{3}})\,, \qquad (1)$$

where A_T and A_P are the target and projectile atomic masses, respectively. The distance of closest approach, D_0, was calculated using a proximity potential [15] to account for nuclear-field effects. At the lowest bombarding energies, these effects are negligible, and at 106 MeV (the highest energy for which data were taken) they result in a shift in D_0 of ≈ 0.2 fm for all three systems. At energies above 106 MeV, the difference between pure Coulomb trajectories and those calculated via the proximity potential quickly becomes significant, and in either case results in $d_0 < 1.5$ fm, a limit beyond which the tunneling picture should not apply [2,7]. In earlier measurements, we have observed noticeable deviations from exponential falloff in transfer probability for beam energies above 106 MeV. Since the exact threshold for the tunneling regime is unclear, we base our conclusions on the data taken at beam energies below 106 MeV, where these deviations are not noticeable and the effects that cause them are believed to be negligible. Although the figures include the 106-MeV data, all fits excluded them.

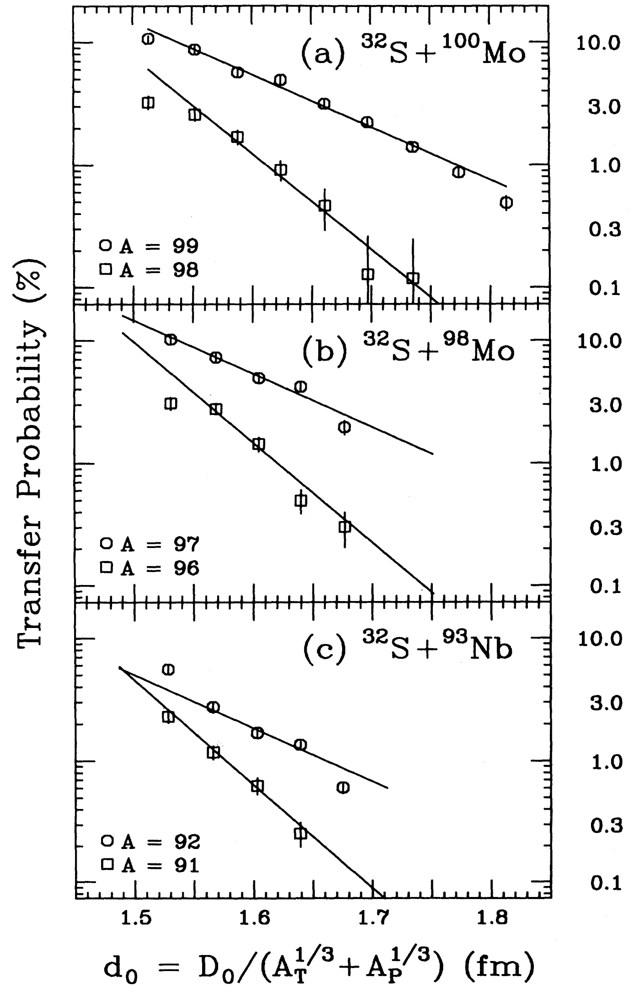

FIG. 3. Measured and calculated neutron-pickup probabilities vs reduced distance of closest approach. The calculation (solid lines) uses a slope parameter from semiclassical tunneling theory, with an overall scaling to the data.

Semiclassical tunneling theory predicts a slope parameter given by $\kappa = \sqrt{2\mu B}/\hbar$, where μ is the reduced mass of the donor (after transfer) and transferred particle/cluster, and B is the particle/cluster binding energy. In Fig. 3, the solid lines are the slopes determined from binding energies, with an overall scaling to the data. Good agreement is seen between the data and binding-energy predictions for both one- and two-neutron transfer on all three targets. A slope parameter may also be extracted from PTOLEMY results by dividing the predicted cross section by the Rutherford cross section. In this figure, the slopes extracted from PTOLEMY are indistinguishable from the binding-energy slopes and are, therefore, not shown. The agreement between measurements and binding-energy predictions for one- and two-neutron pickup indicates there is no slope anomaly in these systems.

An angle-integrated transfer yield can be obtained from the measured probabilities [9,16]. Only two assumptions are required to perform this calculation. First, the orbits should be well described by Coulomb trajectories. Since the difference between distances of closest approach with and without a proximity-potential correction are small, this criterion is well met. Second, the transfer probability is assumed to fall off exponentially with distance,

$$P_{\text{tr}} \propto \sin(\tfrac{1}{2}\theta_{\text{c.m.}})\,\exp(-2\kappa D_0)\,, \qquad (2)$$

where κ is a slope parameter, and D_0 is the distance of closest approach. The assumption of Coulomb trajectories connects D_0 and $\theta_{\text{c.m.}}$ for a given $E_{\text{c.m.}}$, allowing the integration over angles to be done analytically. The resulting expression is

$$\sigma_{\text{tr}} = \frac{5\pi Z_T Z_P e^2}{\kappa E_{\text{c.m.}}} P_{\text{tr}}(E_{\text{c.m.}}, 180^\circ)\,. \qquad (3)$$

Here, Z_T and Z_P are the target and projectile atomic numbers, respectively, κ is the *measured* slope parameter, and P_{tr} is the *measured* transfer probability at 180°. The angle-integrated cross sections obtained in this way are shown in Fig. 4 for the molybdenum data. In the same figure, we show the associated fusion data from

Pengo *et al.* [6]. All cross sections have been scaled by the fusion radius and center-of-mass energies scaled by the fusion barrier (as calculated from [17]), to remove trivial kinematic and geometric differences between the two systems. As can be seen in Fig. 4, above barrier the two systems are essentially identical.

However, the sub-barrier fusion yields exhibit a strong isotopic dependence. For the lowest energies, the reduced fusion cross sections show a full order-of-magnitude difference between ^{98}Mo and ^{100}Mo. This difference cannot be understood in terms of a coupling to one-neutron pickup since the reduced one-neutron yields are identical, and the Q_{gg} values differ by only 0.35 MeV.

Broglia *et al.* [18] suggested that such enhancements in fusion yields may be due to the transfer of a neutron pair with a positive Q value. Pengo *et al.* [6] suggested the same mechanism to explain their fusion data. Our sub-barrier transfer data show only a small enhancement in two-neutron transfer yield for ^{100}Mo compared to ^{98}Mo. However, the relatively large difference in Q_{gg} values for two-neutron pickup (4.60 and 5.84 MeV for ^{98}Mo and ^{100}Mo, respectively) generates a stronger coupling between transfer and fusion for the ^{100}Mo target compared to the ^{98}Mo, leading to fusion enhancements which are in qualitative agreement with the observed fusion results. It is worth noting that our attempts to measure transfer on ^{92}Mo indicate that the yields are down by at least an order of magnitude from those of ^{98}Mo and ^{100}Mo, which correlates with the steeper falloff in the fusion yield measured by Pengo *et al.*

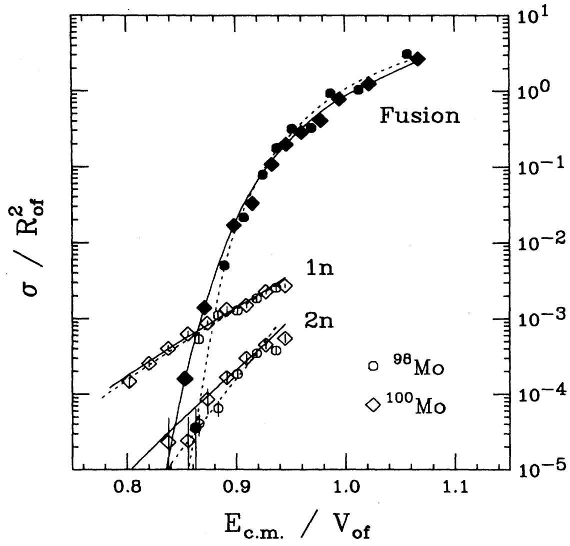

FIG. 4. Angle-integrated transfer yields compared to fusion. The angle-integrated transfer cross sections are derived from measured 180° yields (see text). The fusion cross sections (solid symbols) are from Pengo *et al.* [6]. All cross sections have been scaled to the fusion radius, and energies have been scaled to the fusion barrier. The lines through the transfer data are fits using the measured slope parameter. The lines through the fusion data are to guide the eye.

In conclusion, we observe no slope anomaly in the ^{32}S+^{93}Nb, ^{98,100}Mo systems. All measured transfer probabilites show a dependence on distance of closest approach consistent with binding-energy systematics. PTOLEMY calculations overpredict the one-neutron yields by about a factor of 3 for ^{98}Mo and ^{100}Mo, and by about a factor of 2 for ^{93}Nb. However, slopes extracted from PTOLEMY calculations are in good agreement with the data. The derived angle-integrated transfer yields are consistent with the hypothesis that sub-barrier fusion enhancements are due to two-nucleon transfer with positive Q values. Measurements of inelastic scattering would be an important addition since they would provide a complete set of data for coupled-channels calculations.

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