Single neutron transfer induced by massive heavy ions

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Quasielastic pickup and stripping reactions have been measured for the reaction $^{86}Kr+^{208}Pb$ at 695 MeV with a magnetic spectrometer. The angular distributions observed for single neutron pickup are analyzed with the distorted-wave Born approximation, which accounts well for the absolute differential cross sections. Quasielastic transfer reactions account for about 20% of the total reaction cross section.

Recently, the first high resolution measurement of elastic and inelastic scattering of very heavy nuclei, specifically $^{86}Kr+^{208}Pb$, was reported.[1] The present paper addresses another aspect of the same experiment, namely, transfer reactions to low-lying states, with special emphasis on the single neutron pickup reaction. One proton transfer data for lighter targets with ^{56}Fe projectiles have recently been reported[2] as have one neutron pickup data[3] from ^{37}Cl, ^{48}Ti, and ^{58}Ni reactions at 6–7 MeV/nucleon on ^{208}Pb. While the distorted-wave Born approximation (DWBA) underpredicted the absolute one nucleon transfer cross sections of Refs. 2 and 3 by factors from 2 to 4, the present DWBA analysis is able to account for both the shape and absolute cross section of the one neutron pickup channel. The total quasielastic transfer cross section is found to be roughly 20% of the total reaction cross section.

^{86}Kr ions were accelerated to 695 MeV in the Gesellschaft für Schwerionenforschung UNILAC, momentum analyzed in a 180° magnetic deflection system and focused onto $a\approx 40$ $\mu g/cm^2$ ^{208}Pb target. The outgoing ions were momentum analyzed and identified in a magnetic spectrometer. Further experimental details can be found in Ref. 1. Despite an energy resolution ≈ 1.5 MeV, discrete states in the single nucleon transfer reactions could not be resolved (see Fig. 1), as both final nuclei were odd mass, and the density of states in their mutual excitation was too great. As a result, the transfer data reported here are summed over approximately 10 MeV in excitation energy.

Yields for each isotope were corrected for charge state distributions and converted to the center of mass system. The angular distribution for the ^{87}Kr single neutron pickup reaction is shown in Fig. 2. Two striking features of the angular distribution are the narrow width [$\sim 5°$ full width at half maximum (FWHM)] and the large peak cross section of ≈ 380 mb/sr. The cross sections for the Kr channels have uncertainties of $\approx 20\%$, while the uncertainties in non-Kr channels are about twice as large, not taking any account of reaction fragment evaporation effects.

The ^{87}Kr channel was chosen for a detailed analysis over the equally strong ^{85}Kr channel, because there is little particle decay into ^{87}Kr, since the two neutron ^{88}Kr pickup channel is very weakly populated. Evaporation calculations show that at excitation energies over 8 MeV there may be appreciable ($>15\%$) neutron decay out of the ^{87}Kr channel, with a subsequent loss of strength at the highest excitations. The estimated loss of ^{87}Kr strength in the first 10 MeV of the spectrum of Fig. 1 is less than 5%. ^{85}Kr will suffer from both feeding and loss. The one proton transfer channels were weaker by a factor of 2–3 and the statistics did not allow a detailed analysis. The sum of all the transfer cross sections (one and two nucleon) at the common peak angle, amounted to ≈ 1.3 b/sr.

We made use of two codes for the DWBA calculations, the exact finite range code PTOLEMY[4] and the second order recoil code SRC.[5] Two DWBA calculations for different final states in the ^{87}Kr channel are shown in Fig. 2. The curves shown were calculated with the code SRC, but similar calcu-

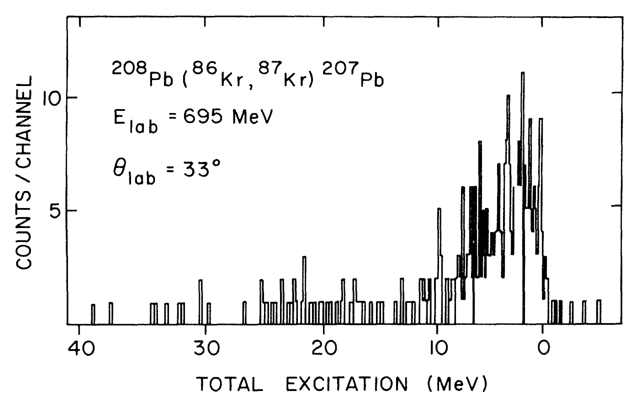

FIG. 1. Energy spectrum of ^{87}Kr in charge state 31 from the one neutron pickup reaction $^{208}Pb(^{86}Kr,^{87}Kr)^{207}Pb$. The laboratory reaction angle is 33°, corresponding to the data point of the next larger angle beyond the maximum in the angular distribution (see Fig. 2). The absolute excitation energy scale is not accurately determined in the experiment; the scale shown with the figure has been moved 1.1 MeV to the left relative to the nominal spectrometer calibration, in order to make the onset of counts coincide with $E_x=0$ MeV.

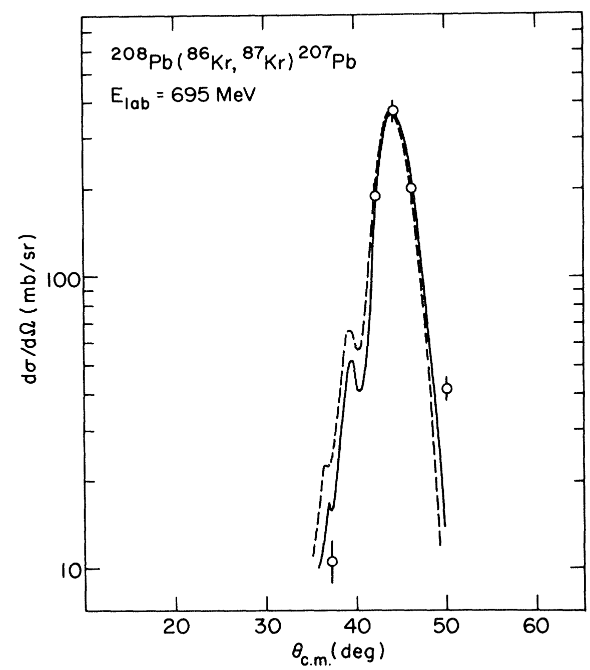

FIG. 2. Summed one neutron pickup data compared with two arbitrarily normalized DWBA calculations. The dotted line is for the transition leading to the $(\frac{1}{2})^-$ (g.s.) in ^{207}Pb and the $(\frac{5}{2})^+$ (g.s.) in ^{87}Kr. The solid line is for the transition to the $(\frac{7}{2})^-$ (2.34 MeV) state in ^{207}Pb and to the $(\frac{7}{2})^+$ (2.52 MeV) state in ^{87}Kr.

lations performed with PTOLEMY gave practically identical shapes (even including the small bumps in the forward direction). The peak position and shape of the angular distribution is well reproduced, using the Woods-Saxon potential parameters of Ref. 1 of $V=40$, $W=25$, $a=0.5$, and $r_0=1.32$. The sensitivity to the optical parameters is small. A potential with a larger diffusivity of 0.65 and $r_0=1.29$ gives equivalent fits. Very slight changes (see Fig. 2) are observed in the position of the peak as a function of excitation energy and angular momentum transfer. The fact that the angular width is much narrower than with lighter mass systems is a consequence of many more partial waves contributing to the cross section.[6]

In order to determine whether the DWBA can account for the observed strength, calculated peak cross sections for various combinations of states in ^{87}Kr + ^{207}Pb are shown in Table I. The form factors were calculated for a Woods-Saxon well of radius $R=1.25A^{1/3}$ and diffusivity $a=0.65$ fm. The states of ^{207}Pb are those strongly excited in one neutron pickup from ^{208}Pb (Ref. 7) and the ^{87}Kr states those observed strongly in ^{86}Kr neutron stripping processes (Ref. 8). The full shell model strength was assigned to the lowest such state of a particular spin and parity. Results of the calculations are shown for the peak angle of 44° (c.m.) in Table I. All listed calculations not marked by an * were performed with PTOLEMY. In a few cases of small cross sections and large angular momentum transfer the calculations were done with the second order recoil code SRC. The normal parity transitions calculated with this code (marked by *) are expected to have an uncertainty of at worst 35%

TABLE I. DWBA cross sections calculated at the 44° peak with parameters listed in the text. Full spectroscopic strengths are assumed. Angular momentum transfers are listed in parentheses next to calculated cross sections in mb. Cross sections with an * were calculated with SRC; all others were calculated with PTOLEMY. For each initial and final state J^P is listed with energy of excitation (MeV) in parentheses.

			^{87}Kr		
^{207}Pb	$(\frac{1}{2})^+$ (0.53)	$(\frac{3}{2})^+$ (1.47)	$(\frac{5}{2})^+$ (0.)	$(\frac{7}{2})^+$ (2.52)	$(\frac{11}{2})^+$ (2.52)
$(\frac{1}{2})^-$ (0.)	8.48(1)	3.51(2)	29.02(3)	1.49(4)	12.75(6)
		13.51(1)	2.63(2)	7.32(3)	0.71(5)
$(\frac{3}{2})^-$ (0.89)	11.37(1)	28.16(3)	20.60(3)	25.25(5)	7.91(6)
		2.28(2)	6.89(2)	1.49(4)	1.50(5)
		1.85(1)	22.96(1)	1.86(3)	5.15(4)
$(\frac{5}{2})^-$ (0.57)	5.51(3)	1.98(4)	23.66(5)	1.44(6)	19.91(8)
		2.67(3)	5.06(4)	1.47(5)	
		2.42(2)	2.65(3)	0.99(4)	*1.49(6)
		2.24(1)	0.91(2)	0.51(3)	
			0.31(1)	0.55(2)	
				0.32(1)	
$(\frac{7}{2})^-$ (2.34)	2.69(3)	13.55(5)	6.95(5)	20.78(7)	5.11(8)
		1.54(4)	2.85(4)	2.29(6)	
		0.66(3)	3.44(3)	0.99(5)	*1.63(6)
		0.13(2)	2.32(2)	0.25(4)	
			2.56(1)		
$(\frac{9}{2})^-$ (3.43)	0.21(5)	0.12(6)	*3.26(7)	0.13(7)	7.88(10)
		0.10(5)			1.11(9)
		0.05(4)			*0.41(8)
		0.03(3)			
$(\frac{13}{2})^+$ (1.64)	0.29(6)	*2.02(8)	*1.25(8)	5.56(10)	*1.80(11)
			*0.44(6)	*3.67(8)	

based on comparison of a number of SRC runs with the listed PTOLEMY calculations. Some of the allowed angular momentum transfer cross sections were not calculated and are missing from the table because it seemed obvious that their contribution would be small. The calculated peak cross section summed over all channels in Table I is 387 mb/sr which should be compared to the observed cross section of 380 mb/sr. The uncertainty in the calculation is roughly 35% mainly reflecting the uncertainty of the form factor geometry. (When the bound state radius was reduced to 1.20, a sample cross section was reduced by 35%.) The calculated centroid for the expected excitation spectrum from Table I is 2.2 MeV which is only a little less than the observed centroid ≈ 2.6 MeV. The division of excitation energy between ^{87}Kr and ^{207}Pb from Table I is

$$\langle E_x(^{87}\mathrm{Kr})\rangle / \langle E_x(^{207}\mathrm{Pb})\rangle = 1.2/1.0 \ (\mathrm{MeV/MeV}) \ ,$$

i.e., very far from the thermal equilibrium partition of $87/207=0.42$.

The rest of the transfer channels have not been analyzed in such a detailed manner. The total peak cross section summed over all transfer channels is 1.3 b/sr corresponding to a total cross section integrated over the bell shaped angular distributions of roughly 700 mb. The analysis of Ref. 1 determined a reaction cross section of 3.2 b so the quasielastic transfer channels account for roughly 22% of the reaction cross section. The one neutron pickup cross sections reported in Ref. 3 were 160, 250, and 265 mb for projectiles of ^{37}Cl, ^{48}Ti, and ^{58}Ni on ^{208}Pb, respectively, corresponding to 9%, 18%, and 18% of the total reaction cross sections. In the present case of ^{86}Kr on ^{208}Pb, the energy in the c.m. system is 5.7 MeV/nucleon, the same as for ^{37}Cl above, and the one-neutron pickup cross section was ≈ 200 mb or 6% of the total reaction cross section.

In the present analysis, we have ignored two-step processes. As shown in Ref. 1, the ^{86}Kr inelastic cross section to the 1.56 MeV $2+$ state is comparable to the elastic cross section near the grazing angle of 33° lab. Thus, the projectile, when it appears at the ^{208}Pb surface, is as often in its $2+$ state as in its ground state. While this will affect the analysis of any single transition strongly, it is not likely to change the summed cross sections substantially, as the DWBA calculations show a very modest dependence on Q value. The present result, somewhat in contrast to the work of Ref. 3, gives confidence that the simple ideas of grazing collisions treated in a distorted-wave Born approximation may suffice to understand the main features of quasielastic heavy-ion data.

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