Inelastic and transfer reactions in ^{92}Mo+255 MeV ^{60}Ni collisions studied by $\gamma\gamma$ coincidences ☆

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For the ^{92}Mo+255 MeV ^{60}Ni system, inelastic and few-nucleon transfer events populating non-collective states of moderately high spin have been studied by $\gamma\gamma$ coincidence measurements. Besides the strong inelastic scattering channel, twelve transfer processes were identified, ranging from 1n to 2α transfer; typically, cross coincidences between the γ-rays from both products were observed. Potential spectroscopic applications are indicated.

Transfer reactions induced by heavy ions with incident energies close to the Coulomb barrier have been intensively investigated using both charged particle spectroscopy and particle–gamma coincidence methods. The good energy resolution available in γ-ray spectroscopy allows measurement of discrete state populations, and is particularly important when the target nuclei are deformed and Coulomb excitation in both entrance and exit channels leads to population of high-spin states in the heavier product. Particle–γ-ray coincidence techniques were used as long ago as 1973 to study such processes in ^{16}O-induced reactions [1], and recent experiments employing much heavier beams have demonstrated [2–4] the population of states with spins up to around $I=20$. The use of particle detection improves channel selectivity and yields valuable information about the reaction kinematics. A significant practical disadvantage is the necessity to compromise between particle detection and γ-ray yield requirements by using rather thin (<0.5 mg/cm^2) self-supporting targets; Doppler shift corrections must then be applied to restore the γ-ray energy resolution.

A different approach is to forgo particle detection and to use $\gamma\gamma$ coincidence techniques to study inelastic/transfer processes that populate states of moderately high spin in the product nuclei. Here, the emission of known γ-rays identify the final nuclei; an especially important feature is that the mutual excitation of both reaction products may be directly observed through coincidences of γ-rays emitted from reaction partners. The advent of multidetector arrays of Compton-suppressed Ge spectrometers, providing greatly improved sensitivity and selectivity in $\gamma\gamma$ co-

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incidence spectrometry, has made this method of study particularly attractive.

In a recent ^{92}Mo + 255 MeV ^{60}Ni experiment, which initially had as its main objective the elucidation of high-spin level structures in the fusion–evaporation products ^{149}Ho and ^{150}Er, the excellent $\gamma\gamma$ coincidence data acquired were found to include many events arising from inelastic and transfer reaction products. Here we present the results of a thorough analysis of these events. The target consisted of 99% enriched ^{92}Mo of 0.8 mg/cm^2 thickness with a thick Pb backing to stop both recoils and beam. It was located at the center of the Argonne–Notre Dame BGO γ-ray facility (which consisted, at that time, of eight Compton-suppressed Ge detectors and a central ball of 14 BGO hexagons), and it was bombarded with 255 MeV ^{60}Ni ions from the ATLAS accelerator. The experimental conditions were optimized for observation of high-lying cascades in the fusion–evaporation products, and only those coincidence events were stored in which at least two Ge detectors and two BGO elements fired within a 200 ns interval. This multiplicity condition effectively suppressed Coulomb excitation events, and it also selected those inelastic/transfer events in which states of at least moderately high spin were populated. The BGO coincidence pulses were used to define the time of reaction, and, in the latter comprehensive sorting of the Ge coincidence data, delayed and prompt events could be cleanly separated. Both the $A\sim150$ fusion evaporation products and the $A\sim92$ transfer products are spherical nuclei having many isomers, and in both cases the separation of the delayed events greatly improved the γ detection sensitivity.

Examples of the γ-ray coincidence spectra obtained are shown in fig. 1. For four different reactions, we show spectra with separate gates set on the lowest-lying transitions in both product nuclei; cross coincidences arising from simultaneous mutual excitation of both products are evident, and they provide unambiguous identification of the reaction. For most γ-rays no appreciable Doppler broadening was observed, indicating that the feeding and state lifetimes involved are longer than the stopping time of the reaction products.

In addition to the strong inelastic channel, twelve transfer processes were identified, ranging from 1n to 2α transfer, and involving excitation to high-spin (up

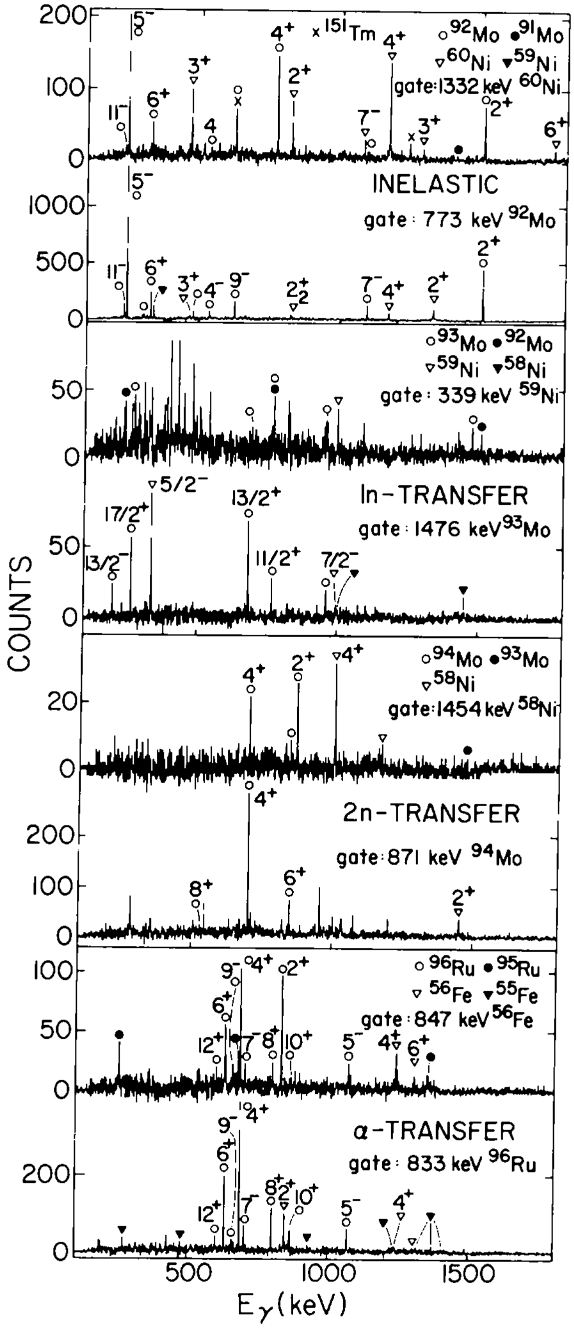

Fig. 1. Sample γ-ray coincidence data for the four reactions specified, showing γ-ray spectra coincident with known low-lying transitions in both product nuclei. For individual transitions, the isotopic assignment and the spin-parity of the parent level are generally indicated. The unlabelled peaks in the 339 and 871 keV gates are identified as transitions coincident with strong ^{150}Er γ-rays in the gating regions.

Table 1
List of reactions identified and their Q_{gg} values. Relative coincidence yields (including prompt and off-beam events and taking account of detector efficiencies) are given for the specified grating transitions.

Reaction	products	Q_{gg} (MeV)	Heavy product			Light product	
			gating γ-ray (keV)	observed coincidence γ (keV)	relative coincidence yield	observed coincidence γ (keV)	relative coincidence yield
inelastic	$^{92}Mo+^{60}Ni$	0	773	1509	93(5)	1332	34(4)
+1n	$^{93}Mo+^{59}Ni$	−3.3	1476	684	9.3(8)	339	7.2(6)
+1n	$^{91}Mo+^{61}Ni$	−4.9	1414	654	18(2)	unobserved	–
−1p	$^{93}Tc+^{59}Co$	−5.4	750	1434	5.3(8)	1190	1.8(6)
+1p	$^{91}Nb+^{61}Cu$	−2.7	2291	819	2.5(6)	unobserved	–
−2n	$^{94}Mo+^{58}Ni$	−2.6	871	703	33(2)	1454	13(1)
+2n	$^{90}Mo+^{62}Ni$	−4.4	948	unobserved		1173	2(1)
−2p	$^{94}Ru+^{58}Fe$	−6.6	1428	755	1.8(6)	unobserved	–
+2p	$^{90}Zr+^{62}Zn$	−1.3	1129	141	0.6(3)	954	<0.3
−α	$^{96}Ru+^{56}Fe$	−4.6	833	685	33(2)	847	15(1)
+α	$^{88}Zr+^{64}Zn$	−1.7	1057	1082	11.5(1.6)	992	5(1)
−2α	$^{100}Pd+^{52}Cr$	−10.6	665	750	3.8(5)	1434	~1
+2α	$^{84}Sr+^{68}Ge$	−3.7	974	793	7.3(5)	1016	2.3(4)
CN*	$^{150}Er+2p$		1203 [a)]	490	100		
CN*	$^{149}Ho+3p$		1560 [a)]	727	145(8)		

[a)] The 1203 keV γ-ray is the strongest transition feeding the 2.5 μs 10^+ isomer in ^{150}Er [6], and 1560 keV is the strongest transition feeding the $11/2^-$ ground state in ^{149}Ho [7].

to $I=12$) and moderately high energy. In table 1, the observed processes are listed along with relative yield estimates for both reaction products which were obtained by quantitative analysis of the coincidence intensities in spectra gated on the lowest (or next to lowest) transition in each heavy product nucleus. For each process, the gating γ-ray and the two coincident γ-rays used to estimate the yields of the heavy and light products are specified in the table (typically, γ cross coincidences between both products were observed in more than 30% of the events). Yields for the two strongest fusion–evaporation products ^{149}Ho and ^{150}Er are also given for comparison. In view of the selection imposed by the coincidence conditions, the yields given in table 1 should reflect the relative high-spin populations resulting from the different processes. For products having isomers, the delayed events were included in these estimates, but when the isomeric half-lives exceeded a few hundred nanoseconds only a fraction of the isomer population was detected. [For example, the ^{90}Zr produced by 2p pick-up was especially difficult to observe because of its long-lived 5^- isomer and the high-energy (~2.2 MeV) of the lowest transition.] Nevertheless, in most cases the listed yield should fairly represent the high-spin part of the reaction cross section, with low multiplicity events including those arising from Coulomb excitation essentially excluded.

The observed yields of the inelastic scattering product nuclei are comparable to those of the fusion evaporation products, and the data obtained are consequently of highest quality. Fig. 2 shows the level schemes of both colliding nuclei, with the population of various states indicated by transition arrows having widths proportional to the measured γ-ray intensities. The ^{60}Ni population was normalized to reflect the γ-ray intensities observed in the ^{92}Mo $2^+\to0^+$ gate.

In the ^{92}Mo target nucleus, states with excitation energies up to 6 MeV, and spins up to 11, were significantly populated, including rather strong population of known 8^+ and 11^- isomers. The dominant configurations of these isomers are $(\pi g_{9/2}^2)8^+$, seniority $v=2$, and $(\pi g_{9/2}^3 p_{1/2})11^-$, $v=4$, and it is clear that Coulomb excitation plays little part in their population, which must instead occur through a nuclear excitation process during overlap of the nuclear matter of the two colliding species. The ^{60}Ni projectile is

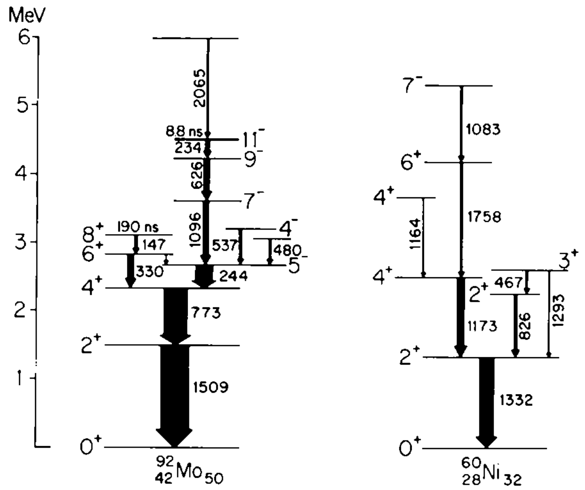

Fig. 2. The ^{92}Mo and ^{60}Ni level schemes. The widths of the transition arrows are proportional to the measured γ-ray intensities and they illustrate the relative population of individual levels by inelastic scattering.

excited up to comparable energies, and states up to the 7^- level at 5.35 MeV could be observed. In both nuclei, non-yrast states were also populated as indicated in the schemes of fig. 2. To answer the interesting question of how much excitation energy could be transferred to the colliding nuclei would require higher statistics, together with detailed examination of the γ-ray spectra, possibly including the quasicontinuum, up to much higher energies than were encompassed in the present measurements. However, a significant result is that excitations to energies exceeding the neutron separation energy clearly occur. The three lowest transitions of ^{92}Mo were found to coincide with a 339.5 keV γ-ray which was not seen in any gates set on ^{60}Ni transitions. Such a transition does not occur in the well-known ^{92}Mo level scheme but it is instead identified as the known $\frac{5}{2}^- \to \frac{3}{2}^-$ transition to ground in the ^{59}Ni nucleus. From the observed intensities, we deduce that ~5% of the events in which ^{92}Mo is excited results in the ejection of a neutron from the projectile yielding a ^{59}Ni product nucleus rather than ^{60}Ni. It appears further that the mirror process in which the excited ^{92}Mo nucleus emits a neutron happens even more frequently. In table 1, the process labelled 1n-pickup and showing rather high coincidence intensities for ^{91}Mo γ-rays, reveals no trace of ^{61}Ni γ-rays. Instead, the 1332 keV ground state transition in ^{60}Ni was observed with low intensity in coincidence with the ^{91}Mo γ-rays. Although other mechanisms cannot be excluded, it seems likely that the ^{91}Mo yield comes mainly from inelastic collisions followed by one neutron emission from the excited ^{92}Mo. Similar features were observed for the process designated 1p pick-up, but with significantly lower yield.

A comparison of the yields of various transfer reactions given in table 1, bearing in mind the selection imposed by the experimental multiplicity condition, leads to the following general conclusions. In the ^{92}Mo+255 MeV ^{60}Ni collisions, transfer reactions contribute a substantial fraction of the reaction cross section, with particularly strong contributions from 2n- and α-stripping. Transfer of particles from projectile to target generally dominates, but no clearcut correlation between the yields and the ground state Q-values is apparent. For neutron transfers, the Q_{gg} values are fairly similar but the yields are quite dissimilar e.g. merely a trace of 2n pickup was observed, whereas 2n stripping, with a less than 2 MeV more favorable Q-value, is one of the dominant processes. Considerations of the Q-matching model [5] are consistent with the observed larger cross section for α-stripping relative to α-pickup, but for 2α transfers the trend is opposite. Clearly, the observed processes are quite different from the gentle quasi-elastic transfers studied with kinematic selection around the grazing angle region.

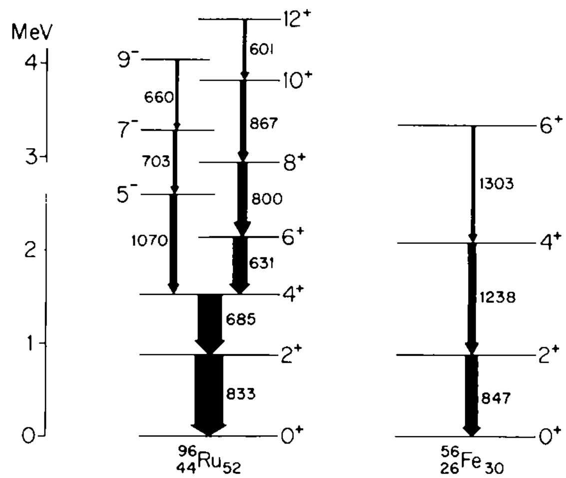

Fig. 3. The ^{96}Ru and ^{56}Fe level schemes, illustrating the relative population of individual levels in the α-transfer process.

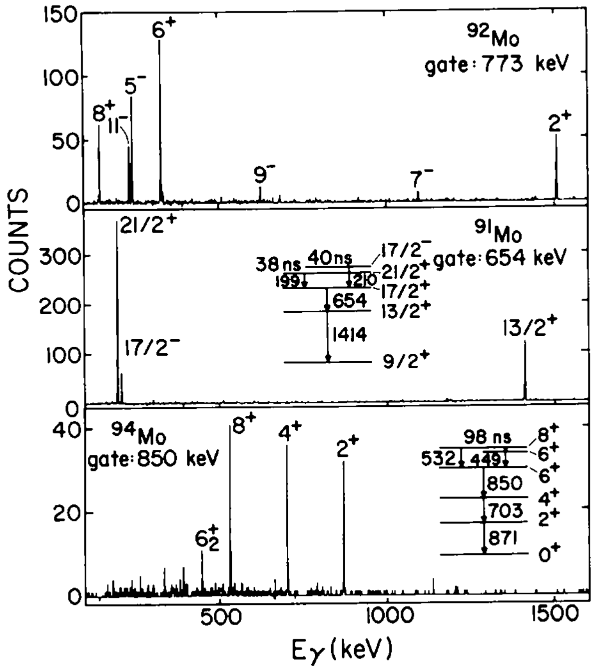

Fig. 4. Delayed coincidence spectra for three reaction products having known high-spin isomers. Transitions are labelled by their parent level I^{π} values. Isomeric decay schemes for ^{91}Mo and ^{94}Mo are displayed inset, while the two ^{92}Mo isomeric levels have already been shown in fig. 2.

A particularly striking example, the mutual excitation of the product nuclei from α-stripping, is illustrated in fig. 3. The ^{96}Ru states up to 12^+ could be easily identified, and the ^{56}Fe excitation extends to its 6^+ state. In the coincidence spectrum gated on the ^{56}Fe 847 keV $2^+ \to 0^+$ transition, in addition to ^{56}Fe and ^{96}Ru γ-rays, several weak γ-rays from the deexcitation of the 8 ns $\frac{17}{2}^+$ isomer in ^{95}Ru were observed. These arise through one neutron emission from highly excited ^{96}Ru nuclei produced in α-transfer. Similarly, the spectrum gated on the 833 keV ^{96}Ru $2^+ \to 0^+$ transition shows coincident ^{55}Fe γ-rays. Other transfer processes also gave indications of the deposition of excitation energy sufficient to allow subsequent neutron emission. For example, the spectrum coincident with the 1476 keV transition from the 1n-stripping product ^{93}Mo showed ^{58}Ni γ-rays as well as much stronger ^{93}Mo and ^{59}Ni γ-rays. With higher statistics, such processes could be studied in more satisfactory detail. We show in fig. 4 examples of delayed coincidence spectra for three nuclei in which isomers are populated rather strongly. They demonstrate particularly clearly that these types of excitation processes should be useful in spectroscopic studies, especially for investigations of non-collective nuclear excitations.

In summary, by γγ coincidence measurements we have identified inelastic and transfer reaction products from collisions of 255 MeV ^{60}Ni with ^{92}Mo. Mutual excitation of both reaction products was typically observed, providing clearcut identification of the reaction involved. Population of high-spin (up to $I=12$) non-collective states was seen, along with high excitation energy transfer which sometimes led to subsequent neutron emission. The results illustrate the potential of γγ coincidence techniques for examining at high resolution some aspects of inelastic/transfer processes, such as correlated energy and angular momentum transfers into both product nuclei. Specific applications may include the spectroscopy of certain neutron-excessive nuclei that cannot be reached by fusion–evaporation reactions. The prospect of much larger γ-ray detector arrays in the near future enhances the attractiveness of these lines of investigation.

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References

[1] R. Broda et al., Proc. Intern. Conf. on Nuclear physics (Munich, 1973) p. 470.
[2] A.O. Machiavelli et al., Nucl. Phys. A 432 (1985) 436.
[3] M.W. Guidry et al., Phys. Lett. B 163 (1985) 79; C.Y. Wu et al., Phys. Lett. B 188 (1987) 25; S. Juutinen et al., Phys. Lett. B 192 (1987) 307.
[4] F.W.N. de Boer et al., Z. Phys. A 325 (1986) 457.
[5] P.J.A. Buttle and L.J.B. Goldfarb, Nucl. Phys. A 176 (1971) 299.
[6] Y.H. Chung et al., Phys. Rev. C 29 (1984) 2153.
[7] J. Wilson et al., Z. Phys. A 296 (1980) 185.