Neutron Multiplicity Distributions and the Role of Transfer and Breakup in Quasielastic Heavy-Ion Reactions at 15 MeV/Nucleon

U. Jahnke, G. Ingold, H. Homeyer, M. Bürgel, Ch. Egelhaaf, H. Fuchs, and D. Hilscher
Hahn-Meitner-Institut für Kernforschung Berlin, D-1000 Berlin 39, Germany
(Received 18 November 1982)

A new tool for the study of heavy-ion reactions is obtained by adapting a 4π-neutron-multiplicity counter to accelerator experiments. The instrument registers almost all neutrons emitted in each single reaction event. For quasielastic reactions of 290-MeV $^{20}Ne + ^{197}Au$ the measured neutron multiplicity distributions allow a quantitative decompsotion of the cross section into two contributions: one with higher Q value from transfer reactions, one with lower Q value due to the decay of the decay of the projectilelike fragments.

PACS numbers: 25.70.Cd, 29.40.Mc

In this paper we present the application to heavy-ion reactions of a high-efficiency neutron counting device which has already earned its merits in the study of the physics of spontaneous and induced fission,[1] in the study of photonuclear reactions,[2] and last but not least, in the search for superheavy elements.[3,4] Ideally, it counts all neutrons emitted in a reaction event, i.e., it yields the complete neutron multiplicity distribution, not only the average multiplicity. The information provided thus is analogous to that obtained for γ rays with a modern 4π-multifold-scintillation-detector assembly ("Crystal Ball"), and like the number of γ rays, which is a measure of the angular momentum, the number of evaporated neutrons measures the amount of kinetic energy dissipated into internal excitation, at least for heavy nuclei.

The apparatus essentially consists of a large volume (500 L) of liquid scintillator in a sphere surrounding the source or the target for the accelerator experiments reported in this note. Neutrons released simultaneously from a reaction are moderated in the liquid, and after thermalization they diffuse in the tank until finally after an average storage time of about 11 μs they are captured by gadolinium. Gadolinium is added to the liquid in doses up to 0.5 wt.% because of its very high thermal capture cross section. The scintillation light from the capture γ rays indicates the presence of a neutron. Because of the time spread in the thermalization and diffusion processes, the signals for the individual neutrons arrive conveniently one by one, spread statistically over a period of about 35 μs.

For the heavy-ion experiments, the detector was installed on the beam line of the VICKSI accelerator of the Hahn-Meitner-Institut Berlin. The 12-cm-wide tube passing through the center of the tank accommodates a target wheel and two or three solid-state detector telescopes for the identification of charged reaction fragments. The heavy-ion beam is chopped into blocks of 0.5-μs length with pauses of 60 μs for the neutron counting in between. Also, the beam intensity is reduced in order to avoid multiple reactions in a single burst because they would simulate an enhanced neutron multiplicity. The detection efficiency ideally is nearly 1, but in practice with our present detector it is only between 80% and 90% [in the course of the experiment the efficiency was checked with a ^{252}Cf source and found to be $(83 \pm 1)\%$]. As a consequence, the multiplicity response function is shifted and broadened with respect to the δ function valid for an efficiency of 1. Thus the real multiplicity distribution must be derived by an unfolding procedure from the measured distribution. (The discussion of this problem as well as other aspects related to the operation of the detector with the heavy-ion beam will be published elsewhere.[5])

Substantial conclusions, however, can often be drawn directly from the measured raw multiplicity distributions. This is, for instance, the case for quasielastic collisions of lighter ($A \leq 20$) heavy ions chosen for a first application of the method. Their interpretation in the regime of 10 to 20 MeV/nucleon bombarding energy is a question widely and controversially discussed in the past years. Generally one observes[6-9] the inclusive cross section of projectilelike fragments to be dominated by a forward-peaked component concentrated at an energy corresponding to a velocity close to that of the projectile (see, for example, in Fig. 1 some spectra from the present investigation). Gelbke *et al.*[8,9] from the shape of this component guessed that there is a marked change in reaction mechanism when one goes from 10 to

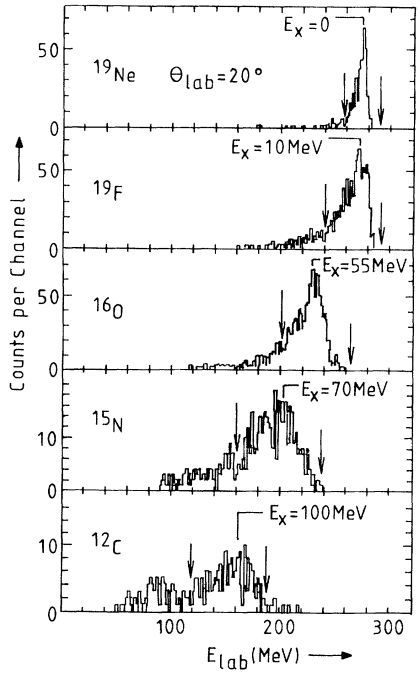

FIG. 1. Some inclusive energy spectra of fragments from ^{20}Ne + ^{197}Au at 290 MeV. The arrows mark the edges of the windows for which the multiplicities in Fig. 2 were evaluated. The total excitation energies corresponding to the most probable ejectile energies in two-body kinematics are indicated.

20 MeV/nucleon thus passing the velocity of sound in nuclear matter. Calculations by McVoy and Nemes[10] suggest this change to be the transition from transfer to direct projectile breakup. A later analysis of similar experimental data[6] contradicted the suggestions of Ref. 8 and 9. In any case, if there is a change of reaction mechanism, the contributions of both mechansims (transfer, breakup) must be mixed at intermediate bombarding energies. On a theoretical basis, Udagawa *et al.*[11] proposed a decomposition of the inclusive energy spectra from ^{20}Ne-induced reactions into a transfer and a breakup component. The beam-velocity component, for instance, of ^{16}O fragments at 262-MeV bombarding energy is attributed by these authors mainly to the breakup process of ^{20}Ne into $\alpha + ^{16}$O. The same group in a later publication[12] explains the same component as dominantly due to a process where the α particle is captured by the target, hence by α transfer. Obviously, both the transfer and the breakup processes give rise to ejectiles flying with about the beam velocity (because of velocity matching). Therefore, it is no surprise that the energy spectra do not exhibit features which might serve as a handle for a decomposition into two components. Nevertheless, as noted previously,[7] the two processes correspond to very different excitation of the target. In the breakup the α particle moves on with, on the average, the beam velocity. If, instead, it is transferred to the target, it deposits about its share of the projectile kinetic energy in the target, giving rise to a higher excitation and the corresponding evaporation of additional neutrons. This offers the highly desirable opportunity to make a distinction between processes by just counting the neutrons.

In the following we discuss the results obtained for the 290-MeV ^{20}Ne + ^{197}Au system which was already studied previously in some detail.[6,7,13] In particular, a correlation experiment[13] indicated that the breakup events are dominantly due to sequential breakup, i.e., formation of an excited projectilelike fragment in a first reaction step, followed by later emission of (generally) an α particle in the case when the excitation energy is above threshold.

Some representative spectra of projectilelike fragments are shown in Fig. 1. For each detected fragment the number of coincident neutrons was counted. With a window on the quasielastic peak as indicated in Fig. 1, the experimental (uncorrected) multiplicity distributions as shown in Fig. 2 for a number of isotopes are obtained.

Consider first the series of isotopes denoted by encircled numbers going from 0 to 8, which give the number of nucleons removed from the projectile. In their multiplicity distributions one notes a component which shifts monotonically to higher multiplicities as the number of missing nucleons increases. Approximately, the centroid of this component is at 0.8 times the number of missing nucleons. We note that—in view of the counting efficiency of about 0.8—on the average one neutron is emitted per removed nucleon. This identifies the component under discussion as due to the transfer of the removed nucleons to the target nucleus, because for each transferred nucleon about 13 MeV (binding energy plus kinetic energy, according to velocity matching) is added to the target excitation energy, and this equals approximately the energy removed by one evaporated neutron. There are some minor deviations from the regular behavior, notably for the one-nucleon transfer where the proximity of the ground-state transition to the Q-value window may restrict the available phase space. In ^{21}Ne and ^{19}Ne, for instance, the most probable multiplicity is 0 instead of 1. For ^{20}Ne the window is

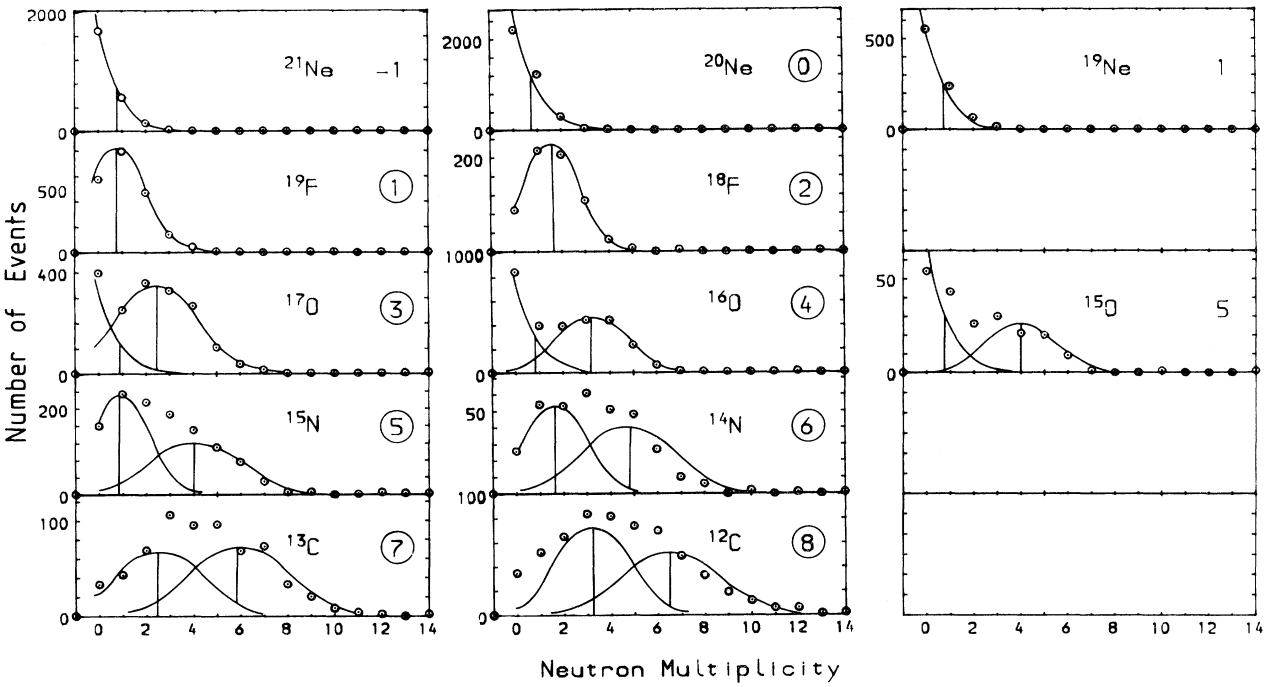

FIG. 2. Multiplicity distributions (not corrected for efficiency) of neutrons coincident with quasielastic projectilelike fragments observed at 20° (see Fig. 1). The curves are Gaussians (or exponentials for $^{19-21}$Ne), the centroids of which are indicated by vertical bars. Inserted numbers indicate the number of nucleons removed from the projectile.

set on 5 to 30 MeV inelasticity, excluding the elastic peak. We also note that the width of the transfer component increases with the number of transferred nucleons and is compatible with what one expects from the estimated[14] fluctuation of excitation energy.

The transfer component is the only one for neon and fluorine isotopes, but from oxygen on we observe a second pronounced component appearing at lower mean multiplicity than the transfer component. In each case, actually, this component is nearly identical in shape to the transfer component appearing precisely two rows above in Fig. 2, i.e., for that isotope which contains just one α particle in addition to the isotope considered. Apparently, in the collisions associated with this component, one α particle is removed without the corresponding energy deposit into the target, i.e., the α particle is set free with, on the average, the beam velocity. This is just the breakup of the projectilelike fragment into an α particle and the remainder. We recall that for most isotopes considered here the lowest threshold for particle emission is that of α particles and that fast forward-peaked α particles are found much more frequently than other light ejectiles. It is also useful to remember that the neutron multiplicity measures essentially the excitation of the target nucleus, since in the very asymmetric system ^{20}Ne + ^{197}Au the projectilelike fragment receives little excitation energy, which, furthermore, because of fluctuations about the average is not strongly correlated with the target excitation. Therefore, whether the projectilelike fragment is excited above its α particle threshold or not, it will have about the same multiplicity of accompanying neutrons determined by Q matching.

The strength of the breakup contribution can easily be read off from the multiplicity distributions. For the most frequent breakup product of ^{20}Ne, the nucleus ^{16}O, we find the breakup to account for 40% of the inclusive ^{16}O cross section, in pleasing agreement with the estimate derived from the coincidence experiment.[13]

To summarize, we have demonstrated a method which measures the number of neutrons emitted in a heavy-ion reaction. Numerous applications of this method are obvious, but could not be discussed in this note. For quasielastic reactions of 15-MeV/nucleon ^{20}Ne with gold we found that transfer and breakup close to the grazing angle

are of about equal importance. A consistent and simple interpretation of the neutron multiplicity patterns is possible on the basis of the previous finding[13] that the breakup is dominantly due to α-particle emission from excited projectilelike fragments which were formed, prior to the decay, by ordinary transfer processes. The decomposition of the neutron multiplicity distributions provides us with an instrument serving to reconstruct the primary distributions of projectilelike fragments prior to eventual sequential decay.

We are indebted to R. Brandt at Philipps University Marburg for putting the 4π-neutron-multiplicity counter at our disposal.

[1]B. C. Diven, H. C. Martin, R. F. Taschek, and J. Terrell, Phys. Rev. 101, 1012 (1956).

[2]A. Leprêtre, H. Beil, R. Bergère, P. Carlos, J. Fagot, A. De Miniac, and A. Veyssière, Nucl. Phys. A367, 237 (1981).

[3]E. Cheifetz, R. C. Jared, E. R. Giusti, and S. G. Thompson, Phys. Rev. C 6, 1348 (1972).

[4]This also has been the use of our present detector for the past seven years [H. J. Becker, T. Lund, and R. Brandt, Radiochim. Acta 26, 15 (1979)].

[5]U. Jahnke, G. Ingold, D. Hilscher, H. Orf, E. A. Koop, G. Feige, and R. Brandt, in Proceedings of a Conference on Detectors in Heavy Ion Reactions, Berlin, 1982 (Springer-Verlag, Berlin, to be published).

[6]Ch. Egelhaaf, G. Bohlen, H. Fuchs, A. Gamp, H. Homeyer, and H. Kluge, Phys. Rev. Lett. 46, 813 (1981).

[7]Ch. Egelhaaf, H. Fuchs, A. Gamp, and H. Homeyer, Phys. Rev. C 24, 759 (1981).

[8]C. K. Gelbke, D. K. Scott, M. Bini, D. L. Hendrie, J. L. Laville, J. Mahoney, M. C. Mermaz, and C. Olmer, Phys. Lett. 70B, 415 (1977).

[9]C. K. Gelbke, in *Proceedings of the Symposium on Deep Inelastic and Fusion Reactions with Heavy Ions, Berlin, 1979,* edited by W. von Oertzen, Lecture Notes in Physics Vol. 117 (Springer-Verlag, Berlin, 1980), p. 207.

[10]K. W. McVoy and M. Carolina Nemes, Z. Phys. A 295, 177 (1980).

[11]T. Udagawa, T. Tamura, T. Shimoda, H. Fröhlich, M. Ishihara, and K. Nagatani, Phys. Rev. C 20, 1949 (1979).

[12]E. Takada, T. Shimoda, N. Takahashi, T. Yamaya, K. Nagatani, T. Udagawa, and T. Tamura, Phys. Rev. C 23, 772 (1981).

[13]H. Homeyer, M. Bürgel, M. Clover, Ch. Egelhaaf, H. Fuchs, A. Gamp, D. Kovar, and W. Rauch, Phys. Rev. C 26, 1335 (1982).

[14]D. J. Morrissey and L. G. Moretto, Phys. Rev. C 23, 1835 (1981).