MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

CHARGE BINARY REACTION PRODUCTS FROM THE REACTION OF ^{14}N WITH ^{165}Ho AND ^{164}Dy AT 20 MeV/NUCLEON

H. UTSUNOMIYA, D.J. MORRISSEY, R.A. BLUE, L.H. HARWOOD,
R.M. RONNINGEN, K. SIWEK-WILCZYNSKA and J. WILCZYNSKI

Invited paper presented at the INS-RIKEN International
Symposium on Heavy Ion Physics, Aug. 27-31, 1984,
Mt. Fuji, Japan

OCTOBER 1984

MSUCL-490

MSUCL-490
October 1984

Charge Binary Reaction Products from the Reaction of ^{14}N with ^{165}Ho and ^{164}Dy at 20 MeV/nucleon†

H. Utsunomiya, D.J. Morrissey, R.A. Blue, L. H. Harwood, R.M. Ronningen,
K. Siwek-Wilczynska[a], and J. Wilczynski[b]

National Superconducting Cyclotron Laboratory
Michigan State University
East Lansing, MI 48824

Abstract

Particle-gamma ray coincidence measurements were carried out to study charge binary reactions in the collisions of 20 MeV/nucleon ^{14}N projectiles with ^{165}Ho and ^{164}Dy targets. Discrete gamma rays from heavy residual nuclei were recorded with two high purity germanium detectors in coincidence with projectile-like fragments emitted near the grazing angle. The following reaction channels were observed: $^{165}Ho(^{14}N,^{12}C\ xn)Er$, $^{165}Ho(^{14}N,^{13}C\ xn)Er$, and $^{164}Dy(^{14}N,^{11}B\ xn)Er$. A preliminary analysis found only a small fraction (2 to 5%) of the carbon and boron isotopes originated in charge binary reactions. In addition, γ-ray multiplicities deduced from 1-fold and 2-fold events taken with four bismuth germanate detectors suggest a bimodal distribution, i.e., existence of both low and high γ-multiplicities in coincidence with projectile-like products.

I. INTRODUCTION

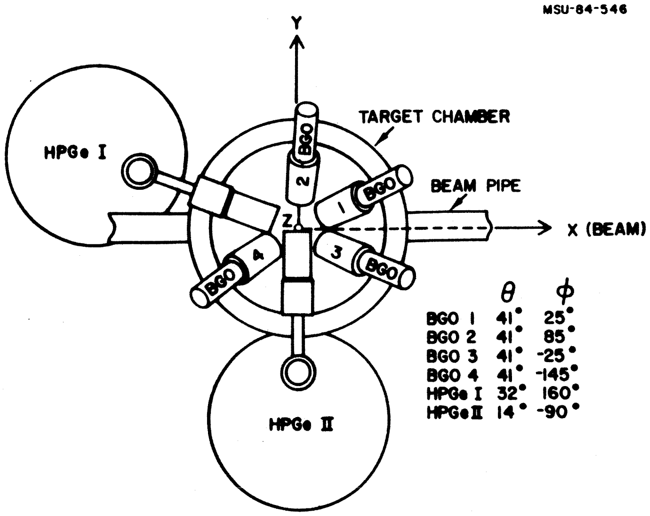
The importance of non-fusion reactions in collisions of complex nuclei increases with increasing bombarding energy. Already at about 10 MeV/nucleon non-fusion reactions represent a significant part of the total reaction cross section. The general trend in the non-fusion reactions is that with increasing total cross section, more and more complex processes are observed: larger groups of nucleons are transferred or exchanged, large amounts of energy and angular momentum are injected into the fragments, and more importantly, binary reactions give way to ternary, and multi-particle fragmentation reactions.

One of the essential steps in the study of reaction mechanisms is to distinguish binary reactions from other processes which make up the inclusive cross section. The charged-particle-γ-coincidence method has been successfully used at energies up to about 12 MeV/nucleon (1-3). Discrete lines of γ-transitions in target-residue nuclei are used to identify the heavy reaction products that have too low energies to escape from the target. Coincidences of these γ-rays with fully identified projectile-like fragments (i.e. charge and mass) establish the conservation of charge in the reaction and, consequently, determine the amount of binary reactions in the inclusive cross sections. Similar information has been obtained from the coincidences of projectile-like fragments with K X-rays which also emanate from the target-residue nuclei (4). However, this method suffers from the lack of reliable information on the absolute cross sections due to the unknown multiplicity of the K X-rays. Stokstad et al. (5) recently reported on the application of a "plastic box" that records the presence or absence of additional charged particles accompanying the projectile-like fragment. All of these methods are somewhat complementary in that each has its own range of application, advantages and disadvantages. The contribution of binary reactions to the inclusive cross sections, i.e., the ratio σ(charge binary)/σ(inclusive) for various ejectiles has been found to decrease from almost 100% near the Coulomb barrier to about 20%-40% at 10 MeV/nucleon (3). Particle-particle coincidence measurements at higher energies also indicate that the ratio continues to decrease (6).

In the present work we extend the investigation of charge transfer reactions to 20 MeV/nucleon by the particle-γ coincidence technique. Contrary to the low energy region the method is suitable for a large range of charge transfer reactions, at 20 MeV/nucleon the technique is limited to the transfer of one or at most two units of charge, because for larger transfers the excitation energies are too high. Transfer of one and two charge units were studied separately on two targets (^{165}Ho and ^{164}Dy, respectively) in order to produce even-Z target residue nuclei (isotopes of Er) in both cases.

II. EXPERIMENTAL SET-UP

A beam of 20 MeV/nucleon ^{14}N produced by the K500 cyclotron at the National Superconducting Cyclotron Laboratory of Michigan State University impinged on self-supporting metallic ^{165}Ho and ^{164}Dy foils of 2.0 mg/cm^2 and 1.95 mg/cm^2 thickness, respectively (††). Projectile-like fragments were detected at 14° (near the classical grazing angle of 12°) with a Si telescope (100μm ΔE, 1mm E). The <1μm planarity of the ΔE detector ensured excellent isotope resolution which was maintained throughout the experiment by cooling the detectors to -30°C. Gamma rays were measured with two high purity germanium (HPGe) detectors and four 7.6 cm x 7.6 cm bismuth germanate (BGO) detectors. A schematic diagram of the γ-ray detectors is shown in Fig.1. The coincidence efficiency of the setup was measured with ^{60}Co, ^{207}Bi and ^{22}Na sources.



	θ	ϕ
BGO 1	41°	25°
BGO 2	41°	85°
BGO 3	41°	-25°
BGO 4	41°	-145°
HPGe I	32°	160°
HPGe II	14°	-90°

Figure 1. Schematic diagram of the experimental setup. Θ and Φ denote the spherical polar and azimuthal angles, respectively.

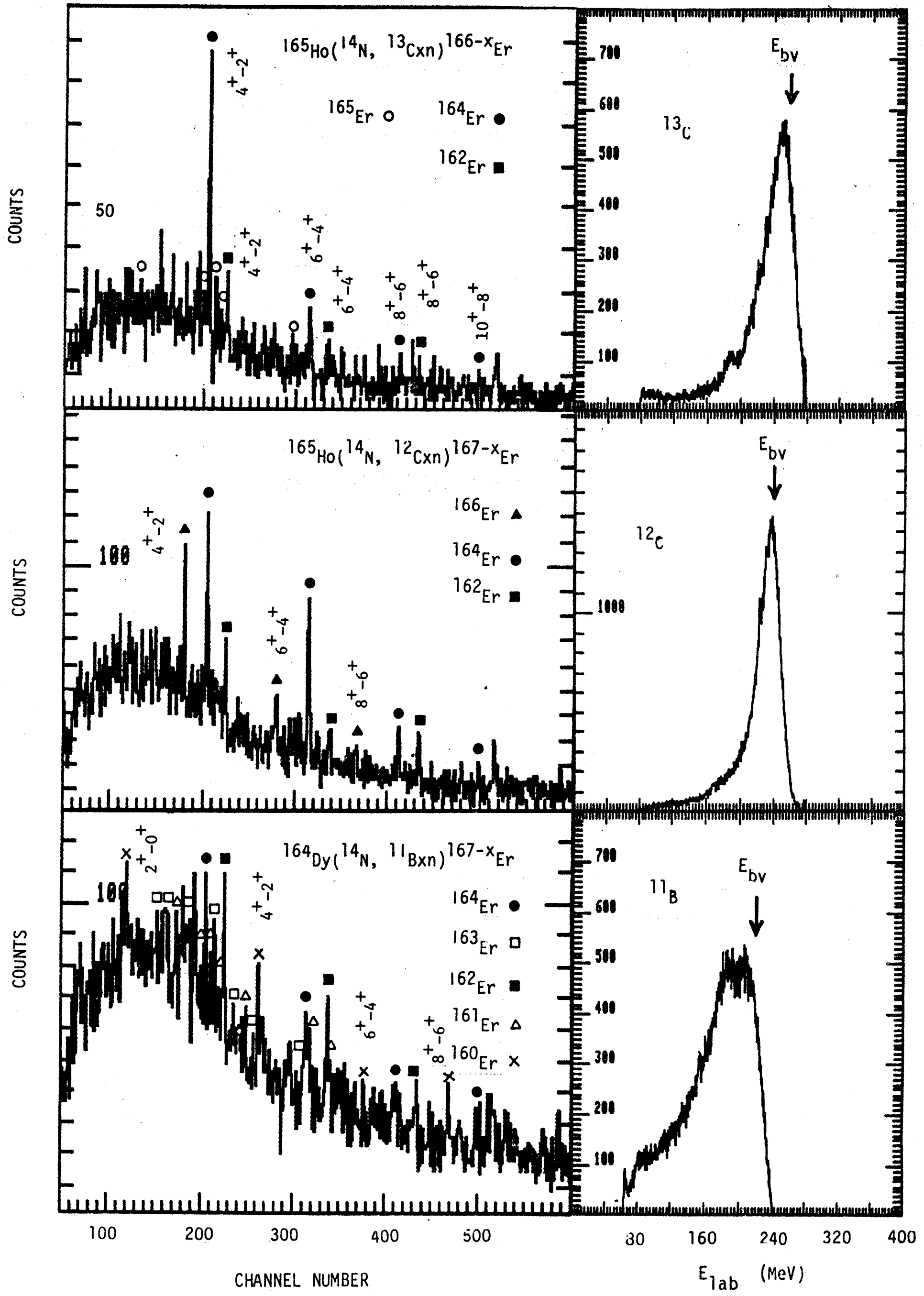
III. EXPERIMENTAL RESULTS AND DISCUSSION

1. Discrete γ-ray Spectra

Figure 2 shows results of a preliminary analysis of the discrete γ-ray spectra in coincidence with ^{13}C, ^{12}C, and ^{11}B. The singles kinetic energy spectra of these ejectiles are also shown. The kinetic energy distributions of the ^{13}C, ^{12}C and ^{11}B were peaked near the values corresponding to the beam velocity. In the three cases, γ-transitions corresponding to the rotational bands of Er isotopes were observed. Strong yrast transitions identified the even mass Er nuclei, but the intensities of the transitions from the odd mass Er are relatively weak because several rotational bands were populated. The identifiable γ-transitions show that the most probable target-like fragment is an Er isotope in all three reactions, just indicating a binary reaction in the primary stage. It is seen that the distribution of cross section among the final target-like nuclei shifts toward more neutron deficient isotopes as the ejectile mass decreases. This is the trend that would be expected on the basis of a constant average energy transfer per unit mass. In addition, the number of unresolved γ-rays increases going from ^{13}C to ^{11}B which indicates the production of a broader range of target-like nuclei.

2. Relative Cross Sections

The relative cross sections of the charge-binary reactions (relative to the inclusive projectile-like fragment cross sections) have been estimated as in ref. 7. The ratio of the number of γ-ray coincidences to particle singles was corrected for the electron conversion coefficient, coincidence summing and angular anisotropy of the discrete γ-rays. The angular anisotropy was determined by comparison of the spectra from the two HPGe detectors. In the



case of even Er isotopes it was assumed that the 4+ - 2+ transitions represented 100% of the production cross section. (As an exception, the cross section of the ^{165}Ho(^{14}N,^{13}C 2n)^{164}Er reaction was estimated with the 6+ - 4+ transition because of the anomalously strong population of the 4+ state.) The cross sections of the reactions leading to odd mass Er isotopes were estimated with the 17/2+ - 13/2+ transitions in ^{161}Er and ^{163}Er and the doublet 19/2+ - 15/2+ and 21/2+ - 17/2+ transitions in ^{165}Er. The branching ratios of these transitions were taken from the literature (8). The cross sections presented in Table I are given as a percentage of the singles cross sections for each ejectile. The number of missing neutrons is also listed in the table. By summing the fractional relative cross section for each of the individual residual nuclei, we found a range of 2 to 5 percent of the particle singles cross section for a given charge binary reaction.

Table I. Relative Cross Sections

target	ejectile	residual nucleus	number of neutrons	relative cross section (%)
^{165}Ho	^{13}C	^{165}Er	1	0.42 ± 0.26
		^{164}Er	2	0.81 ± 0.22
		^{163}Er	3	0.53 ± 0.28
		^{162}Er	4	0.62 ± 0.20
^{165}Ho	^{12}C	^{166}Er	1	0.82 ± 0.17
		^{165}Er	2	0.62 ± 0.22
		^{164}Er	3	1.31 ± 0.22
		^{163}Er	4	0.54 ± 0.30
		^{162}Er	5	0.41 ± 0.16
^{164}Dy	^{11}B	^{164}Er	3	0.71 ± 0.19
		^{163}Er	4	1.08 ± 0.32
		^{162}Er	5	0.77 ± 0.19
		^{161}Er	6	1.29 ± 0.34
		^{160}Er	7	0.68 ± 0.19

It is interesting to compare our data to data for the same reaction channels measured with the same method at 10 MeV/nucleon (3). At the lower energy, the ratio σ(charge binary)/σ(inclusive) is 0.20 for the (^{14}N, ^{11}B) channel, 0.29 for the (^{14}N,^{12}C) channel and 0.27 for the (^{14}N, ^{13}C) channel. Our small values are thus consistent with the established trend of the decreasing importance of binary processes with bombarding energy. Our results indicate these charge binary channels represent a substantially smaller fraction of the inclusive cross section than those reported by Stokstad et al. (5). This difference needs to be explored.

3. γ-ray Multiplicities.

The previous discussion indicated the presence of at least two different mechanisms that produce carbon and boron isotopes. In a subsequent analysis we hope to distinguish between the two on the basis of γ-ray multiplicity. In a preliminary analysis, the average γ-ray multiplicities were calculated for each reaction channel from the coincidence data obtained with the BGO detectors. Table II summarizes the estimated γ-ray multiplicities for the carbon and boron isotopes. Because the number of γ-ray detectors and their efficiencies were both small, only the first moment of the multiplicity distribution can be accurately determined. We can determine the γ-ray multiplicity in two different ways:

$$M_\gamma = \frac{1}{4} \frac{N_{k \geq 1}}{N_{SINGLES}} \frac{1}{\epsilon_\gamma} \qquad (1)$$

$$m_\gamma = \frac{4}{3} \frac{N_{k \geq 2}}{N_{k \geq 1}} \frac{1}{\epsilon_\gamma} + 1 \qquad (2)$$

Here, $N_{singles}$ stands for the number of particle singles events , $N_{k \geq n}$ stands for the events that at least n out of the four BGO detectors fire and ε_γ is the efficiency of each BGO detector. The number of events with k greater than or equal to n, $N_{k \geq n}$, is written:

$$N_{k \geq n} = \binom{4}{n} \sum_{M=0}^{\infty} P(M) \binom{M}{n} \epsilon_\gamma^{n} \qquad (3)$$

where P(M) is the probability of multiplicity M (M being either M_γ or m_γ) and, therefore, $N_{singles}$ must be the sum over P(M). With these definitions m_γ will be approximately equal to M_γ only in the limit of large average multiplicities because the former value is not sensitive to low γ-ray multiplicities. In our a case, M_γ should be smaller than m_γ, as seen in Table II.

The discrete γ-ray spectra have shown that the charge binary reactions represent a small fraction of the inclusive projectile-like fragment cross sections. If we assume the presence of two mechanisms, one with a γ-ray multiplicity near zero (non-absorptive events) and another with a larger value (charge binary events), then m_γ will approximate the larger value and the difference between the two values can be used to estimate the relative contributions from the two mechanisms. The estimated fractions are listed in the last column of Table II. These values are within experimental uncertainties of those obtained from the independent analyses of the discrete γ-ray spectra. Because the difference between M_γ and m_γ arises from a mechanism that contains only 5% of the cross section, the γ-ray multiplicity of the non absorptive processes must be very small.

The present preliminary analysis of the γ-ray multiplicities was limited to coincidences between particles and BGO detectors. The analysis will have to be supplimented by higher order coincidences (e.g., particle-HPGe-BGO). Such a more complete analysis (to be presented in a forthcoming paper) will provide information on the average γ-multiplicities in specific binary reaction channels, independent of the present assumptions.

Table II. γ-ray multiplicities.

target	ejectile	M_γ	m_γ	$N^{ab}_{singles}/N_{singles}$ (%)
^{165}Ho	^{11}C	0.625 ± 0.012	12.2 ± 0.8	5.1 ± 0.3
	^{12}C	0.496 ± 0.004	11.1 ± 0.3	4.5 ± 0.1
	^{13}C	0.457 ± 0.005	11.0 ± 0.4	4.2 ± 0.2
^{164}Dy	^{10}B	0.778 ± 0.008	17.1 ± 0.5	4.6 ± 0.1
	^{11}B	0.775 ± 0.005	16.7 ± 0.3	5.0 ± 0.1
	^{12}B	0.869 ± 0.015	15.6 ± 0.8	5.6 ± 0.3

IV. SUMMARY

We have performed a study of charge binary reactions by observing particle-gamma ray coincidences from the reaction of ^{165}and ^{164}Dy targets with 20 MeV/nucleon ^{14}N projectiles. Analysis of the discrete γ-ray spectra enabled us to completely identify the following reaction channels: ^{165}Ho(^{14}N, ^{13}C xn) Er with $1 \leq x \leq 4$, ^{165}Ho(^{14}N, ^{12}C xn) Er with $1 \leq x \leq 5$, and ^{164}Dy(^{14}N, ^{11}B xn) Er with $3 \leq x \leq 7$. Very small fractions of the inclusive cross sections were observed in the charge binary channels. The measurements of the 1-fold (particle-γ_1) and 2-fold (particle-γ_1-γ_2) events suggest existence of high γ-ray multiplicity components, i.e., absorptive processes in the inclusive cross sections. We also deduced the γ-ray multiplicity associated with the absorptive processes and their fraction of the inclusive cross sections. These results were consistent with the discrete γ-ray measurement.

References

a) Permanent address: Institute of Experimental Physics,
University of Warsaw, 00-681 Warsaw, Poland

b) Permanent address: Institute for Nuclear Studies,
05-400 Swierk(Warsaw), Poland

† The work is supported by the National Science Foundation under Grant No. PHY-83-12245.

†† The ^{164}Dy target was supplied by Mr. T. Sugai of the Institute for Nuclear Study at University of Tokyo.

1. T. Inamura et al., Phys. Lett. 68B, 51(1977).
2. K.A. Geoffroy et al., Phys. Rev. Lett. 43, 1303(1979).
3. J. Wilczynski et al., Nucl. Phys. A373, 109(1982)
4. H.W. Wilschut et al., Phys. Lett. 123B, 173(1983).
5. R.G. Stokstad et al., Report LBL-18240 (1984), and this conference.
6. R.K. Bhowmik et al., Nucl. Phys. A390, 117(1982).
7. L. Westerberg et al., Nucl. Instr. Method 145, 295(1977).
8. S.A. Hjorth et al., Nucl. Phys. A144, 513(1970).