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MULTIPLE PRE-EQUILIBRIUM EMISSION AND THE INTERPRETATION OF EXPERIMENTAL RESULTS[1]

A.A. Cowley[2]
Department of Physics, University of Stellenbosch, Stellenbosch, 7600, South Africa

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Direct experimental measurements of coincident proton emission induced by protons of 100 to 200 MeV are considered. These results are discussed in the context of multiparticle emission from the pre-equilibrium stage of the interaction of protons with nuclei. It is inferred how the multiparticle reaction mechanism is related to the primary process.

1. Introduction

The influence of multiple pre-equilibrium emission in inclusive reactions induced by nucleons has recently become of renewed interest (see for example the work of Chadwick *et al.* [1]). This is as a result of the successful description of experimental inclusive (p,p') and (p,n) reactions in terms of the statistical multistep direct reaction theory of Feshbach, Kerman and Koonin [2] (FKK) at incident energies between 100 and 200 MeV [3]. Clearly the agreement between the theoretical and experimental results suggests that emission of a single nucleon, as assumed in the FKK theory, followed by subsequent emissions from an equilibrated system, should dominate. However, as was pointed out by Wu *et al.* [4] and more recently by Chadwick *et al.* [1], the yield of particles observed in inclusive reactions induced by nucleons usually violates unitarity. The extent to which the yield exceeds the reaction cross section is estimated [1, 5] to be 30 to 50 % for protons on ^{90}Zr at an incident energy range of 160 MeV. Consequently the excellent quantitative agreement between the FKK theory and the experimental data may be an artefact of a somewhat arbitrary normalisation, which is related to the poorly known strength of the effective nucleon-nucleon interaction.

Our ability to draw conclusions from comparisons between experimental inclusive spectra and results of an extended FKK theory that includes two-particle emission, is somewhat limited, because the signature of coincident emission is fairly obscure in such inclusive reactions. It will be shown in this paper that direct investigations of coincident

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[2]E-mail address: AAC@MATIES.SUN.AC.ZA

proton emission can provide valuable guidance on the reaction mechanism involved. This, in turn, should facilitate the inclusion of multiple pre-equilibrium emission in the framework of the FKK treatment.

2. Experimental aspects of coincident proton-emission studies

The coincident proton-emission reaction $(p,p'p'')$ has been investigated on ^{58}Ni at 100 MeV [6] and 200 MeV [7], and on ^{12}C [8, 9] and ^{197}Au [10, 11] at 200 MeV. A typical coincident spectrum, for ^{58}Ni$(p,p'p'')$ from the work of Cowley *et al.* [6] , is shown in Fig. 1. As may be seen, the coincident $(p,p'p'')$ yield includes events for which one particle has a low energy that is characteristic of emission from an equilibrated nuclear system, while the other proton has an energy usually associated with a pre-equilibrium process. These events are labelled EVAP in Fig. 1. The prominence of this process is in agreement with the FKK assumption that the major mechanism involves only one particle that emerges from the pre-equilibrium stage.

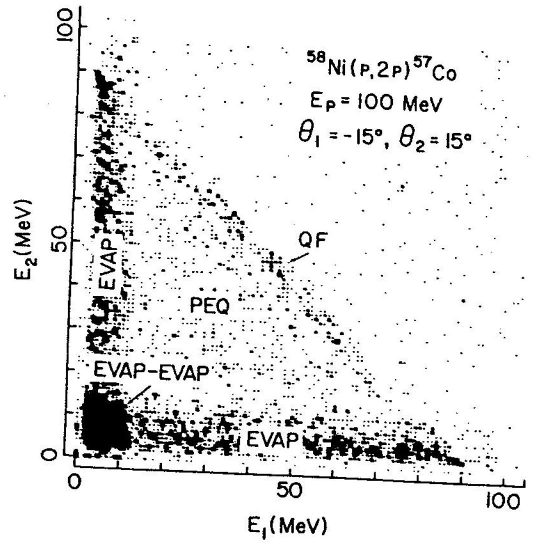


Fig. 1. Typical energy spectrum for the ^{58}Ni$(p,p'p'')$ reaction at an incident energy of 100 MeV [6] . Different regions of interest are indicated.

Further confirmation of the dominance of the single pre-equilibrium emission is obtained from the distribution (as a function of the scattering angle of the high-energy proton) of the integrated coincidence yield of events in the EVAP region of Fig. 1. As is shown in Fig. 2, the angular distribution of the integrated yields from the $(p,p'p'')$ and (p,p') reactions are in excellent agreement with regard to shape, and to within the experimental uncertainty, also in absolute magnitude. This means that a major part of the yield of the reaction of protons on ^{58}Ni, at an incident energy of 100 MeV, can be regarded as leading to only one pre-equilibrium particle. It is tempting to interpret

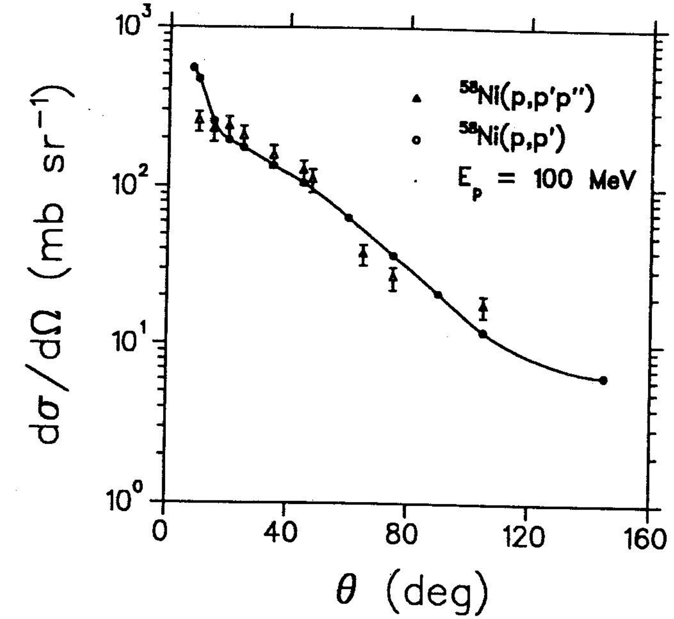


Fig. 2. Comparison between energy-integrated singles (circles) and coincident (triangles) (p,p') yields for the region indicated as EVAP for $E_{p''}$ in Fig. 1 for the reaction $(p,p'p'')$. Both sets of data have been integrated between energies $E_{p'}$ of 9 and 90 MeV. Results are given in the laboratory co-ordinate system.

the agreement in absolute magnitude as an indication that more than 90 % (when the systematic error is taken into consideration) of the yield can be accounted for by primary-particle pre-equilibrium. However, without knowledge of the multiplicity of particles from the equilibrated stage, such a conclusion might not be reliable.

The angular distribution of the low-energy proton from the equilibrated recoiling nucleus has to be isotropic in the centre-of-mass, which is also evident in the experimental yield shown in Fig. 3. For comparison, angular distributions of the quasifree knockout (QF) region and the kinematic range for two high-energy protons outside the region that can unambiguously be identified with discrete knockout, are also shown in Fig. 3. In contrast with the isotropic (in the centre-of-mass) EVAP distribution, the latter two are strongly forward-peaked.

A part of the spectrum of events shown in Fig. 1 that is understood reasonably well, is the region indicated as QF. The reaction corresponds to knockout of protons from valence orbitals to leave the recoiling nucleus in the ground state, or alternatively, in well-defined excited states. This part of the spectrum is dominated by quasifree knockout, in which the heavy nucleus remains at rest and merely acts as a spectator to the knockout process. This prominence of quasifree knockout is determined by the momentum distributions of the bound nucleons, and the knockout events are generally limited to a narrow region of momentum and co-ordinate space.

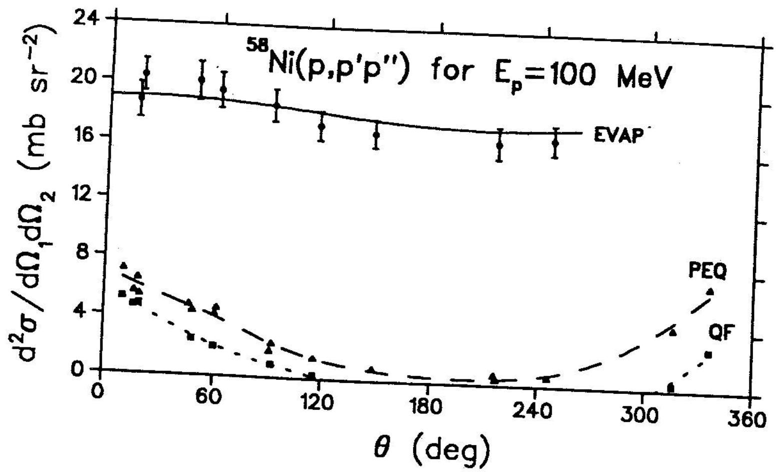
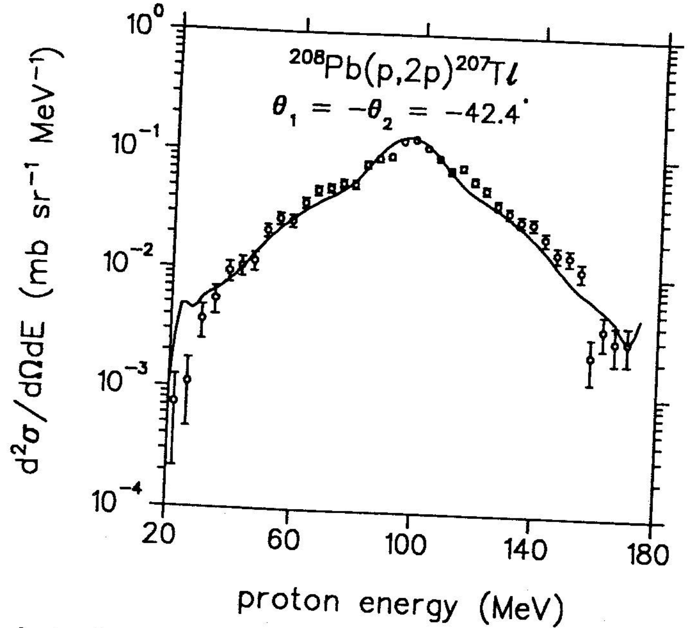


Fig. 3. Angular distributions for three energy regions identified in Fig. 1 for the reaction ^{58}Ni$(p, p'p'')$ at an incident energy of 100 MeV. Results are given in the laboratory co-ordinate system. The solid line indicates the predicted lab yield for an isotropic centre-of-mass distribution. The broken curves serve to guide the eye.



. 4. Energy-sharing distribution (laboratory differential cross section versus kinetic energy one of the observed protons) for the reaction ^{208}Pb$(p, 2p)^{207}$Tl, at an incident energy of MeV, corresponding to knockout of protons from the valence orbitals. Measured cross ions are shown with statistical error bars and the continuous curve is the result of a DWIA ulation.

The quasifree knockout reaction mechanism is formulated in terms of the distorted-wave impulse approximation [12] (DWIA). An example of the agreement between theory and experimental results is shown in Fig. 4. This shows that even for a target nucleus as heavy as ^{208}Pb, for which rescattering decreases the $(p, 2p)$ cross section to only 5 % of the plane wave limit, the shape of the energy sharing distribution is retained. Furthermore, the measured spectroscopic factors [13] are in agreement with theoretical predictions and also with results from electron-knockout studies.

It is well known that rescattering effects are dominant in nucleon knockout reactions with energetic protons. Although a proportion of the multiple scattering is manifested as events which are redistributed along a specific kinematic locus, a large fraction should proceed with energy transfer to the recoiling heavy system. Therefore these reactions, which could originate from collisions with valence nucleons in the target nucleus, would interfere with pure knockout from deep-lying shell-model orbitals.

For the knockout yield to discrete final states, the region of phase space which is of interest is limited to a range where only a small part of the rescattering is observed. Consequently the coincident emission simply provides a background upon which the discrete knockout from deeper shell model orbitals is superimposed. Typically, as was already mentioned, this rescattering represents the major part of the original (as described in the plane wave limit) knockout yield. Furthermore, because the yield of discrete knockout from deeper-lying shells are attenuated even more severely than for valence orbitals [14], the main portion of events appearing in the PEQ region of Fig. 1 should be associated with rescattering of knockout reactions in which one or both emerging nucleons suffer a further violent interaction with the rest of the recoiling nucleus.

Therefore the reaction mechanism leading to two-proton pre-equilibrium emission may be interpreted as an initial nucleon-nucleon collision between the projectile and a valence nucleon bound in the target nucleus, with subsequent rescattering of the struck nucleon from the remainder of the target. Thus the struck nucleon behaves like an intranuclear projectile, and the angular and energy distributions of the protons observed in coincidence are similar to primary pre-equilibrium emission at the projectile energy transferred in the initial collision.

These ideas about the likely reaction mechanism whereby two-particle pre-equilibrium emission proceeds, were explored for the reaction $(p, p'p'')$ on ^{58}Ni at 100 MeV [6] and 200 MeV [7], and on ^{12}C [8, 9] and ^{197}Au [10, 11] at 200 MeV. A typical result is shown in Fig. 5. The remarkable agreement in the shape between the theory and the experimental data clearly supports the validity of the theoretical interpretation.

3. Influence of two-particle emission in inclusive reactions

Based on comparisons with experimental inclusive data, the addition of two-particle emission to the FKK theory, which considers only primary pre-equilibrium, by appears to have virtue. Fig. 6 shows calculations by Richter *et al.* [15] in which a pure knockout contribution was added incoherently to the single particle pre-equilibrium yield. Also shown are results for which the rescattered knockout PEQ events were crudely included by doubling the discrete knockout portion. A more refined treatment would be appro-

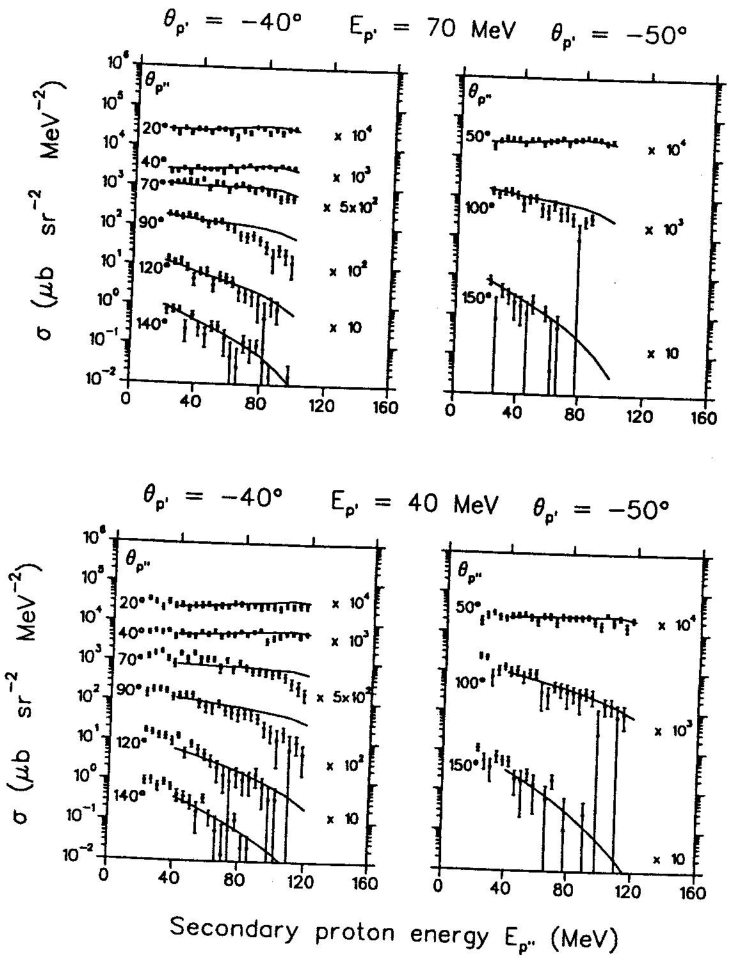


Fig. 5. Experimental coincident proton emission cross section for the reaction ^{197}Au(p,p',p'') at an incident energy of 200 MeV as a function of the secondary proton energy $E_{p''}$ and for coincidence angle pairs of the primary $(\theta_{p'})$ and the secondary $(\theta_{p''})$ scattering angles as indicated. Error bars represent the statistical error. Results have been multiplied by the indicated factors for the purpose of display.

priate, but the results displayed in Fig. 6 already indicate that better agreement with the experimental data is achieved with the full set of reaction types.

4. Summary and conclusions

The interpretation of direct measurements of coincident proton emission induced

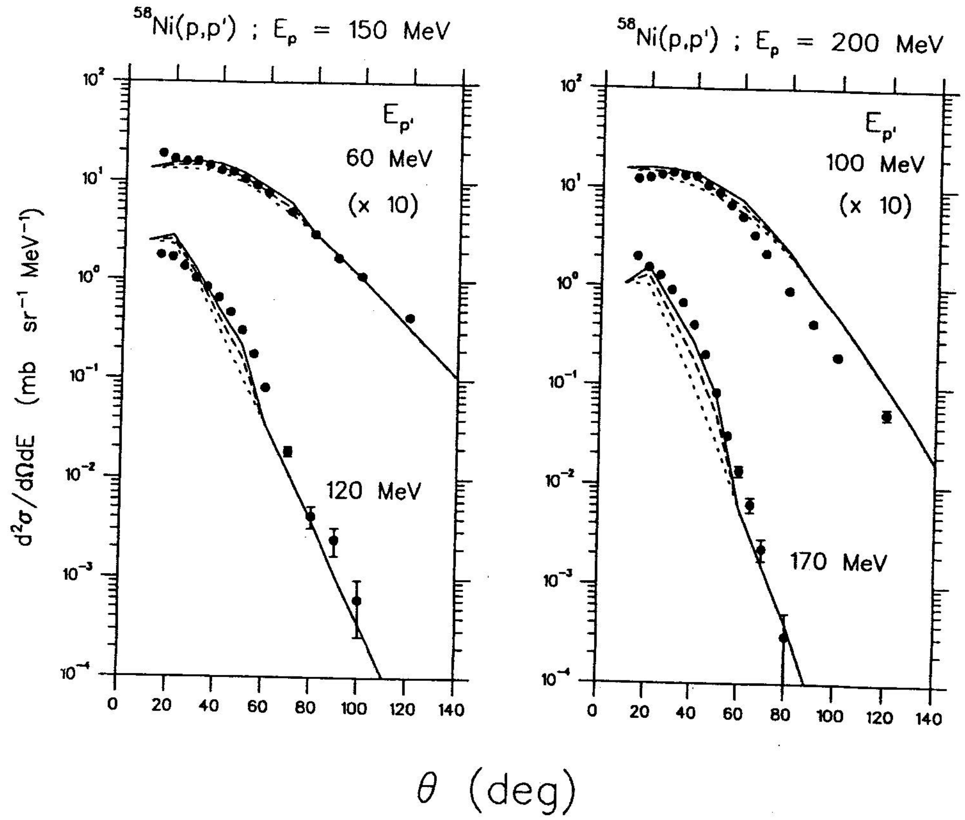


Fig. 6. Angular distributions for the reaction ^{58}Ni(p,p') at different incident energies E_p and emission energies $E_{p'}$. The curves correspond to primary pre-equilibrium emission according to the FKK theory (dotted lines), FKK plus discrete knockout (dashed lines) and the FKK plus full two-nucleon components (solid lines). Results have been multiplied by the indicated factors for the purpose of display.

by protons was reviewed. It is shown that at incident energies between 100 and 200 MeV the experimental data are consistent with a nucleon knockout reaction mechanism, followed by rescattering of one or both of the nucleons participating in the knockout collision. Addition of this component of two-particle emission to the primary pre-equilibrium yield that is given by the FKK multistep direct theory, improves the agreement of the results of the theoretical calculations with the experimental angular distributions.

The encouraging results obtained with this fairly unsophisticated theoretical treatment should motivate the development of a more refined formalism. Clearly such an extended description of the two-particle emission should be incorporated coherently with the primary pre-equilbrium process as part of the multistep direct theory.

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