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Prescission neutron emission from ^{104}Pd

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Neutron spectra in coincidence with fission fragments have been measured for the 190 MeV ^{28}Si+^{76}Ge populating ^{104}Pd compound nucleus at $E_x \sim 133$ MeV excitation energy. The extracted prescission multiplicity for symmetric splitting is $\nu_{\rm pre}=1.1\pm0.2$. The average fission time $\tau_F=6^{+3}_{-2}\times10^{-20}$ s is determined, in good agreement with the systematics of Hinde *et al.* for heavier systems ($A\geq125$ compound nuclei).

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Measurements of the prescission neutron multiplicity have been already performed on a variety of systems [1]. It is now well known that, above a certain excitation energy in the compound nucleus, the emission of particles prior to scission exceeds that predicted by the statistical model. This has been interpreted in terms of neutron evaporation during the motion of the fissioning system from the equilibrium towards the scission configuration, and quantitative information on fission time scale has been extracted for nuclei with $A\geq125$ [2].

Prescission data offer the unique opportunity of testing the present knowledge about diffusion coefficients, fission barrier heights, and level densities in the fissioning nucleus. In this respect, fully microscopic calculations seem to have difficulties in reproducing the diffusion coefficient values needed to account for experimental data [3,4] in the $A\sim160$ region. However, quantitative prediction about the diffusion coefficient D_β for Mg, Ge, Sn, and Eu nuclei have been recently presented [3], so that it seems to be interesting to extend the study of the prescission phenomena in lighter systems, in order to have a complete set of data over a wide mass range to test the diffusion models.

We present here a study of the prescission neutron emission from the compound nucleus ^{104}Pd which was populated at the excitation energy of $E_x\sim133$ MeV by using the reactions 190 MeV ^{28}Si+^{76}Ge.

The experiment was performed at the XTU Tandem facility of the Laboratori Nazionali di Legnaro, Italy. The 190 MeV ^{28}Si beam was focused onto a 0.2 mg/cm^2 target of ^{76}Ge, 90% enriched, supported by a 20 μg/cm^2 C foil. The target was located at the center of a thin-walled (3 mm) nearly spherical aluminum scattering chamber, ~100 cm in diameter.

One fission fragment (FF1) was detected in a time-of-flight (TOF) arm consisting of a 5×4 cm^2 parallel plate avalanche counter (PPAC) as a start and a large area (15×15 cm^2) position sensitive PPAC as a stop detector. The flight path was 34.8 cm and the opening angle $\Delta\theta_1=\pm9°$. Overall resolutions for elastic events of the TOF arm were $\delta t=1.0$ ns [full width at half maximum (FWHM)] and $\delta\theta=0.6°$, the latter determined by wire spacing in the position-sensitive PPAC. The TOF arm was operated in coincidence with a second large area PPAC (15×15 cm^2, opening angle $\Delta\theta_2=\pm26°$) used to detect the complementary fission fragment (FF2). The resolutions of the second PPAC were similar to those quoted above. The TOF arm was positioned at $\theta_{\rm lab}^{\rm FF1}=30°$, the second PPAC at $\theta_{\rm lab}^{\rm FF2}=-55°$. Mass and energy of FF1 were derived by using two-body kinematics from the measured velocity ($v_{\rm FF1}$) and angles ($\theta_{\rm FF1}$, $\theta_{\rm FF2}$). The overall mass and energy resolutions were determined on the elastic scattering peak. $\delta A=2.8$ and $\delta E=16$ MeV were measured.

Neutrons were detected in an array of eight NE213 liquid scintillators (12.8 cm in diameter, 5 cm thick), measuring the time of flight against the same PPAC start detector. The neutron flight paths were about 1 m. The neutron TOF resolution was $\delta t=1.2$ ns (FWHM). Pulse shape discrimination was used to reduce the γ-ray background. The scintillators were placed at angles $\theta_{\rm lab}=30°$, 55°, 80°, 110°, $-60°$, $-90°$, $-125°$, and $-145°$. Neutron yields were corrected for detector efficiencies obtained from Monte Carlo simulations [5].

In Fig. 1 measured diffusion plots are reported for fragment-fragment and fragment-fragment-neutron coincidences. The kinematical coincidence selects directly the elastic and quasielastic projectilelike (PL) events and those associated with total kinetic energy relaxation in a broad mass range. Elastic or quasielastic targetlike (TL) events are suppressed because of the detector angles. Energy relaxed TL events are inside the angular acceptance of detectors, although the performance of the TOF arm, in terms of resolutions and detection efficiency, is expected to be quite poor, because of the thickness of the start PPAC.

Nevertheless, bumps are clearly seen in the region of

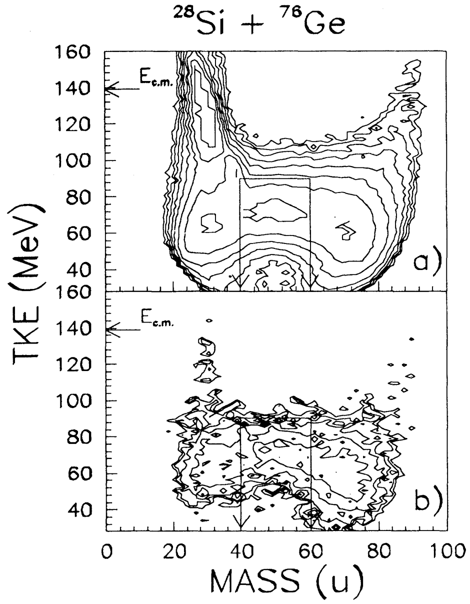

FIG. 1. Diffusion plots for (a) fragment-fragment and (b) fragment-fragment-neutron coincidences.

energy relaxed events, corresponding to symmetric splitting of the compound system, as well as to the PL and TL masses. The latter events might be associated to deep inelastic collisions, as well as to asymmetric fission because the fissility of the $^{28}Si+^{76}Ge$ system is close to the Businaro-Gallone limit [6]. Asymmetric fissionlike mechanisms have been studied in the past in this mass region [7].

The measured total kinetic energy for symmetric splitting is TKE=72 MeV, to be compared with $\langle E_k \rangle =61$ MeV as predicted by the Viola systematics [8]. We note that the experimental TKE value agrees well with high resolution data for the reaction $^{32}S+^{76}Ge$ [9].

A window was defined on the fragment mass ($A_{FF1}=40-60$) for symmetric splitting events with TKE corresponding to total energy relaxation (TKE$\leq$90 MeV).

Neutron energy spectra (efficiency corrected) corresponding to the symmetric splitting window are shown in Fig. 2.

Multiplicities of the neutrons emitted from the composite system prior to scission and from the fully accelerated fragments have been determined from the experimental spectra by using a least-squares fitting procedure based on Monte Carlo simulations, as described in Ref. [10]. In the present case, a search was performed on the prescission ν_{pre} and postscission ν_{post} multiplicities, having fixed the temperatures of the sources (T_{pre} and T_{post}). The values of $T_{post}=1.7$ MeV was used, as suggested in Ref. [2] from the analysis of several reactions. The T_{pre} value was fixed at $T_{pre}=2.0$ MeV, as expected for neutron emission from the nucleus of $A=104$ at excitation energy of 133 MeV and spin $J=74\hbar$ considering a level density parameter $a=A/8$. The latter angular momentum value is the first moment of the spin distribution of the fissioning states as predicted by the PACE2 sta-

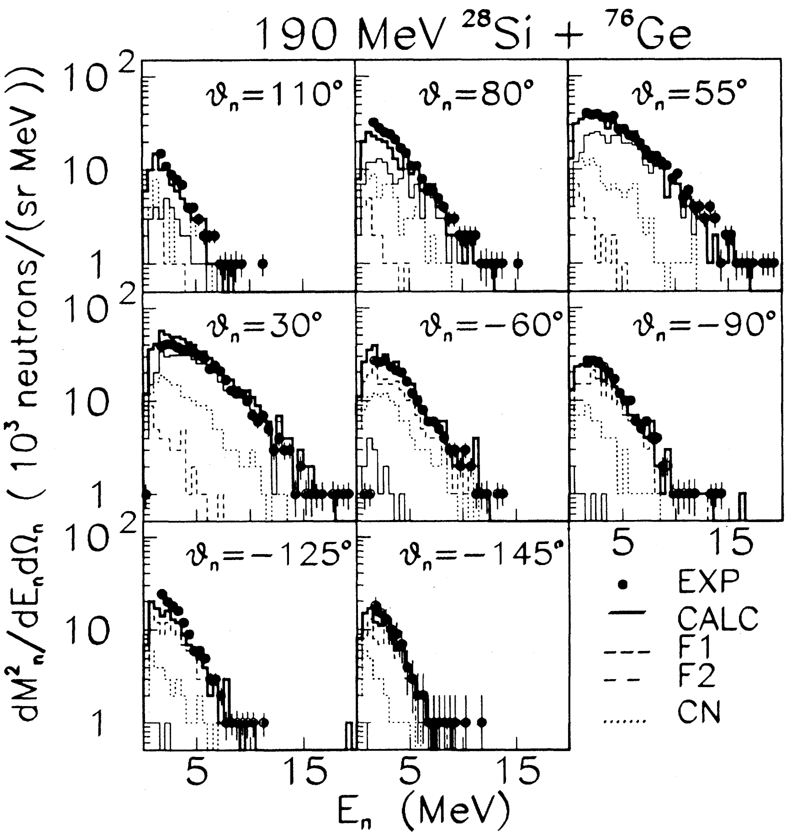

FIG. 2. Measured neutron energy spectra. Results of Monte Carlo calculations are also reported. For details see the text.

tistical model code. We have verified that a four-free-parameter search, in which also temperatures are searched for, does not improve the fit of the experimental spectra, leading to parameter values very close to those resulting from the two-parameter fitting.

Simulated spectra from two-parameter fit are compared with the experimental data in Fig. 2. A rather good reproduction of the experimental data is achieved.

The extracted ν_{post} per fission fragment is $\nu_{\text{post}}=1.3\pm0.2$, substantially in agreement with the value reported by Hinde *et al.* for the reaction 288 MeV ^{16}O+^{109}Ag [2]. The prescission neutron multiplicity was determined to be $\nu_{\text{pre}}=1.1\pm0.2$, to be compared with the prediction of the statistical model $\nu_{\text{pre}}^{\text{stat}}=0.4$.

The total neutron multiplicity measured is therefore $\nu_{\text{tot}}=3.7\pm0.4$, yielding 0.04 neutrons per MeV of the excitation energy exceeding the fission Q value ($Q_F=47.5$ MeV) [11]. For ^{16}O+^{107}Ag [2], the reported total neutron multiplicity was $\nu_{\text{tot}}=6.3$, yielding 0.04 neutrons per MeV ($Q_F=44$ MeV), in very good agreement with the present results.

Following the statistical model predictions, the fissioning nucleus is supposed to be at an average angular momentum $\langle J\rangle=74\hbar$, so that its excitation energy above the equilibrium deformation is $E_{\text{thermal}}=133-64=69$ MeV. The prescission neutron emission corresponds to the measured ν_{pre} costs $\Delta E=16\pm2.5$ MeV. It has to be noticed that charged particles are also emitted prior to the scission, although with a lower multiplicity with respect to neutrons. Following the statistical model predictions, the multiplicities of protons and alpha particles are relatively small ($\nu_{\text{pre}}^{p}=0.03$ and $\nu_{\text{pre}}^{\alpha}=0.04$) as compared to the precission neutrons, defining the lower limit of the contribution (~1.4 MeV) to the excitation energy dissipated in the prescission cascade. This contribution would not be negligible if charged-particle emission were amplified by the same dynamical effects as for neutrons. This hypothesis sets the upper limit of the cost of charged-particle emission to ~3.7 MeV. We note that the available experimental data, mainly for $A_{\text{C.N.}}\geq200$ [12], indicate that the dynamical amplification of the charged-particle multiplicity is indeed not as strong as the neutron one.

Lacking a direct measurement of charged particles in the $A_{\text{C.N.}}\sim100$ region, we use as correction factor the central value of $\Delta E=2.6\pm1.2$ MeV, finally determining the average excitation energy of fission to be $E_F=50\pm3$ MeV. This excitation energy can be converted in average fission time by computing the statistical lifetime of a ^{103}Pd nucleus at excitation energy corresponding to E_F.

The result is $\tau_F=6^{+3}_{-2}\times10^{-20}$ s. The average excitation energy and time for fission determined in the present work for the compound nucleus ^{104}Pd are in good agreement with the data for heavier systems reported in Ref. [2] and are also consistent with the results for lighter masses recently obtained by Morgenstern *et al.* [13] using a new experimental method.

The above conversion procedure is in principle similar to that used by Hinde *et al.* [2] assuming no excitation energy shift ($\Delta E_x=0$ MeV) caused by the deformation dependence of the potential energy surface during the motion of the fissioning system towards the scission point. This assumption is supported by the fact that the temperature of the prescission source found in the four parameter search coincides, within the sensitivity of the present experiment, with the value $T_{\text{pre}}=2.0$ MeV expected from the nominal excitation energy.

As a conclusion, we have extended the systematics of prefission phenomena in a lighter system by measuring neutron multiplicities. Corrections for the charged particle emission starts to be important for $A\sim100$ compound nuclei in determining the average excitation energy at which fission occurs. Further investigations in this direction will need a direct measure of protons and alpha particles emitted prior to fission.

By comparing measured and statistical model predicted ν_{pre}, it is verified that dynamical effects are definitely important in the decay of compound nuclei with $A\sim100$, already at excitation energies $E_x\sim130$ MeV. This should be considered when interpreting the giant dipole resonance data as experimentally determined for those nuclei at and above such an excitation energy [14].

[1] D. J. Hinde, D. Hilscher, and H. Rossner, Nucl. Phys. **A538**, 243c (1992), and references therein.
[2] D. J. Hinde, D. Hilscher, H. Rossner, B. Gebauer, M. Lehmann, and M. Wilpert, Phys. Rev. C **45**, 1229 (1992).
[3] B. W. Bush, G. F. Bertsch, and B. A. Brown, Phys. Rev. C **45**, 1709 (1992).
[4] D. Cha and G. F. Bertsch, Phys. Rev. C **46**, 306 (1992).
[5] A. Pantaleo, L. Fiore, G. Guarino, V. Paticchio, G. D'Erasmo, E. M. Fiore, and N. Colonna, Nucl. Instrum. Methods A **291**, 570 (1990).
[6] U. L. Businaro and S. Gallone, Nuovo Cimento **1**, 629 (1955).
[7] H. Oeschler, P. Wagner, J. P. Coffin, P. Engelstein, and B. Heusch, Phys. Lett. **87B**, 193 (1979).
[8] V. E. Viola, K. Kwiatkowski, and M. Walker, Phys. Rev. C **31**, 1550 (1985).
[9] G. Guillaume, J. P. Coffin, F. Rami, P. Engelstein, B. Heusch, P. Wagner, P. Fintz, J. Barrette, and H. E. Wegner, Phys. Rev. C **26**, 2458 (1982).
[10] L. Fiore *et al.*, Phys. Lett. B **298**, 283 (1993).
[11] D. J. Hinde, R. J. Charity, G. S. Foote, J. R. Leigh, J. O. Newton, S. Ogaza, and A. Chatterjee, Nucl. Phys. **A452**, 550 (1986).
[12] H. Ikezoe *et al.*, Nucl. Phys. **A538**, 299c (1992).
[13] H. Morgenstern, W. Bohne, and S. Proschitzki, Z. Phys. A **344**, 259 (1993).
[14] J. J. Gaardhoje, A. Atac, A. Maj, A. Bracco, F. Camera, B. Million, M. Pignanelli, and E. Rebesco, Nucl. Phys. **A538**, 573 (1992).