MICHIGAN STATE UNIVERSITY

CYCLOTRON LABORATORY

DETECTION OF HEAVY-ION REACTION PRODUCTS IN BOUND EXCITED STATES

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

MAY 1985

MSUCL-523

MSUCL-523
May 1985

DETECTION OF HEAVY-ION REACTION PRODUCTS IN BOUND EXCITED STATES

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

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

and

D. J. Morrissey

National Superconducting Cyclotron Laboratory and Department of Chemistry,
Michigan State University, East Lansing, MI 48824

Abstract

The population of bound (γ-decaying) states of the projectile-like fragments from the $^{14}N + ^{164}Dy$ reaction at 20 MeV/nucleon was studied by measuring coincidences between these fragments and γ-rays detected with large-volume bismuth germanate detectors. The results indicate that products of pickup and exchange reactions are more likely to be excited than products of stripping reactions, particularly in fast, peripheral collisions.

In this Communication we report on an application of the gamma-particle coincidence method to select events in which light products of heavy-ion induced reactions (i.e., the projectile-like fragments, PLF) are produced in specific excited states that decay via gamma emission. In this method, projectile-like fragments (fully identified by Z and A) are detected in coincidence with discrete γ-rays emitted from them. Typical γ-transitions in these light reaction products (A = 10-20) are rather energetic, up to about 8 MeV.

Information on the population of various ejectiles in specific bound excited states can give important information on the question of the partition of the excitation energy between the reaction partners in asymmetric systems. A partition of the excitation energy in such systems that is not consistent with statistical equilibrium has already been reported by Awes et al. [1] and Vandenbosch et al. [2]. These indications were based on an analysis of the results on charge distributions and neutron multiplicity in supposedly binary reactions of rather heavy systems, as well as on mass asymmetry of fission fragments.

The average excitation energy of light fragments in very asymmetric systems can be studied more directly by observing either the particle decay or the γ-decay of the known excited states of the primary light products. Whereas the α-PLF coincidence measurements at high angular resolution [3,4] enable one to single out sequential decay of discrete unbound states of the primary reaction products, the γ-PLF coincidences yield similar information in the lower region of excitations, i.e., below the particle decay threshold. Thus, both methods complement one another, making possible a study of light fragment excitations over a broad range.

The present work was done in conjunction with an experiment that provided complementary information on target-like fragments in charge binary reactions [5]. A beam of 20 MeV/nucleon ^{14}N from the K500 cyclotron at the National Superconducting

Cyclotron Laboratory of Michigan State University was used to bombard a metallic ^{164}Dy target of 1.95 mg/cm^2 thickness. Projectile-like fragments were detected at an angle of 14^o (i.e., near the classical grazing angle) with a solid-state telescope consisting of a high planarity 100 μm ΔE detector and a 1 mm E detector. Isotopes of the elements up to oxygen were clearly resolved. Energetic γ-rays corresponding to transitions of up to 6 or 8 MeV (depending on the sign and magnitude of the Doppler shift correction) were detected in coincidence with PLF by four large-volume (7.6 cm x 7.6 cm) bismuth germanate (BGO) detectors. These detectors have a considerably larger photofraction for energetic photons than NaI(Tl) detectors of comparable volume [6]. The BGO detectors were placed at a distance of 17.5 cm from the target, above the reaction plane, with their axes pointing at the target and inclined at an angle of about 49^o with respect to the horizontal plane (the corresponding azimuthal angles were 25^o, 85^o, -25^o, and -145^o).

Fig. 1 shows six γ-ray spectra obtained with one of the BGO detectors, gated by ^{11}B, ^{12}C, ^{14}C, ^{15}N, ^{15}O and ^{16}O ejectiles, respectively. We selected these particular ejectiles because they have high-lying excited states (above 4 MeV) which decay by γ-rays directly to the ground state. These energetic γ-rays can be relatively easily distinguished from the background of the continuum γ-rays emitted by the target-residue nuclei. The γ-ray spectra were calibrated with a Be-Pu source (the 4.44 MeV transition in ^{12}C) and other standard calibration sources. The energies corresponding to the positions of the peaks (indicated by the arrows in fig. 1) were calculated from the calibration curves, and corrected for the Doppler shift corresponding to the average ejectile velocity given by the centroid of the ejectile energy spectrum. These calculated energies exactly agree with the known γ-transitions in the respective nuclei.

The excited states of the ejectiles identified via their γ-decay as demonstrated in fig. 1 can be populated either directly or sequentially (i.e., via higher γ-decaying states). The former mode can be best exemplified by excitation of the 4.4 MeV state in ^{12}C which is the only bound excited state in this nucleus. On the other hand, the observed γ-ray spectrum of ^{15}N shows that the 1.9 and 2.3 MeV γ-rays which feed the 5.2 MeV state in ^{15}N are clearly present. Similarly, the 2.0 MeV γ-rays in ^{15}O feed the observed 5.2 MeV state in this nucleus. We will not attempt to unravel the direct and sequential population of various excited states. Nevertheless, the present results on the population of selected excited states (or group of states in the case of the sequential γ-decay) are very useful, especially for comparisons of the same reaction channels at different energy losses.

Figs. 2 and 3 (middle rows) show the kinetic energy spectra of the chosen ejectiles observed in coincidence with the known γ-ray transitions. As seen from fig. 1, the γ-photopeaks used as the gates contain some continuum background associated presumably with the γ-decay of the heavy fragment. The background corresponding to these underlying events has been subtracted from the coincidence energy spectra of the ejectiles. Inclusive energy spectra (singles) of the same ejectiles obtained in a separate run are shown above (upper rows) for comparison. The coincidence and singles spectra for each ejectile look very similar. However, their ratio (bottom rows) exhibits quite an interesting dependence on ejectile kinetic energy. The quantity that is plotted in the bottom rows of figs. 2 and 3 is the ratio of the cross section for the production of a given ejectile in a specific excited state to the inclusive cross section, $\sigma(Ex)/\sigma(singles)$. This ratio is a measure of population of the excited state (produced either directly or sequentially) relative to the population of all bound states of that ejectile. The magnitudes of the ratio $\sigma(Ex)/\sigma(singles)$ were calculated by summing up the data for all four BGO detectors and by using the known energy dependence of the photopeak efficiency of these detectors [7] and the beam normalization between the singles and coincidence runs. The γ-rays angular distributions were assumed to be isotropic in the rest frame of the ejectile.

The ratio σ(Ex)/σ(singles) ranges from 5% to 15%, depending on the ejectile, its observed excited state, and the energy of the ejectile. It is interesting to note that the magnitude of this ratio does not much differ from nucleus to nucleus, in spite of the fact that some of the nuclei in question have many bound excited states (^{11}B, ^{15}N) while others, such as ^{12}C or ^{16}O, have only a few of them. It remains an open question to what extent this reflects the primary populations of the excited states in question.

It appears that the most important feature of the present data can be found in the dependence of the ratio σ(Ex)/σ(singles) on the ejectile's energy. There is a clear difference in the energy dependence of this ratio between stripping-like reaction products (^{11}B and ^{12}C) and pick-up or exchange reaction products (^{14}C, ^{15}N, ^{15}O and ^{16}O). In stripping reactions the ratio σ(Ex)/σ(singles) is almost constant over the whole range of ejectile energies. In contrast, the ratio for pickup and exchange reactions is small at low energies, but increases by a factor of 2 or 3 at high kinetic energies, i.e., in the region that is commonly associated with peripheral collisions ("quasi-elastic peak"). This indicates that the total excitation energy produced in the collision is not shared statistically (i.e., according to the available phase space of the equilibrated system), but rather depends on the direction of the mass transfer. One can speculate that the excitation energy associated with the transfer of mass is primarily shared as in the Oppenheimer-Phillips mechanism [8,9]. (A generalization of this mechanism for multinucleon transfer or exchange reactions has been proposed by Siemens et al. [10]). In this mechanism the transferred nucleons leave the parent nucleus near the ground state and bring their individual momenta into the receiving fragment. Consequently, the receiving fragment gets all the excitation energy in the earliest stages of the collision, i.e., immediately after the transfer. Any redistribution of the excitation energy presumably depends on the length of time of the nuclear interaction: the longer the collision time, the more "relaxed" the expected partition of the excitation energy. As a result, the fastest reactions (peripheral collisions which show up as the quasi-elastic peak in the energy spectra) would be expected to retain the pattern of the primary partition of the excitation energy. Thus, this model predicts that the population of excited pickup or exchange reaction products should be enhanced in the region of the quasi-elastic peak. The data shown in figs. 2 and 3 agree with this prediction.

Summarizing, we have shown that the γ-deexcitation of light projectile-like fragments can be relatively easily studied by measuring coincidences between these light fragments and γ-rays detected with large-volume bismuth germanate detectors. The first measurements with this technique, a study of the $^{14}N + ^{164}Dy$ reaction at 20 MeV/nucleon, showed a distinct difference, in the population of excited states, between stripping and pickup (or exchange) reactions. In the latter type of reaction one observes an enhanced population of the excited states in the region of final kinetic energies corresponding to peripheral collisions.

We would like to thank the staff of the National Superconducting Cyclotron Laboratory for making this work possible. We would like to thank E. Deci for his comments on the manuscript. Two of us (K.S.-W. and J.W.) would like to thank the members of the NSCL for the hospitality extended to us during our visit. This work was supported by the NSF under grant PHY-83-12245.

References

(a) On leave from Institute of Experimental Physics, University of Warsaw, 00-681 Warsaw, Poland; present address: Lawrence Berkeley Laboratory, Nuclear Science Division, Berkeley, CA 94720

(b) On leave from Institute for Nuclear Studies, 05-400 Swierk (Warsaw), Poland; present address: Lawrence Berkeley Laboratory, Nuclear Science Division, Berkeley, CA 94720

1. T. C. Awes, R. L. Ferguson, R. Novotny, F. E. Obenshain, F. Plasil, S. Pontoppidan, V. Rauch and G. R. Young, Phys. Rev. Lett. 52, 252 (1984)
2. R. Vandenbosch, A. Lazzarini, D. Leach, D. K. Lock, A. Ray and A. Seamster, Phys. Rev. Lett. 52, 1964 (1984)
3. J. van Driel, S. Gonggrijp, R. V. Janssens, R. H. Siemssen, K. Siwek-Wilczynska and J. Wilczynski, Phys. Lett. 98B, 351 (1981)
4. W. D. M. Rae, A. J. Cole, B. G. Harvey and R. G. Stockstad Phys. Rev. C30, 158 (1984)
5. H. Utsunomiya, D. J. Morrissey, R. A. Blue, L. H. Harwood, R. M. Ronningen, K. Siwek-Wilczynska and J. Wilczynski, Proc. the INS-RIKEN International Symposium on Heavy-Ion Physics, Mt. Fuji, Japan, 1984
6. D. J. Morrissey, S. H. Wernig and R. A. Blue, Nucl. Inst. and Methods 221, 641 (1984)
7. C. E. Moss and E. W. Tissinger, Nucl. Instr. and Methods 221, 378 (1984)
8. J. R. Oppenheimer and M. Phillips, Phys. Rev. 48, 500 (1935)

9. R. Serber, Phys. Rev. 72, 1008 (1947)

10. P. J. Siemens, J. P. Bondorf, D. H. E. Gross and F. Dickmann Phys. Lett. 36B, 24 (1971)

Figure captions

Fig. 1

Gamma-ray spectra taken in coincidence with selected ejectiles (^{11}B, ^{12}C, ^{14}C, ^{15}N, ^{15}O and ^{16}O) from the ^{14}N + ^{164}Dy reaction at 20 MeV/nucleon.

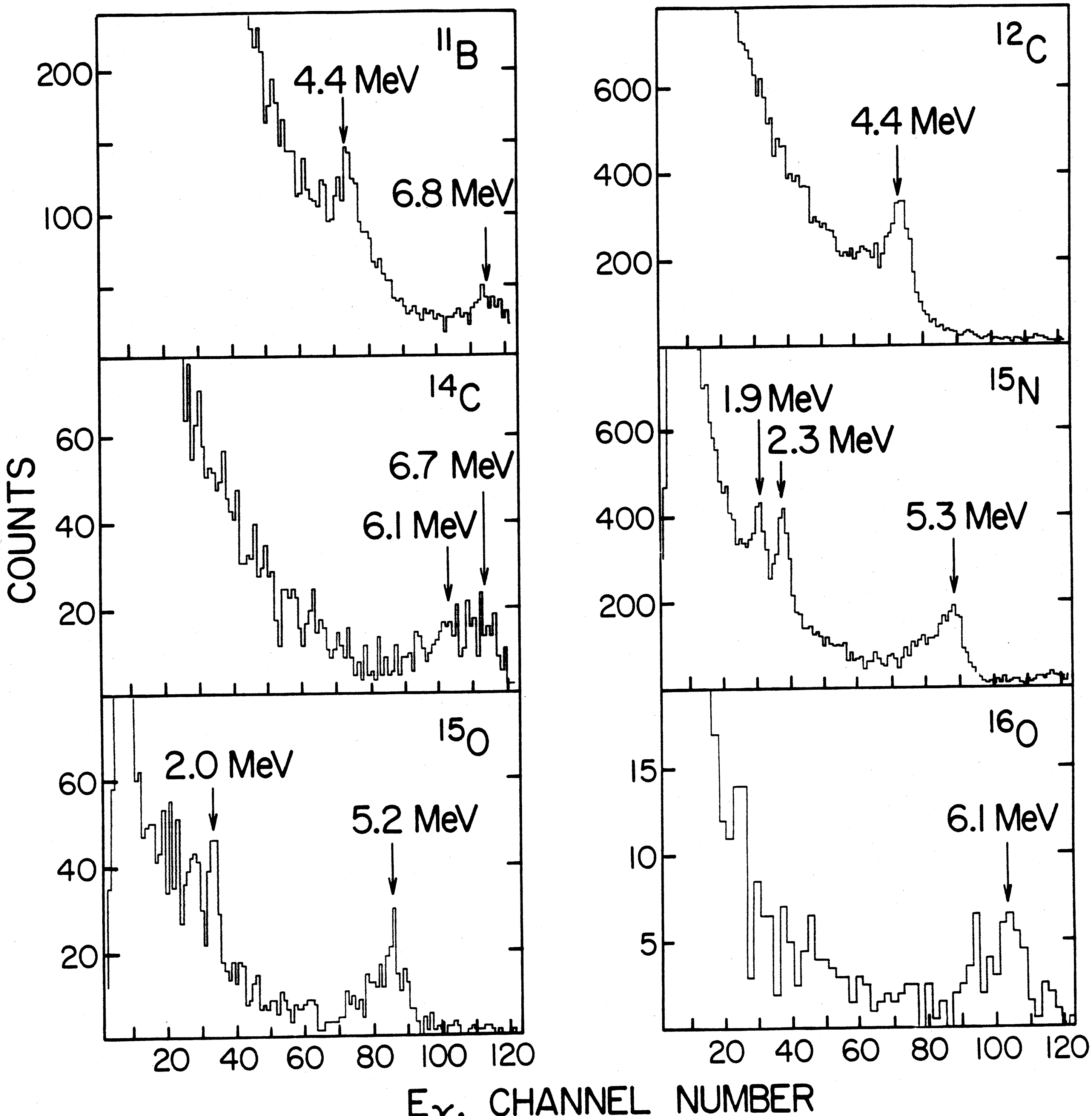
Fig. 2

Comparison of the singles energy spectra of ^{11}B, ^{12}C and ^{14}C with those gated by photopeaks corresponding to specific γ-transitions in these nuclei. The diagrams at the bottom show the cross section for the population of the excited state in question relative to the inclusive cross section, as a function of the kinetic energy of the ejectile. The kinetic energies corresponding to the binary reactions leading to both fragments in the ground states are indicated by the arrows (Q_{gg}).

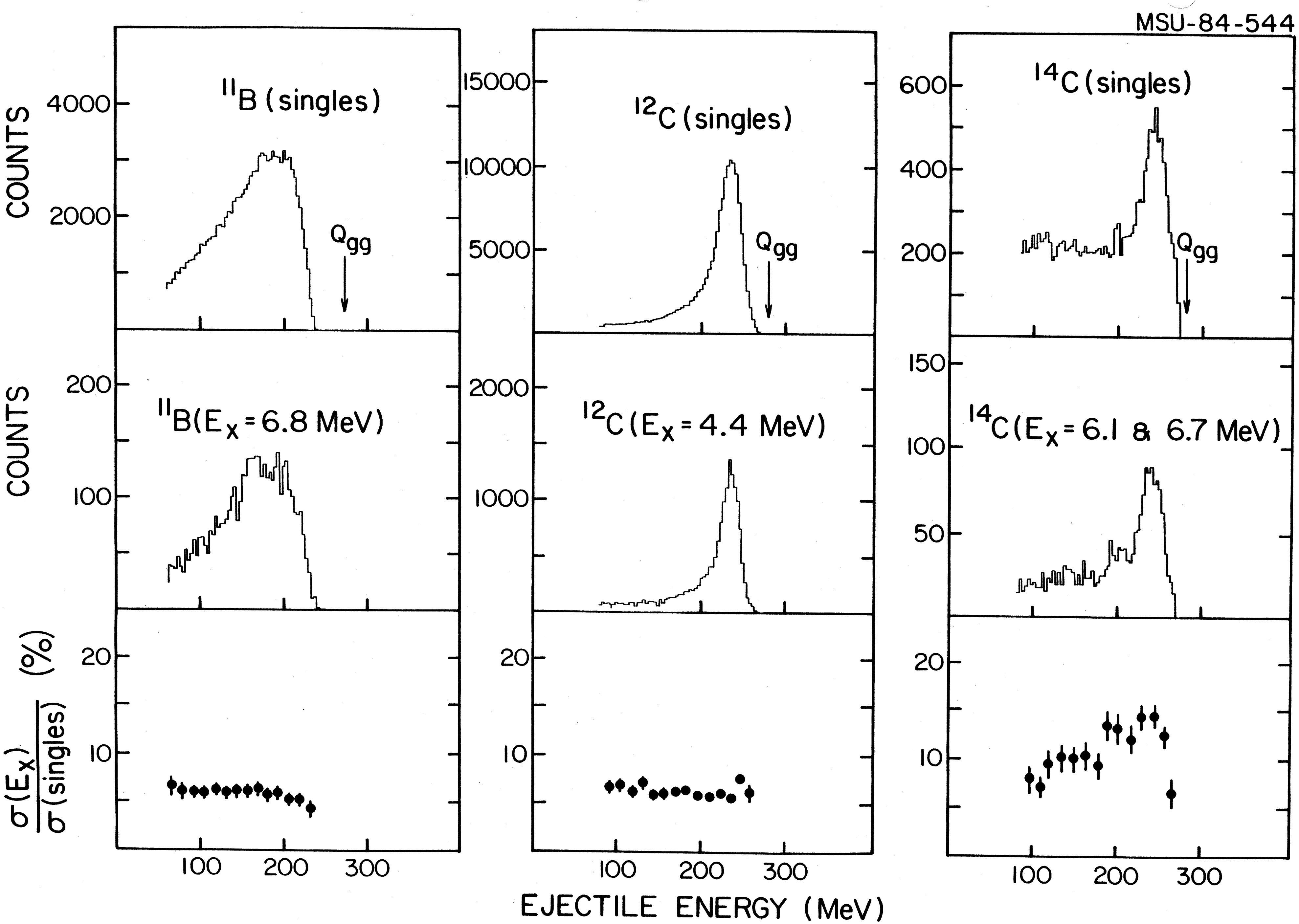
Fig. 3

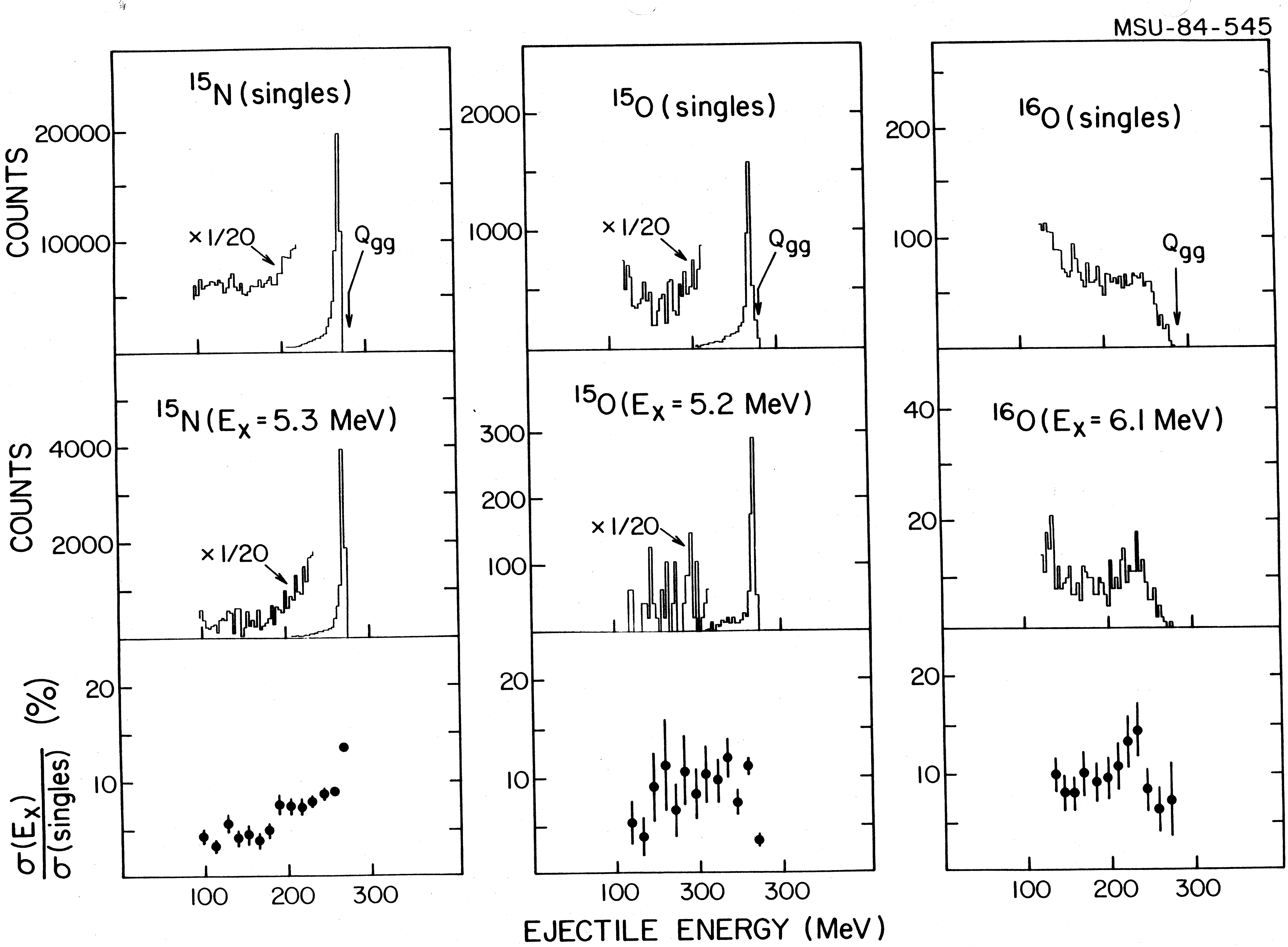
Same as fig. 2, except that the ejectiles are ^{15}N, ^{15}O and ^{16}O.

MSU-84-543



^{11}B
4.4 MeV
6.8 MeV
200
100
^{12}C
4.4 MeV
600
400
200
^{14}C
6.7 MeV
6.1 MeV
60
40
20
^{15}N
1.9 MeV
2.3 MeV
5.3 MeV
600
400
200
^{15}O
2.0 MeV
5.2 MeV
60
40
20
^{16}O
6.1 MeV
15
10
5
COUNTS
20 40 60 80 100 120
20 40 60 80 100 120
E_γ, CHANNEL NUMBER


MSU-84-544
COUNTS
COUNTS
$\frac{\sigma(E_x)}{\sigma(\text{singles})}$ (%)
^{11}B (singles)
^{11}B(E_x = 6.8 MeV)
^{12}C (singles)
^{12}C (E_x = 4.4 MeV)
^{14}C (singles)
^{14}C (E_x = 6.1 & 6.7 MeV)
Q_{gg}
EJECTILE ENERGY (MeV)


MSU-84-545
COUNTS
20000
10000
15N (singles)
× 1/20
Qgg
2000
1000
15O (singles)
× 1/20
Qgg
200
100
16O (singles)
Qgg
COUNTS
4000
2000
15N (Ex = 5.3 MeV)
× 1/20
300
200
100
15O (Ex = 5.2 MeV)
× 1/20
40
20
16O (Ex = 6.1 MeV)
σ(Ex) / σ(singles) (%)
20
10
100
200
300
100
300
300
EJECTILE ENERGY (MeV)