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Pre-scission neutron multiplicity following the $^{16}O+^{142}Nd$ reaction

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Fission fragment-neutron angular correlations have been measured for the reaction 178 MeV $^{16}O+^{142}Nd$, allowing determination of the pre-scission and total neutron multiplicities. The total multiplicity agrees well with expectations based on energy balance, unlike the value obtained in a previous measurement. The pre-scission multiplicity of 4.2 ± 0.3 is much higher than the previous value (2.7 ± 0.4), leading to a considerably longer fission time scale and higher nuclear viscosity.

Recently, measurements of the pre-scission neutron multiplicity (υ_{pre}) for a variety of fissioning systems have been made.[1-6] In general, it has been found that the multiplicity exceeds that predicted by the statistical model, the excess yield increasing with excitation energy and fissility. This has been interpreted in terms of neutron evaporation during the time taken to pass from the equilibrium to the scission configuration, and quantitative information on the fission time scale has been extracted, which in turn, through modeling of the fission process, gives important information on nuclear viscosity. It is thus imperative that the experimental results receiving theoretical attention should be reliable.

One simple method which has previously[4,6] been used to test the reliability of such measurements is to compare the measured total neutron multiplicity (υ_{tot}) with that derived from energy balance. At high bombarding energies per nucleon ($E/A > 15$ MeV) it may be difficult to make reliable predictions since complete fusion can no longer be expected; however, at lower energies it has been shown[6] that agreement to $< 5\%$ can be obtained.

The experimental values of υ_{pre} for fission following formation of the compound system ^{158}Er (Ref. 5) by four different reactions have been the subject of extensive interpretation, particularly the $^{16}O+^{142}Nd$ reaction.[7] However, until now an analysis of υ_{tot} as described above has not been reported. This is shown in Fig. 1, where υ_{tot} (excluding preequilibrium neutrons) is plotted as a function of the total available decay energy for fission $E_x(f)$ (see Appendix 1 of Ref. 4), both for ^{158}Er and $^{168,170}Yb$ (Refs. 1 and 4). The excitation energies are calculated assuming complete fusion, but are reduced by 20 MeV (Ref. 5) per preequilibrium neutron. The results for $^{168,170}Yb$ are in excellent agreement with a simple calculation[4] assuming decay by neutron and γ-ray emission only. Those for ^{158}Er are, however, substantially lower. Since the calculation also gives agreement for many other experimental data,[4] two possible explanations of the discrepancy for ^{158}Er remain; firstly the experimental data may be in error, which would certainly affect the deduced fission time scale, and secondly there may be a substantial yield of charged particles associated with these reactions. It was concluded that incomplete fusion does not significantly precede fission;[5] however, it is possible that the evaporated yield of charged particles is large for the neutron-deficient ^{158}Er system. If so, the pre-scission charged par-

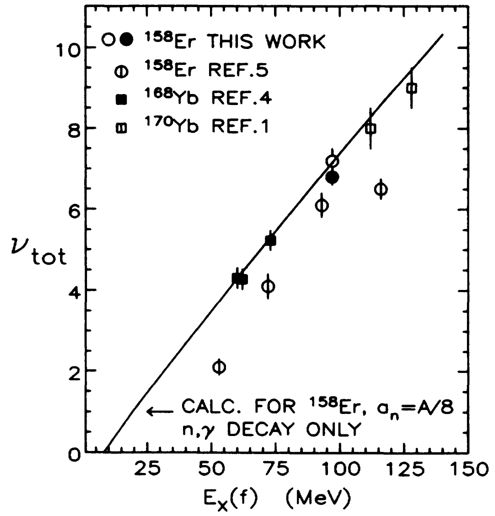

FIG. 1. Total neutron multiplicity (υ_{tot}) shown as a function of the available decay energy $E_x(f)$. The present result for ^{158}Er is shown by the solid circle; adding the contribution due to charged particle evaporation equivalent to 0.42 ± 0.15 neutrons gives the hollow circle. The results of Ref. 5 represent neutron multiplicities only, for the reactions 207 MeV $^{16}O+^{142}Nd$ [highest value of $E_x(f)$], 180 MeV $^{24}Mg+^{134}Ba$, 180 MeV $^{32}S+^{126}Te$, and at the lowest value of $E_x(f)$, 216 MeV $^{50}Ti+^{108}Pd$.

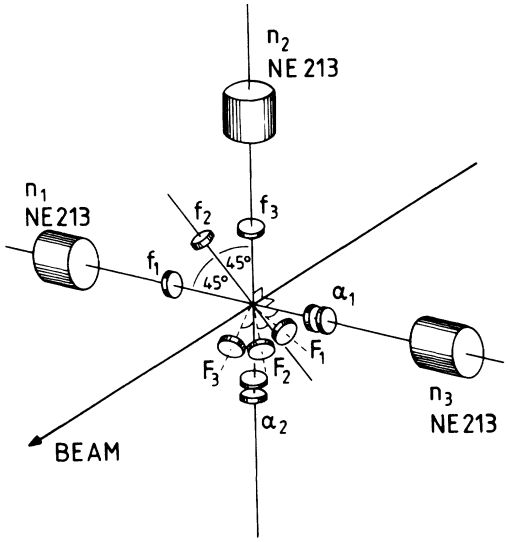

FIG. 2. Schematic diagram of the present experimental configuration. For further details, see text.

ticle multiplicities must be measured and included explicitly in the analysis, otherwise the deduced fission time scales would be too short.

Because of the emphasis placed on the $^{16}O+^{142}Nd$ reaction, it was chosen as the best measurement to repeat, and by also measuring the charged particles, the origin of the discrepancy in υ_{tot} should become clear.

The experiment was carried out at the Research Center for Nuclear Physics, Osaka (RCNP), a 178-MeV-^{16}O beam from the azimuthally varying field cyclotron bombarding a 1 mg cm^{-2} neodymium oxide target. The experimental configuration (shown in Fig. 2) was similar to that used previously,[4] being designed to best utilize the kinematic focusing of post-scission neutrons (υ_{post}) by the fission fragment velocity. All detectors were in the plane perpendicular to the beam, except the 500 mm^2 Si detectors $F_{1\text{-}3}$, which were at an angle of ~45° to intercept the fission fragments complementary to those detected in the principal detectors $f_{1\text{-}3}$. Two Si detector telescopes ($\alpha_{1,2}$) were included. All these Si detectors were in a cylindrical aluminum scattering chamber of 21 cm inner diameter and 0.5 cm wall thickness. The efficiencies of the NE-213 neutron detectors (12.7 cm × 12.7 cm) were determined before and after the bombardment by measuring the spectrum from a ^{252}Cf source using a 2π multiwire proportional counter start detector.[4] The energy thresholds were set low so that their possible fluctuation would have a negligible effect on the efficiency at energies where the neutron yield was high. During the bombardment, the ~5% contribution due to random coincidences was determined by recording the spectrum from the next beam burst. The arrival times of the fission fragments at $f_{1\text{-}3}$ were used to start the neutron time-of-flight measurement; after correcting for the dependence of flight time on fragment energy, a full width at half maximum of 1.8 ns was obtained for the γ-ray peak. The effects of this resolution, the range of interaction depths in the scintillators, the solid angles of the f and n detectors (13 and 27 msr), and the range of total kinetic energies and fragment masses were included in calculating the laboratory velocity spectra for pre- and post-scission neutrons. The c.m. frame neutron spectra were calculated realistically from a simple neutron evaporation cascade calculation. For a given step, the form of the neutron energy (E_n) spectrum was taken as $E_n \exp(-E_n/T)$, where T was calculated from the excitation energy using a level density parameter $a_n = A/10$. From a given starting excitation energy, the mean temperature at each step of the cascade was determined by the energy removed in previous steps; by summing the contribution from all steps, the final spectral shape was determined. The starting and stopping energies of the prescission cascade were varied independently (from the fission Q-value the latter fixed the starting energy of the post-scission cascade), together with the pre- and post-scission neutron multiplicities. The X^2 surface was mapped out, and best fitting values, with standard statistical uncertainties were determined. Further details will be published.[8]

The experimental geometry does not allow determination of the preequilibrium neutron multiplicity (υ_{pee}); however, this was done in the previous measurement at 207 MeV bombarding energy, and the multiplicity at 178 MeV was estimated to be reduced to 0.7, from systematics,[9] which also allowed calculation of the expected spectrum at 90° to the beam. It constituted only ~5% of the observed yield, and gave an equal contribution in each n detector, so any error in this procedure will not have a significant effect.

From the above discussion, the systematic error in the neutron multiplicities is expected to be $< \pm 5\%$. The uncertainties in the proton and α-particle multiplicities are much larger, since due to poor statistics (low multiplicities) it was impossible to separate pre- and post-scission emission. Thus the total multiplicities only ($p_{\rm tot}$, $\alpha_{\rm tot}$) were estimated, taking into consideration the kinematics, energy thresholds, and likely pre/post-scission division.[10] The error may be as large as ± 35%.

The neutron velocity spectra at 0° and 90° for detector n_1 are shown in Fig. 3. Within ± 2%, all equivalent spectra from different detectors were the same, and the fits to the full data set are shown. The associated pre- and post-scission and total neutron multiplicities are given in Table I, together with the total proton and α-particle multiplicities. For the purpose of comparison of the total multiplicity with the simple calculation shown in Fig. 1, $p_{\rm tot}$ and $\alpha_{\rm tot}$ were converted to an equivalent neutron multiplicity of 0.42 ± 0.15. Thus the equivalent total evaporated neutron multiplicity was 7.2 ± 0.3, while including $\upsilon_{\rm pee}$ gives 7.9 ± 0.3. The former value is plotted in Fig. 1 at a value of $E_x(f)$ corrected for $\upsilon_{\rm pee}$ as previously described. The agreement with the calculation is very good, as was found for the ^{168,170}Yb results. Even if an energy-dependent[10] contribution due to charged particle emission is added to the previous ^{158}Er results, the disagreement is still present for all but the ^{24}Mg induced reaction, which throws doubt on the $\upsilon_{\rm pre}$ results deduced. These are shown in Fig. 4 as a function of the excitation energy above the compound nucleus ground state [E_x(CN)]. The present result (excluding $\upsilon_{\rm pee}$ and charged particle contributions) of 4.2 ± 0.3 is much higher than the previous value of 2.7 ± 0.4 for the ^{16}O reaction, despite the lower bombarding (excitation) energy (the calculated statistical model multiplicity is almost unchanged in going to the present energy). It is in good agreement with the data for ^{168,170}Yb (see Fig. 4), as might be expected from the systematic trends in neutron multiplicities.[4,8] Thus, it is concluded that the previous results for ^{158}Er contain some error, and theoretical interpretations should rather focus on the present result, and those previously reported for other systems.[1-4,6]

The implications of the present value of $\upsilon_{\rm pre}$ are quite extensive. The fission time scale and nuclear viscosity will be much higher (see Ref. 5, Fig. 16). This will further reduce the fission probability due to the Kramers factor, and will require an even higher value of a_f/a_n which may be hard to reconcile with theory, or with measurements at lower energies. This then raises questions regarding the validity of the model of fusion-fission, either in terms of fission barrier heights and a_f/a_n values, or nuclear viscosity and the reaction mechanism itself. It is not the purpose of this paper to examine these points in detail; they will be discussed in a further paper.[8]

In conclusion, it has been shown that a previous measurement of neutron multiplicities for reactions leading to fission following formation of the compound nucleus ^{158}Er gave $\upsilon_{\rm tot}$ results inconsistent with expectations based on energy balance, and $\upsilon_{\rm pre}$ results surprisingly different from those for ^{168,170}Yb. A new measurement was made for the

TABLE I. Neutron and charged particle multiplicities. The symbols are defined in the text.

$\upsilon_{\rm pre}$	$\upsilon_{\rm post}$	$\upsilon_{\rm tot}$	$p_{\rm tot}$	$\alpha_{\rm tot}$
4.2 ± 0.3	1.32 ± 0.15	6.8 ± 0.2	0.15 ± 0.05	0.09 ± 0.03

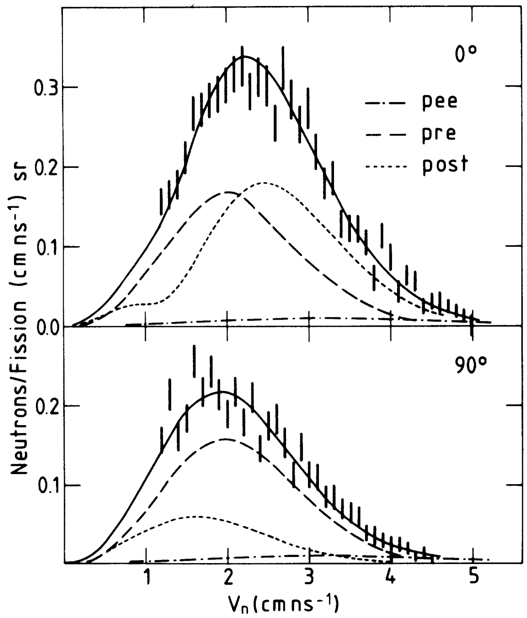

FIG. 3. Neutron velocity spectra for detector n_1 and correlation angles of 0° and 90°. The spectral contributions from the pre- and post-scission neutrons ($\upsilon_{\rm pre}$ and $\upsilon_{\rm post}$) and the preequilibrium neutrons ($\upsilon_{\rm pee}$) are indicated, as is the full fit including all these components (solid line).

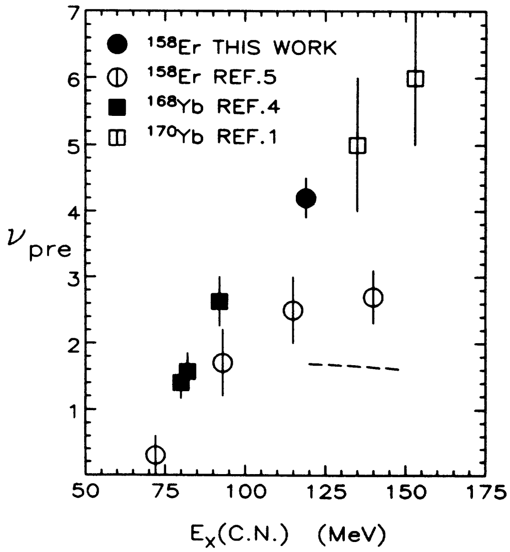

FIG. 4. Pre-scission neutron multiplicity ($\upsilon_{\rm pre}$) as a function of the excitation energy above the ground state. The data points of Ref. 5 are in the same order as described in the caption of Fig. 1. The statistical model prediction for the ^{16}O induced reaction is shown by the dashed line.

reaction of 178-MeV $^{16}O+^{142}Nd$ which resulted in values of ν_{tot} and ν_{pre} higher than those reported previously, and which were consistent with expectations and systematics. The evaporated charged particle multiplicities were found to be low. The new value of $\nu_{pre}=4.2\pm0.3$ will require a nuclear viscosity several times larger than that required to fit the previous result.

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