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SPECTROSCOPIC STUDY OF SUB-BARRIER QUASI-ELASTIC NUCLEAR REACTIONS

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Recent studies have revealed anomalous behaviour in the low energy reactions of colliding heavy nuclei [1]. Examples of intriguing phenomena have appeared in the fusion and elastic scattering of heavy nuclei occuring at energies approaching their classical interaction barrier. Fusion, traditionally understood to occur through the single channel tunnelling of the imposed potential barrier, is found to be orders of magnitude stronger than expected. Elastic scattering measurements, conventionally described by folding model prescriptions of the nucleus–nucleus interaction, indicate the real part of the collision potential to be considerably deeper than such simple treatments would suggest. It would thus appear that toward lower energies the reaction processes become more sensitive to the details of the collision mechanism and hence the structure of the partners begins to play a dominant role. This realization indicates the potential importance of surface degrees of freedom of the colliding nuclei and it is these elements of the inclusive reaction mechanism which must be addressed to develop a coherent description of the collision process.

One may expect the character of the surface degrees of freedom to be reflected in the quasi–elastic reaction channels. For the purpose of experiment these may be divided into three classes; inelastic excitation, nucleon transfer and the combination of these two. At energies below the Coulomb barrier inelastic excitation is expected to be well described by pure electromagnetic interaction and is thus calculable. However, nucleon transfer and its interplay with inelastic excitation is less well determined and the physics of both must be explored by experiment.

Such studies are faced with considerable experimental difficulties which explain the lack of data currently available [2]. At energies near and below the Coulomb barrier transfer reactions are controlled by the classical distance of closest approach of the collision partners. As a consequence the reactions are strongly backward peaked with the ejectile recoiling with a small fraction of the incident collision energy. Positive identification of the fragment is, therefore, no longer possible. However, associated with the low energy ejectile is a heavy, energetic target–like recoil which, providing it can be separated from the beam and elastic flux, may be used to analyze the reaction process [3]. Such a separation is achieved using a recoil mass separator which is capable of efficiently rejecting beam and unwanted products so as to isolate the complementary recoil nucleus. Studies of the inclusive neutron transfer strength have been made using this technique [4] and suggest the process to be strongly influenced by the structure of the collision partners [5].

Information concerning the detailed mechanism of nucleon transfer may be obtained through a spectroscopic study of the the recoil product. However, once again, conventional techniques are no longer applicable. Charged particle spectroscopy, successful in analyzing higher energy reactions induced by light projectiles, is not suited to systems in which the nuclei are heavy. At energies close to the Coulomb barrier transfer angular distributions have little structure. Furthermore, the considerable straggling associated with the passage of a heavy fragment through target and window material precludes the the resolution of close–lying residual nuclear states. Alternatively, one may study the reaction spectroscopy through the γ–radiation associated with the decay of the residual nuclei. In this manner the detailed distribution of the inclusive reaction strength across the spectrum of available nuclear states may be determined and the reaction mechanism subsequently studied.

The arrangement used in these studies comprised the recoil mass separator (RMS) [6] at Daresbury Laboratory in conjunction with the POLYTESSA array of sixteen Compton suppressed intrinsic germanium γ–ray detectors [7]. The unit mass resolution of the RMS was used to identify the reaction channel of interest and prompt γ–radiation, detected in delayed coincidence with the recoiling nucleus, provided spectroscopic information. Of the many collision systems which may be studied with this technique we here principally address a single example: ^{124}Sn(^{58}Ni,^{59}Ni)^{123}Sn at 220 MeV. In this system the target is a spherical–vibrational nucleus and one would expect the transfer to follow a relatively simple mechanism. A mass spectrum of the three groups accepted by the separator focal plane is presented in Figure 1 and illustrates the clean separation of elastic and inelastic (124), neutron pickup (123) and two neutron pickup (122) reaction channels. Spectra of γ–rays coincident with the recoil products are presented in Figure 2. In this figure the upper ((a), (b)) and lower ((c), (d)) quadrants respectively show γ-rays coincident with recoil products of all masses observed in the focal plane and with the mass 123 fragments alone. The left hand section of the figure ((a), (c)) comprises spectra corrected for the Doppler shift induced by the motion of the target-like recoil and, similarly, the right hand spectra are corrected for the motion of the ejectile fragment. Lines corresponding to inelastic excitation and single neutron transfer are clearly evident, rising cleanly out of the background.

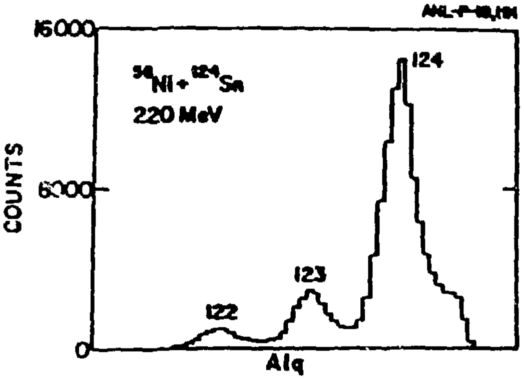

Figure 1

Focal plane mass spectrum of the quasi-elastic recoil products corresponding to the reaction ^{124}Sn(^{58}Ni, ^{58,59,60}Ni)^{124,123,122}Sn at 220 MeV

Yields extracted from these spectra have been corrected for both the energy dependent efficiency of the γ-ray spectrometers and feeding between connected individual levels to obtain estimates of the relative population of residual nuclear states following transfer.

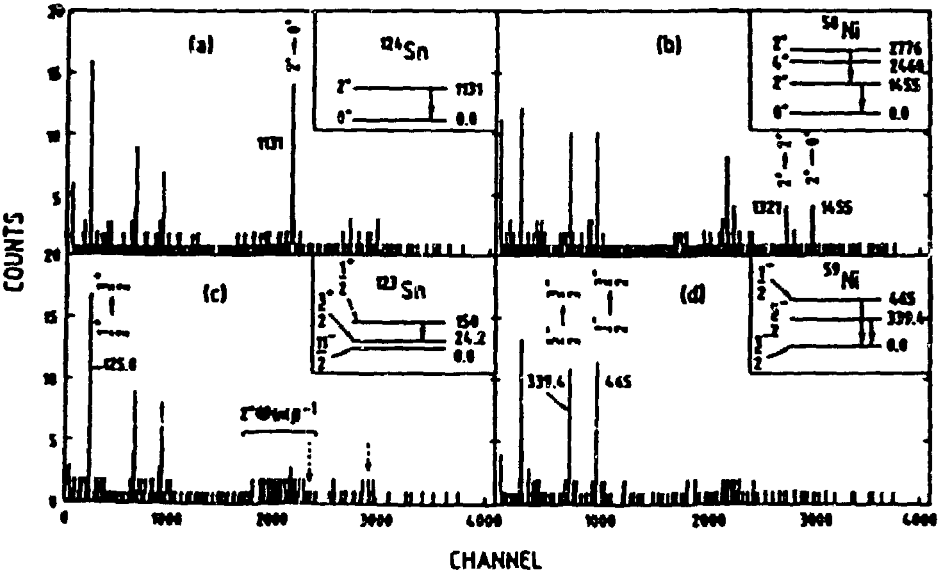

Figure 2

Spectra of total γ-rays detected in delayed coincidence with the recoil nucleus. Figures (a) and (b) present spectra gated by masses all recoil masses observed in the focal plane with (c) and (d) gated by the neutron pickup channel (123) alone. The left hand quadrants are corrected for the Doppler shift induced by the motion of the recoil and similarly those on the right for that of the ejectile nucleus. The dashed arrows indicate the expected position of unobserved lines as discussed in the text.

These estimated yields have then been scaled relative to the calculated Coulomb excitation of the first 2^+ level in the ^{124}Sn target nucleus to obtain cross sections for the population of individual final states and these are presented as solid bars as a function of excitation energy of the parent nucleus in Figure 3. Calculations performed using the DWBA code PTOLEMY [8] successfully reproduced the observed inclusive cross section and the breakdown of these calculations for the direct population of component nuclear states is compared with the data as hollow bars in Figure 3.

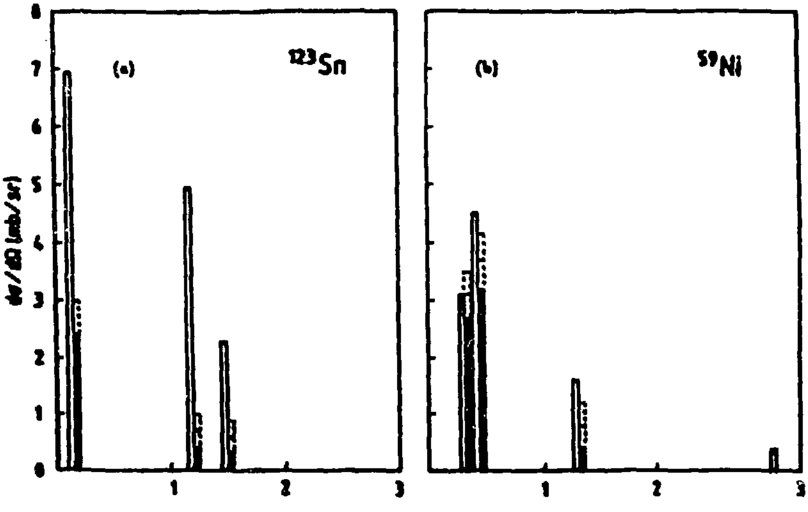

Figure 3

Comparison of observed (solid bars) and predicted direct (hollow bars) population of the residual products of the reaction ^{124}Sn(^{58}Ni, ^{59}Ni)^{123}Sn at 220 MeV as a function of nuclear excitation energy.

We find that the observed distribution of the transfer strength across the spectrum of final states of the ejectile nucleus (^{59}Ni) is well reproduced and thus conclude that states in this nucleus are predominantly populated via direct, one-step, transfer. However, a similar comparison for the recoil nucleus demonstrates no such agreement. We find only a fraction of the population expected appears in the data. The dashed lines in Figure 2(c) indicate the expected location of unobserved lines and an examination of Figure 3(a) suggests a depletion of strength populating the nucleus directly. Indeed, if we consider the population of the $\frac{1}{2}^+_1$ level in ^{123}Sn to be representative of the overall discrepancy, we find some 14 mb/sr of the inclusive 22 mb/sr of the 180° cross section to be missing. This disparity may be accounted for by a re-examination of Figure 2(a) in which a clump of strength is indicated at around 1 MeV. This may potentially correspond to the population of unresolved hole states comprising the weak coupling multiplet built on the single phonon nuclear core excitation. Indeed, following efficiency correction, this yield corresponds to some 10 mb/sr which may suitably account for the remaining fraction of the total inclusive reaction cross section.

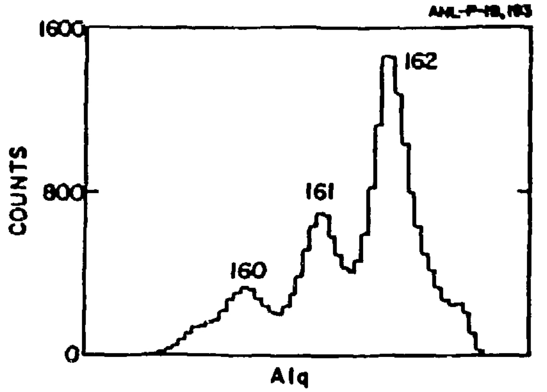

Figure 4

Focal plane mass spectrum of the quasi-elastic recoil products corresponding to the reaction ^{162}Dy(^{58}Ni, ^{58,59,60}Ni)^{162,161,160}Dy at 275 MeV

Despite the limited statistics upon which these measurements are based, the data clearly suggest that as much as half of the neutron transfer is occuring via vibrational core excitation. It is interesting to note that the probability of Coulomb excitation of the 2_1^+ level of the target is only around 10%. In view of the multistep transfer being comparable in strength to that proceeding via a direct mechanism this would suggest a considerably higher probability of neutron transfer from the excited core.

In summary, the technique developed in this paper is particularly well suited to the detailed spectroscopic study of low energy quasi-elastic nuclear reactions and, by overcoming the limitations of conventional procedure, the prospect of detailed studies of inclusive reaction mechanism may be realised. With only limited statistics we find evidence for strong multistep character in the transfer of a single nucleon from spherical vibrational target to spherical projectile nuclei. The suggestive measurements reported here may be made definitive through extended runs based on this technique and experiments planned for the future offer the real prospect of developing a quantified interpretation of the reaction process.

The technique discussed in this paper

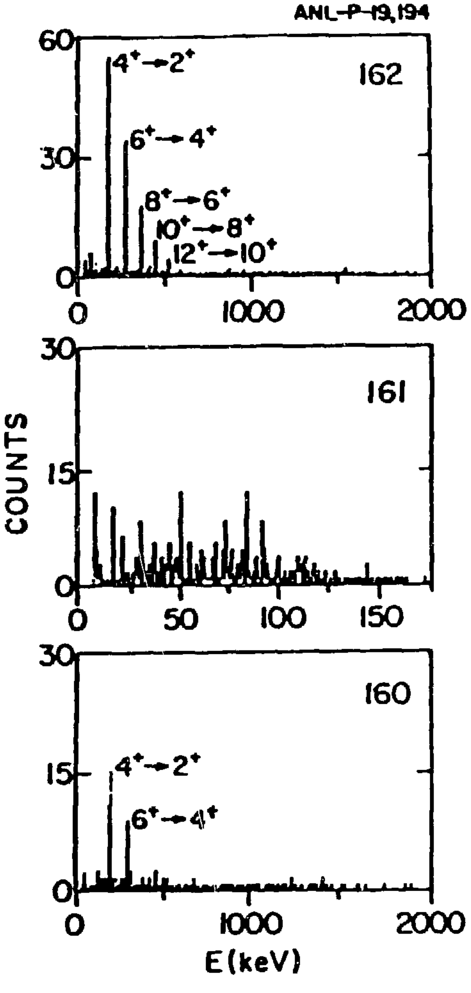

Figure 5

Spectrum of total γ-rays detected in delayed coincidence with the recoil nucleus. Figures (a), (b) and (c) present spectra corresponding to the yrast-like de-excitation of ^{162}Dy, ^{161}Dy and ^{160}Dy respectively. In figure (a) the highest observed line corresponds to the decay of the 12^+ level reached by Coulomb excitation.

may be extended to study rapidly rotating cold nuclei [9]. A heavy nuclear projectile incident on a collectively deformed nucleus at energies approaching the Coulomb barrier will quasi-elastically populate near yrast states to moderately high spin in the residual recoil nucleus and the opportunity is presented to examine the influence of rotation on its structure. Preliminary results for the reactions $^{162}Dy(^{58}Ni,^{58,59,60}Ni)^{162,161,160}Dy$ at 275 MeV are presented in Figures 4 and 5. The clean mass separation of strong transfer channels is observed and lines corresponding to the decay of levels populated through Coulomb excitation (a), single (b) and two (c) neutron transfer may be studied simultaneously. As only five hours of experimental beam time would indicate, the prospect of good, quantifiable data is realistic. Already, with limited statistics, we observe the population of states up to spins of $14\hbar$ in the residual nuclei and a tentative examination of the spectrum corresponding to the decay of ^{161}Dy reveals new aspects of the structure of this complex nucleus.

With many laboratories around the world presently developing recoil separators and sophisticated arrays of γ-ray spectrometers, the opportunity will soon become widely available to study in detail not only low energy nuclear reaction mechanism but also the structure of the exotic nuclei produced.

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