Large Cross Sections for Quasielastic Neutron-Pickup Reactions Induced by ^{37}Cl, ^{48}Ti, and ^{58}Ni on ^{208}Pb

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Large cross sections for neutron-pickup reactions have been observed for ^{37}Cl, ^{48}Ti, and ^{58}Ni + ^{208}Pb at incident energies of 250, 300, and 375 MeV, respectively. These reactions, which occur with energy losses of only ~5 MeV, contribute about 25% to the total reaction cross section.

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Heavy-ion reactions induced by projectiles with $A \gtrsim 40$ at bombarding energies up to about twice the Coulomb barrier are usually considered to be dominated by processes in which a considerable amount of kinetic energy is converted into internal excitation of the two interacting nuclei.[1-3] These deep-inelastic reactions have been the subject of extensive study during the last decade, and their dependences on bombarding energy and projectile-target combination have to a large extent been established. On the other hand, quasielastic processes where the target and projectile leave the interaction region with relatively small excitation energies and mass transfers have been studied much less extensively. In reactions induced by lighter projectiles[4,5] ($A \lesssim 24$), the quasielastic processes are observed to contribute up to 30% to the total reaction cross sections at energies close to the Coulomb barrier, with the percentage decreasing as the energies increase to 2–3 times the Coulomb barrier. For heavier projectiles little has been reported, stemming to a large extent from the experimental difficulties in unambiguously identifying the masses and Z's of the projectilelike fragments and resolving them from the elastic scattering.[6,7] The lack of experimental data with energy losses smaller than ~10 MeV has therefore led to the belief[8] that at bombarding energies up to about twice the Coulomb barrier, the quasielastic contributions for these systems are only a small percentage of the total reaction cross section (see, e.g., Ref. 8, Fig. 2).

In the present Letter we report the results of measurements of the quasielastic yields produced in 250-MeV ^{37}Cl, 300-MeV ^{48}Ti, and 375-MeV ^{58}Ni induced reactions on ^{208}Pb where the individual masses and Z's of the projectilelike fragments were resolved. We find that a significant fraction of the reaction cross section is present in the neutron-pickup channels, where the yield depends on the mass of the projectile and can be as large as ~25% of the total reaction cross section. These results not only raise questions about the reaction mechanism and the conventional picture of the distribution of reaction strength, but also have implications for previous studies where estimates of the total reaction cross sections were obtained from measurements of elastic scattering using detector systems yielding only Z identification.

The experiments were performed with use of beams of ^{37}Cl (250 MeV), ^{48}Ti (300 MeV), and ^{58}Ni (375 MeV) obtained from the Argonne National Laboratory (ANL) superconducting linac. Typical beam currents of 1–3 particle nA were used to bombard isotopically enriched ^{208}Pb targets of thickness 50 μg/cm^2 and 100 μg/cm^2 evaporated on 15-μg/cm^2 C foils. The outgoing particles were momentum analyzed in the ANL Enge split-pole spectrograph and detected in the focal plane with use of a position-sensitive ionization chamber.[9] The measured parameters dE/dx, E_{tot}, $B\rho$ (position), and the angle of incidence α (used to correct dE/dx) were used to obtain mass and Z identification for the quasielastic processes observed. As a result of the increasing influence of the energy-loss straggling in the entrance foil of the detector, it was not possible to resolve the individual masses of the deep-inelastic reaction products with $Z > 28$.

Shown in Fig. 1(a) is a mass spectrum observed for Ni^{23+} ions produced in the reactions ^{58}Ni + ^{208}Pb at $E_{lab} = 375$ MeV. As can be seen in the figure considerable strength is observed for Ni isotopes heavier than ^{58}Ni. Similar behavior was observed for the ^{37}Cl- and ^{48}Ti-induced reactions on ^{208}Pb. The preference of the neutron-pickup reactions over the neutron-stripping reactions is consistent with the matching conditions, since the Q values for the pickup reactions are more positive by 5 MeV (^{37}Cl) to 10 MeV (^{58}Ni). Energy spectra for the one- and two-neutron-pickup reactions (^{58}Ni, ^{59}Ni) and (^{58}Ni, ^{60}Ni) are shown in Figs. 1(b) and

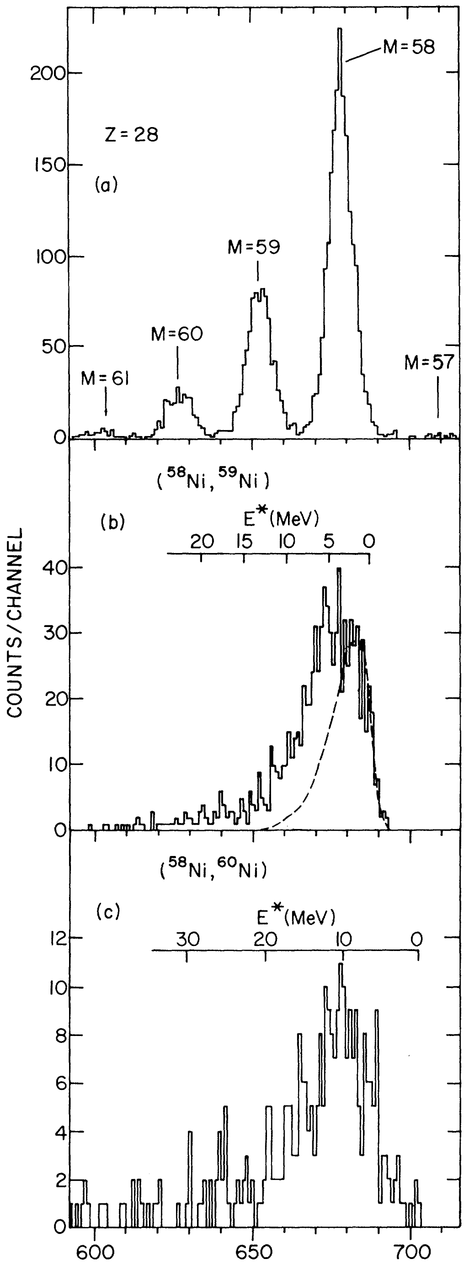

FIG. 1. (a) Mass spectrum for Ni^{23+} ions from the reaction ^{58}Ni + ^{208}Pb at $E_{lab} = 375$ MeV and $\theta_{lab} = 65°$. Energy spectra for the (b) one- and (c) two- neutron-pickup reactions (^{58}Ni, ^{59}Ni) and (^{58}Ni, ^{60}Ni) at $E_{lab} = 375$ MeV and $\theta_{lab} = 65°$. The dashed line represents the smoothed energy spectrum for the 24 states taken into account in the distorted-wave Born-approximation calculations.

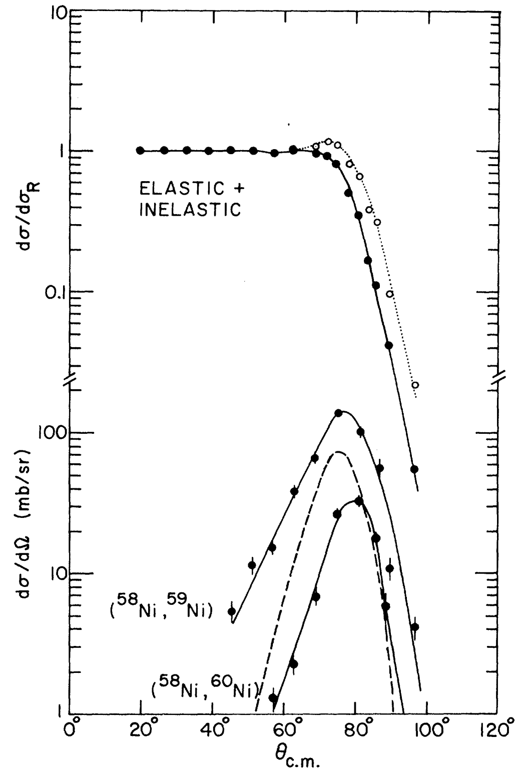

FIG. 2. Angular distribution for elastic scattering (including inelastic excitations up to $E^* = 3$ MeV) and for the (^{58}Ni, ^{59}Ni) and (^{58}Ni, ^{60}Ni) reactions obtained for 375-MeV ^{58}Ni + ^{208}Pb (solid points). The solid lines serve to guide the eye. The dashed line is the result of the distorted-wave Born-approximation calculation for (^{58}Ni, ^{59}Ni) as described in the text. The open circles and the dotted line result from adding all neutron-transfer channels to the elastic and inelastic scattering data.

1(c). The ground states are populated quite weakly with the centroid of the strengths at excitation energies of 6.6 and 11.8 MeV for the (^{58}Ni, ^{59}Ni) and (^{58}Ni, ^{60}Ni) reactions, respectively. Taking the ground-state Q values into account we observe that the neutron-transfer centroids are associated with effective Q values (total kinetic-energy losses) of ~ -5 MeV.

The angular distributions for the elastic scattering including inelastic excitation with $Q > -3$ MeV, and for the neutron-pickup reactions (^{58}Ni, ^{59,60}Ni) on ^{208}Pb are shown in Fig. 2. The angular distributions for the two transfer channels, integrated over all quasielastic yields, are bell shaped with a maximum near the quarter point angle, $\theta_{1/4}$, and with maximum cross sections of ~ 150 mb/sr for (^{58}Ni, ^{59}Ni) and 30 mb/sr for (^{58}Ni, ^{60}Ni). The angular distributions for the neutron-transfer reactions obtained with the other projectiles, ^{37}Cl and ^{48}Ti, show the same general behavior.

The integrated cross sections for the ^{37}Cl, ^{48}Ti, and ^{58}Ni + ^{208}Pb systems, together with the results for the ^{16}O + ^{208}Pb system[5,10] measured at similar energies above the Coulomb barrier, are summarized in Table I. The total reaction cross sections were estimated from optical-model calculations for the ^{16}O, ^{37}Cl + ^{208}Pb systems, and by using the modified sharp-cutoff model of Frahn[11] for the ^{48}Ti, ^{58}Ni + ^{208}Pb systems where elastic and inelastic scattering were not separated.

The quasielastic cross sections for the single neutron-pickup and for all neutron-transfer reactions are shown in columns 5 and 6. The values shown in parentheses correspond to the fraction of the total reaction cross section. The cross sections for the quasielastic neutron-transfer reactions increase from 127 mb for ^{16}O + ^{208}Pb (11.8% of σ_{react}) to about 350–380 mb for ^{48}Ti and ^{58}Ni + ^{208}Pb (24–27% of σ_{react}) with ~260 mb due to the single-neutron-pickup reaction. An estimate for the integrated cross sections for all transfer reactions (quasielastic *and* deep inelastic) was also extracted and is listed in the last column of Table I. The uncertainties associated with these cross sections are ~20% and for the ^{58}Ni + ^{208}Pb system the value given represents a lower limit as a result of the decreasing detector efficiency for low-energy particles with $Z > 28$. It can be seen that with increasing mass of the projectile the transfer reaction channels make an increasingly larger contribution to the total reaction cross section so that for ^{48}Ti and ^{58}Ni + ^{208}Pb they are responsible for ~70% of the total reaction cross section. This behavior is consistent with the results of fusion-cross-section measurements by Bock *et al.*[12] The interesting observation of the present study is that a sizable fraction of the transfer cross section comes from quasielastic neutron-transfer reactions with energy losses $Q \sim -5$ MeV.

Distorted-wave Born-approximation calculations were performed for the ^{208}Pb(^{58}Ni, ^{59}Ni)^{207}Pb reactions with the program PTOLEMY.[13] Transitions to the $\frac{3}{2}^-$, $\frac{1}{2}^-$, $\frac{5}{2}^-$, $\frac{9}{2}^+$ states in ^{59}Ni and the $\frac{3}{2}^-$, $\frac{1}{2}^-$, $\frac{5}{2}^-$, $\frac{7}{2}^-$, $\frac{9}{2}^-$, $\frac{13}{2}^+$ states in ^{207}Pb were taken into account with spectroscopic factors as taken from Refs. 10 and 14. The optical potential parameters were obtained from a fit to the elastic scattering angular distribution in the system ^{37}Cl + ^{208}Pb ($-V = 13.1$ MeV, $r_0 = 1.3$ fm, $a = 0.645$ fm, $-W = 5.5$ MeV, $r_{0I} = 1.446$ fm, $a_I = 0.223$ fm). The smoothed energy spectrum and the summed angular distributions for the 24 transitions are shown in Fig. 1(b) and Fig. 2 (dashed lines), respectively. The position of the maximum in the angular distribution is reproduced quite well, while the width of the experimental angular distributions is somewhat larger. The strength of the cross section is too low by a factor of 2–3, and as can be seen from Fig. 1(b) the energy spectrum at lower excitation energies ($E^* < 4$ MeV) is quite well reproduced. Without further calculations it is not clear which reaction processes are responsible for the missing strength observed at $E^* \geq 4$ MeV. More complicated multistep processes, (e.g., transfer including inelastic excitation as one of the intermediate steps) could make sizable contributions. As a result of the Q values involved, processes involving two-nucleon pickup followed by neutron evaporation are not likely candidates to explain the major fraction of the strength observed.

In order to simulate how the angular distribution for "elastic scattering" would change if no mass separation would have been done we have added all neutron-transfer channels to the elastic and inelastic scattering data (open circles in Fig. 2). The quarter point angle $\theta_{1/4}$ increases by

TABLE I. Cross sections for the systems ^{16}O, ^{37}Cl, ^{48}Ti, ^{58}Ni + ^{208}Pb. Values shown in parentheses are the ratios $\sigma/\sigma_{\text{react}}$.

Projectile	E_{lab} (MeV)	E/V_{Coul}	σ_{react} (mb)	σ_{1n} (mb)	σ_n (mb)	σ_{trans} (mb)
^{16}O	104 [a]	1.30	1100	85 (0.077)		
	138.5 [a]	1.71	2060	95 (0.046)		
	102 [b]	1.29	1080		127 (0.118)	281 (0.260)
^{37}Cl	250	1.43	1800	160 (0.088)	250 (0.139)	760 (0.421)
^{48}Ti	300	1.25	1400	250 (0.18)	380 (0.27)	1010 (0.72)
^{58}Ni	375	1.26	1450	265 (0.18)	350 (0.24)	990 (0.68)

[a] Ref. 10.

[b] Ref. 5.

about 4° and a bump in $\sigma/\sigma_{\text{Rutherford}}$ develops at $\theta_{\text{c.m.}} = 75°$ which is not due to an interference phenomenon but is due to the large cross section for the neutron-pickup channels. The cross section extracted from the dotted curve with the modified sharp-cutoff model is 1250 mb, which should be compared with 1450 mb obtained from the solid curve in Fig. 2. The discrepancy simply reemphasizes the well-known uncertainty in total reaction cross sections extracted from elastic scattering data, where particle identification and energy resolution are marginal.

In summary, we have observed that neutron-pickup reactions which are correlated with small energy losses ($Q \lesssim -5$ MeV) contribute about 25% to the total reaction cross sections for the systems ^{37}Cl, ^{48}Ti, and ^{58}Ni + ^{208}Pb at incident energies of 6–7 MeV/nucleon. The large magnitude of these quasielastic transfer reactions was not expected on the basis of previous studies. The large cross sections observed in our experiments for the neutron-pickup reactions could also have influence on other channels. It would be interesting to investigate correlations between neutron-transfer and fusion cross sections for systems where a strong entrance-channel dependence for σ_{fusion} has been observed.[15]

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