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Heavy residue masses as possible indicators of the impact parameter in the reaction $^{20}Ne+^{60}Ni$ at 742 MeV

A. D'Onofrio,* B. Delaunay, J. Delaunay, H. Dumont, and J. Gomez del Campo†
Service de Physique Nucléaire–Basse Energie, Centre d'Etudes Nucléaires de Saclay, 91191 Gif-sur-Yvette Cédex, France

F. Andreozzi, A. Brondi, R. Moro, M. Romano, and F. Terrasi
Dipartimento di Fisica Nucleare, Struttura della Materia e Fisica Applicata dell'Università, Napoli, Italy and Istituto Nazionale di Fisica Nucleare, 80125 Napoli, Italy

J. F. Bruandet
Institut des Sciences Nucléaires, 38044 Grenoble Cédex, France
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Mass and charge distributions for heavy residues in the reaction $^{20}Ne+^{60}Ni$ at 37.1 MeV/nucleon were measured by both in-beam and radioactivity γ-ray spectrometry. The general features of the experimental data are well reproduced by a massive transfer model. The heavier residues are also interpreted in the framework of a participant spectator model.

In recent years, a great deal of experimental effort has been devoted to the study of the reaction mechanisms involved in heavy-ion collisions at intermediate energies (20–100 MeV/nucleon). A transition between the low energy behavior, characterized by mean field effects, and the relativistic regime, where incoherent nucleon-nucleon interactions dominate, is expected around the Fermi energy.[1] In fact, both inclusive and exclusive measurements[2,3] have shown that at ~40 MeV/nucleon fragmentation-type processes, similar to those observed at higher energies, account for a significant fraction of the reaction cross section, even if many features still resemble the low-energy dissipative phenomena.

In a previous work,[2] we reported on the results of particle-gamma coincidence measurements performed at 44 MeV/nucleon for the reaction $^{20}Ne+^{60}Ni$, where the existence of a participant-spectator mechanism was invoked. In this paper we present the results of an experiment performed on the same system at 37.1 MeV/nucleon at the SARA facility in Grenoble. Integrated residue cross sections have been measured by both in-beam and radioactivity γ techniques. Isotopically enriched self-supporting targets of ^{60}Ni, 1 mg/cm^2 and 5 mg/cm^2 thick were employed. For the in-beam measurements, two γ-x Ge detectors were used. The first one, surrounded by an NaI anti-Compton shield was placed at 90° with respect to the beam axis 17 cm away from the target. The second one was placed at 125°, 15 cm from the target. Absolute detection efficiencies were measured by calibrated sources. Typical beam currents were ~20 nA of $^{20}Ne^{+9}$. The integrated charge was measured by a Faraday cup placed ~6 m away from the target. For each identified residue, the production cross section was extracted from the intensities of the ground-state transitions,[4] measured at 125°, using the known target thicknesses. The activity induced in the targets during the few hours of irradiation was measured using an off-line system of the Centre d'Etudes Nucléaires de Grenoble. Isotopes with lifetimes ranging from ~15 min to ~four months could be identified.

The production cross sections of targetlike residues in the mass range 39–62 were extracted (Table I). The results of the radioactivity measurements are given in Fig. 1, where the ratio of the activities measured with the 5 mg/cm^2 target to those measured with the 1 mg/cm^2 target is plotted versus the residue mass. For a $Z\simeq26$ recoiling nucleus, ranges of 1.4 and 7 mg/cm^2 in Ni (both targets were placed at 45° with respect to the beam direction) correspond to velocities $v/c\sim0.02$ and 0.06, respectively. Residues with $A\geq56$ being stopped in the thinner target have velocity distributions lying below 0.02. On the other hand, the fraction of residues with higher velocity increases with decreasing mass. Thus, on the average,

TABLE I. Experimental residue cross sections (in mb) vs mass and charge. The integrated cross section is equal to 1830 ± 350 mb. The typical error is $\sim 20\%$.

A \ Z	Cl	Ar	K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn
39	0.5													
40				9.4										
41		1.7	17											
42				33										
43			1.3	14	3.3									
44					29									
45					11	10								
46					21	26								
47						38	17.5							
48						35	37	1.4						
49							20	49						
50							40	35						
51							17	58						
52								68	35					
53								25	80					
54									37	60				
55									22	80	7.1			
56									2.4	144	17			
57									17	8	97	6.6		
58										14	137	35		
59											92	103		
60												190	9.8	
61													16	
62														0.7

heavier residue masses correspond to lower velocities.

For the nuclei identified in both in-beam and radioactivity measurements, the values of the cross sections extracted by the two methods, in the case of the 5 mg/cm^2 target, were found to be in agreement within experimental errors. On the other hand, in this mass region the fraction of measurable radioactive residues is relatively small. The combined results of the two measurements are shown in Fig. 2. The total observed residue cross section amounts to 1850 ± 350 mb, which has to be compared with a reaction cross section of 2500 mb estimated on the basis of the parametrization of Ref. 5.

The triangular shape of the mass distribution, together with the mass-velocity correlation discussed previously, suggests the existence of an almost linear relationship between the angular momentum in the entrance channel

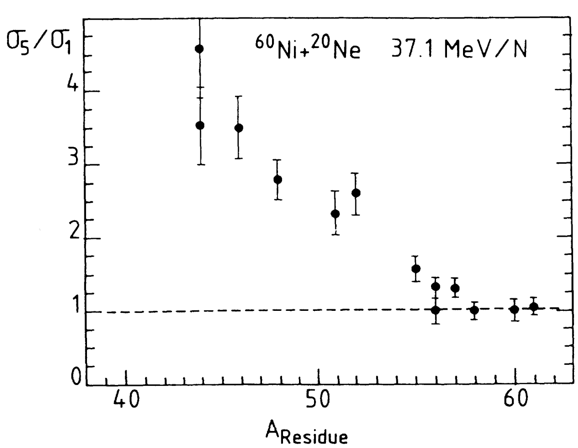

FIG. 1. Ratio of radioactivities induced in the 5 mg/cm^2 target to those induced in the 1 mg/cm^2 target vs mass number of identified residues.

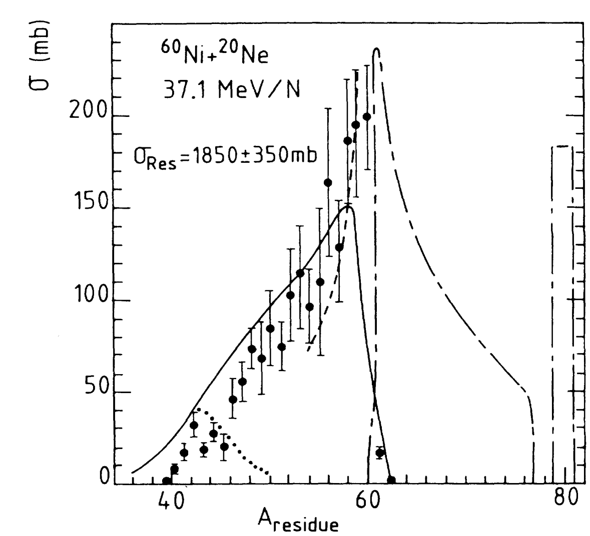

FIG. 2. Production cross section of heavy residues obtained by in-beam and radioactivity measurements. Massive transfer calculations (Refs. 5 and 6): primary distribution (dash-dotted line), secondary distribution (solid line), secondary distribution of complete fusion (dotted line). Fireball calculations (Ref. 7): dashed line.

(i.e., impact parameter) and the mass of the heavy residues. Lighter nuclei can be associated to the most central collisions, while heavier ones can be related to the most peripheral interactions.

This feature can be reproduced in the framework of a massive transfer mechanism in which nucleons are transferred from the projectile to the target up to the complete fusion reaction. The dependence of the average number of transferred nucleons on the impact parameter is determined by geometric considerations. The calculations have been performed with a modified abrasion model[6] in which heavy nuclei are formed by fusion between the target-spectator and the participant nucleons. The dash-dotted line in Fig. 2 gives the result of the calculated primary distribution. Due to the binding energy effect included in the model, the complete fusion takes place even before a complete geometrical overlapping of the projectile with the target. This feature leads to a gap in the calculated primary distribution between the incomplete mass transfer region and the complete fusion corresponding to $A=80$. The values of the excitation energy for the 37.1 MeV/nucleon $^{20}Ne+^{60}Ni$ reaction ranged from about 10 MeV for a few-nucleon transfer to the maximum energy of 553 MeV for the complete fusion reaction. The deexcitation of the primary fragments was calculated using, for the number of evaporated nucleons, a Gaussian distribution with mean value n corresponding to an average energy of 15 MeV removed per evaporated nucleon and a standard deviation $\sigma=0.85\sqrt{n}$. This parametrization was deduced by the final mass distributions calculated by the code LILITA[7] for the decay of compound nuclei of mass ~60–80. The resulting secondary mass distribution is shown in Fig. 2 as a solid line. The dotted curve, centered around $A=43$, represents the contribution due to the complete fusion process. The overestimation of the calculated mass removal for the lighter residue masses could be attributed to a preequilibrium particle emission which would lower the excitation energy prior to the statistical emission.

It is of interest to see if the present results could be interpreted in the framework of a participant model in which the available excitation energy is carried away by a fire ball leaving a cold spectator targetlike fragment. The effects of Coulomb interaction and of energy dissipation in the residual nuclei are taken into account in the model.[8] The calculation predicts that the reaction proceeds via fire-ball formation for impact parameter values greater than 5.4 fm, which corresponds to secondary targetlike fragments of mass 54. For smaller impact parameters fire-ball formation is inhibited by energy dissipation, and massive transfers can be assumed to occur. In Fig. 2 the calculated cross section corresponding to the fire-ball formation is shown as a dashed line.

In conclusion, the present results suggest the existence of a correlation between heavy residue masses and impact parameter. An important test of this picture could be provided by detailed measurements of residue velocity distribution. Our experimental findings can be explained in the framework of a massive transfer mechanism; nevertheless, the heavier residues could also be produced by a participant-spectator process. Exclusive measurements are planned to discriminate between the two mechanisms for the heavier residues.

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*Permanent address: Istituto Nazionale di Fisica Nucleare (INFN) Sezione di Napoli, Italy.

†Permanent address: Oak Ridge National Laboratory, Oak Ridge, TN 37830.

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