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Interaction of 4.22-GeV and 7.54-GeV ^{20}Ne with Cu

K. H. Hicks* and T. E. Ward
Indiana University Cyclotron Facility, Bloomington, Indiana 47405

H. Bowman, J. G. Ingersoll, J. O. Rasmussen, and J. P. Sullivan[†]
Lawrence Berkeley Laboratory, University of California, Berkeley, California 94720

M. Koike
Institute for Nuclear Study, Tokyo 188, Japan

J. Peter
Institut de Physique Nucleaire, Orsay, France

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The cross sections of 15 products produced in the relativistic heavy-ion reactions of 211 and 377 MeV/nucleon ^{20}Ne ions with Cu were measured using activation techniques. The isobaric mass yield curves measured in this study compare well with previous results of relativistic heavy-ion- and proton-induced Cu spallation after taking into account the increased absolute total reaction cross section of ^{20}Ne. The target fragmentation yields resulting from peripheral collisions were compared with abrasion-ablation model calculations. Central collision processes were examined by comparing light mass ^{7}Be yields.

NUCLEAR REACTIONS Cu(^{20}Ne, spallation), $E=4.22$ and 7.54 GeV. Measured absolute $\sigma(A,z)$ 15 products, deduced mass yield. Natural targets Ge(Li) γ-ray spectroscopy.

I. INTRODUCTION

Relativistic heavy-ion (RHI) reactions with Cu targets have been reported by Cumming and collaborators for a variety of projectiles, i.e., 3.9 GeV ^{14}N ions,[1] 25 GeV ^{12}C ions,[2] and 80 GeV ^{40}Ar ions.[3] Those results were compared with measurements of 3.9 and 28 GeV proton induced reactions on Cu and interpreted using concepts of limiting fragmentation and factorization[4–6] for RHI reactions at high energies ($>$GeV/nucleon). Limiting fragmentation would predict that the fragment yields and spectra would become independent of energy at high bombarding energies as evidenced by the invariant relative yields and charge dispersion of products close to the target. Target fragmentation by either RHI or protons would have similar yield patterns and differ only in the total reaction cross section which would be larger for heavy ions as compared with proton induced reactions. Heavy ion projectile fragmentation would yield products whose rapidities were close to that of the projectile and the products would be emitted at small angles in the laboratory system. Factorization concepts relate the yields and spectra of target (or projectile) fragments via a total cross section term which is nearly independent of the energy. Differences due to the heavy ion size would result in only small changes in the relative yields of target fragments while the shape of the isobaric yield of projectile fragmentation would be almost identical for different targets. The abrasion-ablation model takes exception to the target factorization principle as recently noted by Stevenson, Martinis, and Price[7] and by Radi *et al.*[8] The abrasion process depends strongly on the target size.

The results of the present target fragmentation study were compared with the abrasion-ablation calculations of Oliveira, Donangelo, and Rasmussen.[9] They calculated cross sections for the production of heavy target fragments produced in peripheral collisions of RHI with Cu. The abrasion-ablation model[9–12] provides a macroscopic view of RHI reactions. Basically, in the abrasion process both nuclei are hard spheres with straight-line trajectories. At intersection the overlap zones between the two nuclei are sheared away leaving behind residues, which can ablate or evaporate nucleons and alpha particles. The theoretical results compare well with the Cu spallation yields of this study and of the previous experiments using 3.9 GeV ^{14}N (Ref. 1), 25 GeV ^{12}C and ^{1}H (Ref. 2), and 80 GeV ^{40}Ar (Ref. 3).

A third process due to near central collisions in RHI reactions has been widely investigated[13–18] by measuring the energy spectra of protons and light nuclei produced in the interaction. Poskanzer and co-workers[17–20] have studied in detail the central collisions of RHI by measuring the double differential cross sections and multiplicity of low mass products resulting from 250, 400, and 2100 MeV/nucleon ^{20}Ne bombardment of Al and U. The light mass products with intermediate energy resulting from the near central collisions are characterized by their high multiplicity and by the almost complete dissociation of the target and projectile.[18] Central interactions have been studied using activation techniques for the reactions of 80 GeV ^{40}Ar on Cu (Ref. 3), 25 GeV ^{12}C on Ag (Ref. 21), and by 8 GeV ^{20}Ne on Ta and Au (Ref. 22). The medium to heavy mass target measurements have a greater mass range of products than that of Cu and can therefore better distinguish between target fragmentation and near central collision processes. In the present study we compare the low mass ^{7}Be yields produced in various RHI and proton induced reactions on Cu, examining the effects of projectile energy and the mass dependence of the near central collisions.

II. EXPERIMENTAL PROCEDURES

Two copper targets were irradiated with 4.22 GeV (211 MeV/nucleon) and 7.54 GeV (377 MeV/nucleon) ^{20}Ne ions in the external beam of the Bevalac at the Lawrence Berkeley Laboratory. The targets were mounted in air with the beam leaving the vacuum pipe about 1.5 m before the target position. The integrated beam intensity was determined with an ion chamber previously calibrated by individual particle counting at reduced beam intensities and by induced ^{11}C activity. The Cu targets were 10×10 cm^2 in size and the beam spot was about 1 cm in diameter focused on the center of the target. The first (Cu 377) and second (Cu 211) targets had thicknesses of 2.046 g/cm^2 and 3.255 g/cm^2, respectively. The total currents on target were 7.56×10^{7} and 8.57×10^{7} ^{20}Ne ions/sec for Cu 377 and Cu 211, respectively. The targets were transported to the Indiana University Cyclotron Facility (IUCF) 10 days after the irradiation and were γ ray counted periodically over a 4 month time interval.

The Cu targets were γ ray counted using a 45 cm^3 PGT Ge(Li) detector the efficiency of which was calibrated to within $\pm3\%$ using standard pre-

TABLE I. Absolute cross sections of long-lived radionuclides produced in the interaction of 4.22 GeV and 7.54 GeV ^{20}Ne with Cu targets.

Nuclide	Type of yield[a]	Cross section (mb)[b] 4.22 GeV 3.255 g/cm^2	Cross section (mb)[b] 4.22 GeV 0 g/cm^2	Cross section (mb)[b] 4.22 GeV Isobaric yield	Cross section (mb)[b] 7.54 GeV 2.046 g/cm^2	Cross section (mb)[b] 7.54 GeV 0 g/cm^2	Cross section (mb)[b] 7.54 GeV Isobaric yield
^{7}Be	I	53.0 ± 9.3	70.8		71.2 ±10.9	92.9	
^{22}Na	C^+	42.2 ± 9.7	49.1		43.6 ± 9.2	50.7	
^{46}Sc	I	15.3 ± 2.3	15.3	38.3	16.2 ± 2.3	16.2	40.5
^{47}Ca	C^-	1.2 ± 0.2	1.2		1.3 ± 0.2	1.3	
^{48}V	C^+	24.0 ± 2.8	24.0	46.2	27.0 ± 3.1	27.0	51.9
^{51}Cr	C^+	52.0 ± 8.0	52.0	57.8	61.0 ± 8.6	61.0	67.8
^{52}Mn	C^+	22.5 ± 2.6	22.5	77.6	21.8 ± 2.5	21.8	75.2
^{54}Mn	I	46.0 ± 7.3	43.9	74.4	51.8 ± 7.7	49.5	83.9
^{56}Co	C^+	20.8 ± 2.9	18.9	72.7	21.1 ± 2.8	19.2	73.9
^{56}Ni	C^+	0.20± 0.3	0.18		0.36± 0.5	0.33	
^{57}Co	C^+	67.0 ±10.6	58.3	100.5	71.9 ±10.2	62.5	107.8
^{58}Co	I	89.7 ±12.6	74.8	99.7	91.3 ±12.2	76.1	101.5
^{59}Fe	C^-	5.4 ± 1.0	4.5	100.0	6.8 ± 1.1	5.6	124.4
^{60}Co	I	51.7 ±14.9	41.4	159.0	55.0 ±13.8	44.0	169.2
^{65}Zn	C^+	9.3 ± 3.0	6.2		10.2 ± 3.0	6.8	

[a] Independent (I), cumulative positron (C^+), and cumulative negatron (C^-).

[b] See text for explanation of zero target yields. The total uncertainties are estimated to be the same as the thick target errors.

cision γ-ray sources. The targets were counted in a reproducible low geometry at a distance where summing effects of coincident γ rays were negligible. The self-absorption of the low energy γ rays in the $2-3$ g/cm^2 thick targets was taken into account by measuring the efficiency with appropriate Cu absorbers. The measured values agreed within $5-10\%$ with the values one would obtain using the standard efficiency curve and the calculated[23] γ-ray attenuation with various Cu thicknesses.

γ-ray spectra were accumulated daily for the first several weeks and weekly thereafter over a period of 15 weeks. Nuclear properties used in the analysis can be found in Ref. 1 (Table VII) or in the most recent compilation of the Table of Isotopes.[24] Spectrum analyses were performed using a modified version of the SAMPO computer program[25] and the individual γ-ray decay curves were corrected back to the end of bombardment.

III. RESULTS AND DISCUSSION

The production cross sections measured in the present study are listed in Table I. The uncertainties in these measurements are $12-20\%$. Recoil loss effects of target fragments can be neglected for the thick target yields and low mass beam velocity projectile fragments such as ^{7}Be which have ranges in Cu of ≥ 30 g/cm^2 at the energies used in this study and can be assumed to escape completely. The thick-target yields of products near the target were corrected for secondary production processes in the manner outlined by Cumming and co-workers[1-3] for target thicknesses of $2-2000$ mg/cm^2. The corrections amount to a 5% reduction in the thick target yield of ^{54}Mn and increase with mass number to about 20% for ^{60}Co and 35% for ^{65}Zn. The error in these corrections is estimated to be of the order of 20% of the reduction and would amount to increased errors of a few percent or less for the thick target error values. The low-mass products ^{7}Be and ^{24}Na were corrected approximately 30% and 15%, respectively, to obtain their zero-thickness yields.

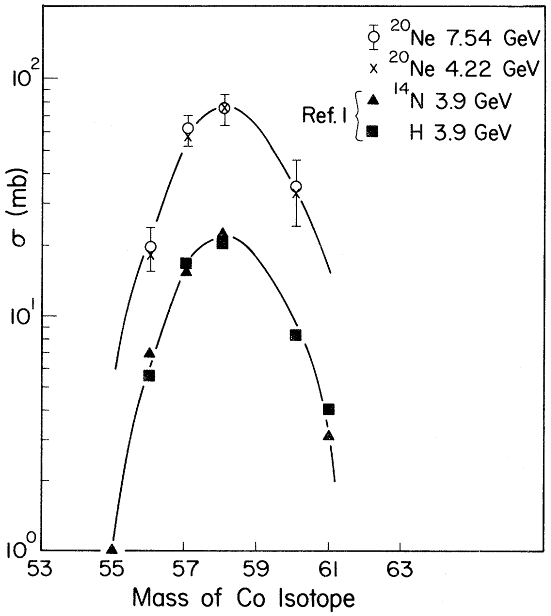

FIG. 1. Comparison of the mass yields of Co isotopes observed in the reaction of 4.22 GeV and 7.54 GeV (open circles) ^{20}Ne with Cu. Results from Ref. 1 of 3.9 GeV ^{14}N (triangles) and ^{1}H (boxes) are also shown. The ^{14}N results are normalized relative to the ^{1}H.

In Fig. 1 are plotted the cross sections or in the case of ^{14}N the relative yields for the cobalt isotopes. The four Co distributions have the same shape within experimental errors although the absolute cross sections vary. Such behavior is expected from concepts of factorization as detailed by Cumming and co-workers.[1-3] Briefly, the factorization hypothesis considers the single particle inclusive reaction

$$P+T \rightarrow F+X ,$$

where projectile (P) and target (T) interact to form the fragment (F) and anything else (X). Accordingly the total cross section for a given class of target fragments can be written as

$$\sigma_{T,P}^{F}=\gamma_{T}^{F}\gamma_{P} , \tag{1}$$

where γ_T^F depends on the target and fragment yield and the projectile factor (γ_P) depends only on the nature of the projectile. The peripheral target fragmentation reactions leading to products near the target appears to be valid as a *first approximation* to the factorization hypothesis.

The isobaric yields were determined by analysis of the charge dispersion and mass yield curves deduced with the aid of the following equation[19,21,26]

$$\ln[\sigma(A,Z)]=Y(A)+C[Z_p(A)-Z] , \tag{2}$$

where the mass yield curve (Y), charge dispersion curve (C), and the position of the maximum yield of a given $Z_p(A)$ defines the independent cross sections of A and Z. We were unable to obtain isobaric ratios of two or more isobars for any given mass due to the time delay between the end of bombardment and the first count and therefore could not uniquely define Z_p. However, as Z_p varies little with projec-

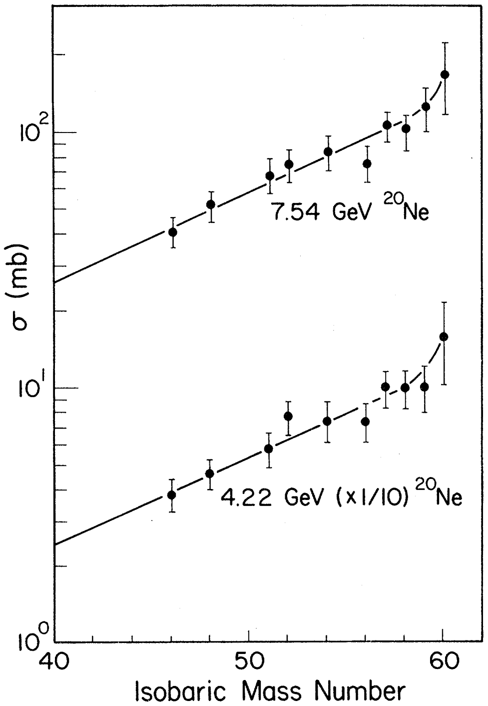

FIG. 2. Isobaric mass yield curves for the spallation of Cu with 4.22 GeV and 7.54 GeV ^{20}Ne. The points represent the zero target thickness yields (see text for details of thick target corrections). The exponential lines represent a best fit to the data as discussed in the text.

tile type and energy (see Table III, Ref. 2) we have used the Z_p values obtained for 3.9 GeV ^{14}N (Ref. 1). The fraction of the total mass chain yield was determined using Eq. (2) and the linear variation of Z with A. In Table I and Fig. 2 are listed and shown the isobaric yields for 4.22 and 7.54 GeV ^{20}Ne interactions with Cu which were determined using the above procedure. The uncertainties of the linear portions of the plots are typically 20%. Linear regression analysis of the fitted line indicates that the slopes of the two lines are quite similar, 7.355%/u and 7.515%/u for 4.22 GeV and 7.54 GeV, respectively, with equal correlation coefficients of 0.956. These results compare well with other RHI and proton induced Cu spallation studies[1-3] as expected from concepts of limiting fragmentation (energy independence) at energies greater than a few GeV. The total cross sections of the target fragmentation process, defined as the sum of the $A=22-64$ mass product, are 2050 mb and 2245 mb for 4.22 GeV and 7.54 GeV, respectively, and are comparable to other RHI or proton induced Cu spallation reactions after taking into account geometric scaling factors.

The cross sections for production of heavy fragments produced in the peripheral collisions were compared with the calculations of Oliveira, Donangelo, and Rasmussen,[9,12] where the reaction was treated as a two-stage process: abrasion or fragmentation followed by ablation or evaporation. The preliminary comparisons showed the need for a frictional spectator interaction process (FSI) between the abraded nucleons and the spectator (target or projectile) fragments. The calculations were performed for the Cu + Ar reaction at 80 GeV.[3] The general trend of the data was well reproduced by the calculations although the absolute values were a factor of 2 lower than the data. A comparison of the theory to the results of this investigation and other RHI or proton induced Cu spallation studies can be made by normalizing to the independent yield of ^{54}Mn. This is a necessary procedure for purposes of comparison since the absolute yields differ by large geometric factors whereas the relative yields of the spallation curve are only affected by small changes at these energies. Clearly the FSI calculation better reproduces the mass yield ratios for the products near the target, where the total primary yield distribution is altered due to the increased energy deposited by a nucleon undergoing FSI. Ultimately it is the increased average energy deposited in the FSI process which alters the number of nucleons removed in the interaction. Since this energy is typically 20−40 MeV, the most dramatic effect will occur for those product yields near the target. (See Fig. 3.)

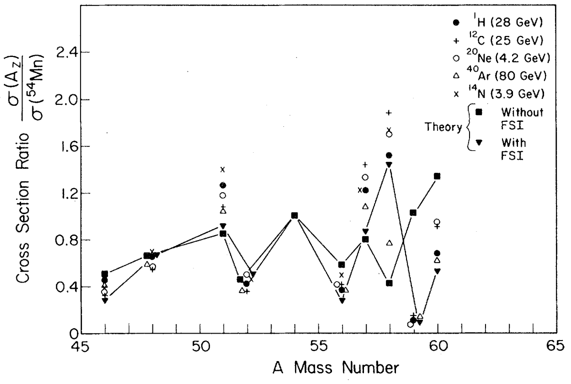

FIG. 3. Comparison between the relative proton-induced and RHI Cu spallation yields and the abrasion-ablation model calculations of Oliveira, Donangelo, and Rasmussen (Refs. 9 and 12) with and without a frictional spectator interaction (FSI). The data are normalized relative to the independent yield of ^{54}Mn, effectively cancelling out large differences in the absolute yields due to geometric factors.

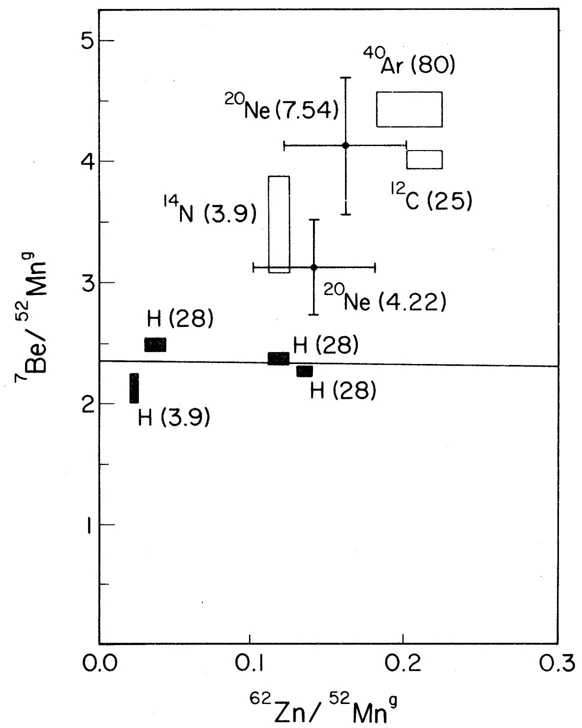

FIG. 4. Correlation plot of ^{7}Be, ^{62}Zn, and ^{52}Mn^g yields for RHI and proton induced Cu spallation at energies of 3.9 – 80 GeV.

The light mass yields, such as ^{7}Be, are more easily characterized by collisions with small impact parameters and large differences between RHI and proton induced reactions as noted by Cumming and co-workers.[1–3] Following the analysis of Refs. 1 – 3 we show in Fig. 4 a correlation plot of the ^{7}Be/^{52}Mn^g vs ^{62}Zn/^{52}Mn^g ratio for various RHI and proton induced Cu reactions. In our study we took advantage of the fact that the ^{65}Zn/^{62}Zn ratio is constant to within 2.03 ± 0.35 (see Table II, Ref. 2) in order to compare our results with previous RHI results.[1–3] Clearly the enhanced ^{7}Be production by RHI over that observed for proton induced reactions indicates little dependence on projectile mass when we compare the results of 2 GeV/nucleon ^{40}Ar and ^{12}C and the 278 MeV/nucleon ^{14}N and 211 MeV/nucleon ^{20}Ne. The excess ^{7}Be production amounts to about 1 – 2 % of the total reaction cross section for ^{20}Ne + Cu at these energies. This is consistent with the earlier measurements[13–18] of central collisions which indicated they constitute about 10% of the total number of reactions.

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[*] Present address: Nuclear Physics Laboratory, University of Colorado, Box 446, Boulder, CO 80309.

[†] Present address: Cyclotron Laboratory, Texas A & M University, College Station, TX 77843.

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