Brief Reports

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Radiochemical measurements of 200-MeV proton-induced fission of ^{133}Cs

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Proton-induced fission of ^{133}Cs ($E_p = 200$ MeV) was investigated radiochemically in order to deduce the relative amounts of symmetric and asymmetric fission from this system. Chemical separation of K, Ni, Cu, Zn, and As was performed in these studies. The radioactive products were analyzed using Ge(Li) γ-ray spectroscopy techniques. Cumulative yields of ^{42}K, ^{65}Ni, ^{66}Ni, ^{67}Cu, ^{72}Zn, and ^{77}As were measured to be 132 ± 40, 245 ± 120, < 168, 218 ± 50, 248 ± 148, and 198 ± 60 nb, respectively. If the results are cumulative yields of symmetric and asymmetric fission components, then the fission cross sections deduced from the average cumulative yields are 2.0 ± 1.3 and 2.7 ± 0.9 μb, respectively, or a total fission cross section of 4.7 ± 1.6 μb. Alternatively, these yields can be interpreted as being due to an admixture of fission events and the high mass tail of intermediate mass fragmentation processes.

Recent studies[1,2] of proton-induced fission ($E_p \geqslant 190$ MeV) of uranium and lighter nuclei in the mass region $140 < A < 200$ have indicated highly asymmetric fission may occur for targets near $A = 140$. In Ref. 1 counter techniques were used to measure angle-correlated fission fragments near 90°, from which the mass division, the total kinetic energy release, and total fission cross sections were deduced. The results were consistent with the prediction of the onset of asymmetric mass division near the Businaro-Gallone (BG)[3] point, $Z^2/A \cong 23$.

The present experiments were undertaken to investigate a similar system with radiochemical techniques, which provide absolute charge and mass identification of the fragments and high sensitivity for these low cross section processes. The fission mass division for the 200-MeV p + ^{133}Cs reaction ($Z^2/A = 23$) has been investigated by radiochemically separating the predominant symmetric and asymmetric radioelements. Fission sources were produced by bombarding thick (~ 100 mg/cm^2) spec-pure cesium nitrate targets with 200-MeV proton beams at the Indiana University Cyclotron Facility. The $CsNO_3$ material was obtained in ultrapure form with less than 10^{-8} parts heavy or medium element contamination. Material with 1 ppm of U, Th, Zn, Cu, or Ni impurities would be sufficient to produce radioactive species which would contaminate the desired fission product spectrum. Typical beam currents of 100–500 particle nA were used to bombard the targets for periods of 4–8 h. The beam currents were monitored by integrating the total current using a Faraday cup.

The radiochemical procedures used were based on those published in Refs. 4 and 5, with some minor modifications on each procedure. The gamma-ray spectra of the radiochemically separated sources were measured in a low background counter which had been calibrated to a precision of $\pm 1\%$–3% with U.S. National Bureau of Standards γ-ray sources. Decay properties were taken from Ref. 6 and the specific radioisotopes searched for are listed in Table I. The Ge(Li) detector energy resolution was 1.9 keV full width at half maximum (FWHM) for a γ-ray energy of 1332 keV. The largest errors in the measurements were the chemical yields and counting statistics.

The chemical yields varied from a few percent for K up to 30% for Zn. Sources were found to be well decontaminated ($> 10^6$) except for K, which was slightly contaminated with ^{129,132}Cs (~ 1 dis/sec) even after four repeated $KClO_4$ recrystallizations. Radiochemical separation times were of the order of 1–2 h. No evidence was seen for the long-lived neutron deficient isotopes of Ni, Cu, Zn, and As, indicating a low level of trace-element contamination from such elements in the target. Only neutron-rich radioisotopes were observed in the spectra, other than natural background from the U and Th series and ^{40}K.

In Table II are listed the results of this study. Limits were put on the cross section of ^{66}Ni since no detectable peak at 1039 keV was observed in the spectrum. Duplicate results were obtained for the Cu fractions with typical uncertainties of $\pm 16\%$. Overall uncertainties of 20%–60% were estimated from such factors as the counting statistics (13%–60%), detection efficiency ($\pm 3\%$), chemical yields ($\pm 10\%$), target thickness ($\pm 5\%$), and current integration ($\pm 5\%$) which combine in the quadrature to yield 18%–62% total uncertainties.

The results suggest a very broad mass distribution with no indication of a dominant asymmetric component. Nonetheless, assuming the existence of both symmetric and asymmetric fission components, the yield for each mode has been estimated from the average mass distributions reported in Ref. 1 for nuclei in this range of Z^2/A. A value of $\Delta m/m = 0.32$, corresponding to a full width at half maximum of approximately ten mass units per fragment, was

TABLE I. Decay properties of radioisotopes searched for in $^{133}Cs+p$ fission (Ref. 6).

Isotope	$t_{1/2}$	E_γ (keV)	Branching ratio (%)
^{42}K	12.4 h	1525	18.8
^{43}K	22.3 h	373	87.8
		397	11.5
		594	11.1
		618	81.0 ± 2%
^{56}Ni	6.1 d	158	98.8 ± 1%
		270	35.6
		481	35.6
		750	49.4
		812	87.4
		1562	14.1
^{57}Ni	36.0 h	127	15.5
		1378	77.6 ± 8%
		1757	7.1
		1919	14.7
^{65}Ni	2.52 h	366	4.7
		1116	15.1
		1482	23.5 ± 1%
^{66}Ni	54.8 h	1039	8 ± 1%
^{67}Cu	61.9 h	91	7.3
		93	16.9
		185	47 ± 3%
^{65}Zn	243.7 d	1115	50.75 ± 0.10%
$^{69}Zn^m$	13.7 h	439	94.8 ± 3.0%
^{72}Zn	46.5 h	145	83 ± 1%
		192	9.4
^{71}As	61 h	175	83.7 ± 1.2%
^{72}As	26.0 h	834	80 ± 2%
^{73}As	80.3 d	53	10.5 ± 0.5%
^{74}As	17.8 d	596	60 ± 2%
		635	15.0
^{76}As	26.4 h	559	45 ± 2%
		657	6.1
^{77}As	38.8 h	239	1.6 ± 0.4%
		250	0.41
		521	0.43

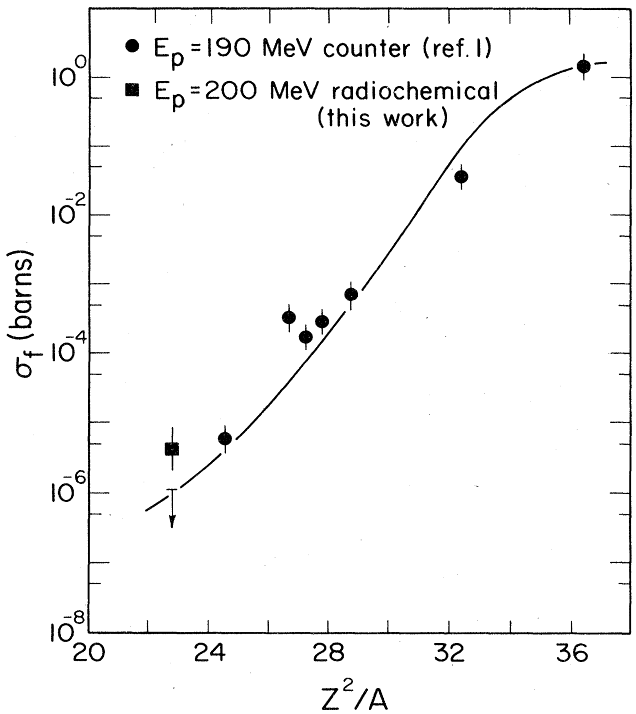

FIG. 1. Plot of fission cross section as a function of Z^2/A of target-projectile composite for 190- and 200-MeV proton-induced fission. Solid circles are data from Ref. 1 and solid square is from this work. Arrow indicates location of the Businaro-Gallone point.[3]

applied to the present data. Maxima were set at $A=67$ for the symmetric mode and $A=42$ and 77 for the asymmetric mode, with total fission chain yields of 15% and 6%, respectively. These values are based on the data of Ref. 1 and assumptions concerning prefission nucleon emission, most probable fissioning nuclei, and measured symmetric and asymmetric fission yields, as discussed in Hyde.[7] The estimated total cross sections obtained in this way are 2.0 ± 1.3 μb for symmetric fission and 2.7 ± 0.9 μb for asymmetric fission. These values, listed in Table II, are averages of the product of the production cross section and the estimated fission yield for each mass chain.

While the above procedures contain many assumptions, particularly in view of the fact that our data do not indicate

TABLE II. Radiochemical results and estimated total symmetric and asymmetric fission cross sections.

Radioisotope	Fission yield (%)	Production cross section (nb)	Estimated total cross section (μb)
^{65}Ni	12.0	245 ± 120	2.0
^{66}Ni	13.5	≤ 168	≲ 1.3
^{67}Cu	15.0	218 ± 50	1.5
^{72}Zn	7.5	248 ± 148	3.3
		Average total symmetric fission	2.0 ± 1.3 μb
^{42}K	6.0	132 ± 40	2.2
^{77}As	6.0	198 ± 60	3.3
		Average total asymmetric fission	2.7 ± 0.9

the distinct mass asymmetry reported in Ref. 1, they nonetheless give a value of the total fission cross section comparable with that for a simple integral over all masses within the quoted limits of error. The total fission cross section summed from data of Table II is $\sigma_f = 4.7 \pm 1.6$ μb which compares favorably with the value of about 6 μb obtained by Beccheti *et al.*[1] for ^{nat}Ce. A comparison of σ_f vs Z^2/A for various proton energies is shown in Fig. 1, taken from Ref. 1. The radiochemical value for σ_f appears to be consistent with previous counter experiments. The mass yield data lend themselves to an interpretation in which asymmetric fission may constitute an important contribution to fission in this region, consistent with the Businaro-Gallone prediction.[3]

An alternative explanation of these yields is that they result, at least in part, from intermediate mass fragmentation (IMF) processes resulting in low-to-intermediate mass residues ($A > 6$). For example, studies of proton-induced reactions on silver nuclei[8,9] have shown that the IMF fragment yields follow a power-law behavior, $Y(A) \propto A^{-3.7}$. Assuming the general validity of this yield dependence, we have attempted to estimate the mass yields of fragments produced in our radiochemical study. Specific assumptions were as follows: (1) the yields from Cs are approximately the same as those from Ag, and (2) the mass yields were then scaled directly from the 210-MeV proton data of Refs. 8 and 9 using the $A^{-3.7}$ power-law dependence. This procedure yields cross sections ranging from ≈ 500 nb for $A = 42$ to ≈ 100 nb for $A = 66$. In the case of $A = 42$ this yield is expected to be distributed among ^{42}K, ^{42}Ca, and ^{42}Sc products, consistent with the observed ^{42}K yield in Table II. For the heavier species these estimates suggest that IMF formation may also contribute in part to the observed fragment yields. Hence, it would appear that two processes —fission, in which the excited nucleus distributes its mass nearly equally between two fragments, and IMF formation, characterized by an exponentially decreasing mass distribution—become difficult to distinguish for nuclei in the $A \lesssim 140$ region. Thus, the rather flat mass yield data curve between $A = 42$ and $A = 77$ determined in this experiment, combined with the data of Refs. 8 and 9 which show an exponentially decreasing yield of fragments with $A \geqslant 6$, suggest that no clear structure exists in the mass yield of this system. We conclude that these results are most probably due to a combination of the fission mass distribution in addition to IMF processes.

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