ОБЪЕДИНЕННЫЙ
ИНСТИТУТ
ЯДЕРНЫХ
ИССЛЕДОВАНИЙ
ДУБНА

E7 - 10615

W.Frank, K.-H.Kaun, P.Manfrass

INVESTIGATION OF THE INTERMEDIATE LK MOLECULAR ORBITAL RADIATION IN HEAVY - ION ATOM COLLISIONS

1977

E7 - 10615

W.Frank, K.-H.Kaun, P.Manfrass

INVESTIGATION OF THE INTERMEDIATE LK MOLECULAR ORBITAL RADIATION IN HEAVY - ION ATOM COLLISIONS

Submitted to "Nuclear Physics"

Франк В., Каун К.Г., Манфрасс П. **E7 - 10615**

Исследование квазимолекулярного промежуточного LK-излучения при столкновениях тяжелых ионов

При столкновениях тяжелых ионов измерены абсолютные выходы квазимолекулярного рентгеновского излучения в области энергии выше характеристического KX-излучения симметричных систем Kr + Kr (43 МэВ) и Nb + Nb (67 МэВ). Дополнительно к этому исследовалось с помощью ионов Kr и Nb квазимолекулярное излучение асимметричной системы Kr + Nb при использовании и твердотельной, и газовой мишеней. Значения выходов квазимолекулярного излучения при асимметричных столкновениях показывают, что низкоэнергетическая компонента квазимолекулярного излучения связана с образованием K-вакансий в более легком из сталкивающихся атомов и вызвана радиационными переходами к $2p\sigma$ - состоянию квазимолекулы.

Работа выполнена в Лаборатории ядерных реакций ОИЯИ.

Препринт Объединенного института ядерных исследований. Дубна 1977

Frank W., Kaun K.-H., Manfrass P. **E7 - 10615**

Investigation of the Intermediate LK Molecular Orbital Radiation in Heavy-Ion Atom Collisions

The absolute yields of quasimolecular radiation above the characteristic KX-rays emitted in the symmetric Kr + Kr (43 MeV) and Nb + Nb (67 MeV) collisions have been determined. In addition, by using Kr and Nb as a projectile and target the asymmetric Kr + Nb system has been investigated with gas and solid targets. The comparison of the MO yields obtained in asymmetric collisions shows that the low-energy component of the X-ray spectrum is associated with the formation of K-vacancies in the lower-Z collision partner and can be interpreted as MO radiation to the $2p\sigma$ orbital.

The investigation has been performed at the Laboratory of Nuclear Reactions, JINR.

Preprint of the Joint Institute for Nuclear Research. Dubna 1977

INTRODUCTION

In heavy-ion-atom collision systems with atomic numbers $Z_1, Z_2 \geq 28$, for the projectile Z_1 and the target atom Z_2 a two-component X-ray spectrum has been observed lying above the atomic K-lines. This continuum consists of an intensive low-energy and a high-energy component, denoted earlier by us as C1 and C2, respectively[1,2]. Heinig et al.[3] have explained this structure as being due to a superposition of K-molecular orbital radiation and an intermediate LK-molecular orbital radiation due to $2p\sigma$ vacancies. The energy limit of the C1 component and the tendencies of the measured yield ratio Y_{C1}/Y_{C2} can be interpreted within the framework of this model. A calculation using the dynamical theory of intermediate phenomena in heavy-ion scattering provided spectra whose shape and intensity agree with experiment[4].

The Doppler-shift investigations of the Nb+Nb system according to the method of Meyerhof[5] confirmed the MO property of the C1 continuum. Nevertheless it is possible that other effects such as radiative electron capture (REC) may account for this continuum. The aim of the present study is to prove that the C1 continuum cannot be caused by REC, being MO radiation to the $2p\sigma$ level. A crucial experiment is a measurement of the absolute C1 and C2 yields with gas and solid targets, since in the case of gas target the REC is absent. Moreover, a drastic change in the ratio between the C1 and C2 yields should be expected if a gas target is used, in which only a one-collision process is possible. This can be concluded from the Br+Br studies performed by Meyerhof [6], which confirmed that in symmetric systems with $Z_1=Z_2\leq 35$ the $1s\sigma$ vacancies and also the C2 continuun are formed mostly during the second collision, whereas the $2p\sigma$ vacancy formation requires only a one-collision process. Therefore the X-ray spectra of the symmetric collision systems Kr+Kr (monatomic gas target) and Nb+Nb (solid target) were measured to obtain information on the character of the C1 continuum. Unfortunately it is difficult to deduce from symmetric systems the correlation between the $2p\sigma$ MO radiation and the corresponding vacancies. In this case the K-yield is proportional to the sum of all the K vacancies irrespective of where they are produced (on the $2p\sigma$ or $1s\sigma$ orbital). A more direct evidence on the C1 continuum as molecular radiation to the $2p\sigma$ orbital is likely to be provided by the ratio of the C1 yields and the lower-Z K-yield in asymmetric collisions, in which the $2p\sigma$ orbital is coupled with the lower-Z $1s_{1/2}$ level. A favorable asymmetric system is the combination of Krypton and Niobium. By using these elements as a projectile and target the same collision system can be investigated with gas and solid targets.

In addition, several experimental properties of the C1 radiation such as the upper energy limit, the half-width of the continuum and relative MO-yields of the collision systems with $Z_1, Z_2 \geq 28$ will be analysed.

EXPERIMENTAL ARRANGEMENET

The experiments were performed at the U-300 heavy-ion cyclotron of the JINR Laboratory of Nuclear Reactions.

The ion intensities on the target amounted to about 10^{12} particles per second. The X-ray spectra were measured using an intrinsic Ge spectrometer with an energy resolution of 250 eV at an X-ray energy of 14 keV. The counting rates amounted to about 100 s^{-1}, i.e., they are low enough to avoid considerable pile-up contributions. Except for the Al chamber wall and 30 μm thick Be window, no absorbers were used.

The experimental arrangement is shown schematically in fig.1. A cubic reaction chamber with a volume of 2000 cm^3 served as a "gas target" separated from the cyclotron vacuum system by a 0.76 mg cm^{-2} Ni foil. In order to reduce the target length to 22 mm, a Cu collimator was placed in front of the Ge detector. A special shape of the collimator provided an energy-independent efficiency of the whole effective volume of the target up to a 100 keV X-ray energy, which was tested with calibrated γ-ray sources. The diameter of the ion beam in the target vicinity was 8 mm and the distance between the beam centre and the detector surface amounted to 30 mm. A distance of 6 mm from the entrance window to the target was sufficiently large not to record the X-ray

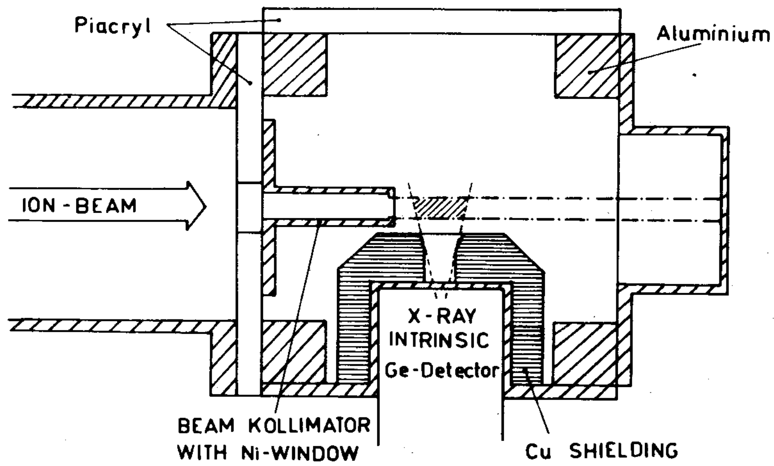

Fig.1. The experimental arrangement for the gas target experiments.

radiation from the Ni-foil. In addition, all the K-vacancies of the projectile produced by its passing through the Ni foil were filled on their way to the target. The reaction chamber without the beam collimator and without the Ni window was used as a Faraday cup for the measurement of the ion number. In spite of the accurate measurement of the ion current it was not possible to deduce the total ion number exactly because of the change of the ion charge in the Ni window. The 40 MeV Kr and Nb ions passing through the Ni foil had a mean charge of 16^+, which was partially compensated by the simultaneously emitted electrons /8/. Therefore the maximum possible correction for the total ion

number was obtained to be a factor of about 3. Since the effective charge of ions in the reaction chamber was unknown, the K- and MO-yields summarized in the table were normalized to the total number of 5^+ ions.

RESULTS

The asymmetric collision systems 43 MeV Kr+Nb and 47 MeV Nb+Kr

The aim of these experiments was to obtain experimental evidence for the correlation of the C1 continuum with the K-yield of the lower-Z collision partner Krypton. By using Kr and Nb both as projectile and target atoms one can investigate the same with a monatomic Kr gas target and metallic Nb target. The kinetic energies of the ^{93}Nb and ^{84}Kr ions after their passing through the 0.76 mg cm^{-2} Ni window amounted to 47 MeV and about 56 MeV, respectively. In order to carry out the investigation at the same c.m. energy, the energy of the Kr ions was decreased from 56 to 43 MeV by means of a 0.6 mg cm^{-2} thick Ni foil. A 200 μg cm^{-2} Nb target on 0.2 mm Al backing was used for the measurements. To have the same number of atoms the effective thickness of the Kr target was 185 μg cm^{-2} corresponding to a target length of 22 mm at a gas pressure of 16 torr. All the investigations were carried out under identical experimental conditions so that systematic errors were excluded. The prompt background involved in the investigations with the gas target was obtained from measurements without Kr gas in the reaction chamber. In the studies using the Nb target the most important background component was the Kr-Al bremsstrahlung of the Al backing. The latter background was measured by using a 0.2 mm Al foil, whereas the Kr-Nb bremsstrahlung was calculated /7/ . Fig.2 shows the measured X-ray spectra for the 43 MeV Kr+Nb (fig.2a) and the 47 MeV Nb+Kr collision systems (fig.2b). In fig.3 the absolute MO-intensities of these systems corrected for absorption, detector efficiency and background are presented. These results show unambiguously that in both cases, irrespective of the target configuration, the C1-radiation is emitted. As expected theoretically, the relative yields $Y_{C1}/Y_K(Kr)$ are equal, whereas the absolute yields differ by about one order of magnitude. The yield ratios for these two systems were measured to be $Y_{C1}/Y_K(Kr) = 8.3\cdot10^{-3}$ and $7.2\cdot10^{-3}$, respectively. From this result it can be concluded that the C1 continuum is not produced by radiative electron capture but correlated with the K-vacancies of the lower-Z collision partner. On the other hand, the C2 radiation is influenced considerably by the target density. The absolute C2 yield in the solid target experiment amounted to $Y_{C2} = 9.0\cdot10^{-10}$ photons per ion. In contrast to the Nb target experiment, no C2 continuum has been observed in the measurement using the Kr gas target. The observed total continuous radiation with an intensity of $3.5\cdot10^{-10}$ photons per ion lying above the C1 energy limit can be explained as the sum of bremsstrahlung and prompt background. The upper limit for the C2 intensity in the gas target experiment was determined to be $Y_{C2} < 6\cdot10^{-12}$ photons per ion. It follows that the yield ratio Y_{C2}/Y_{C1} decreases by a factor

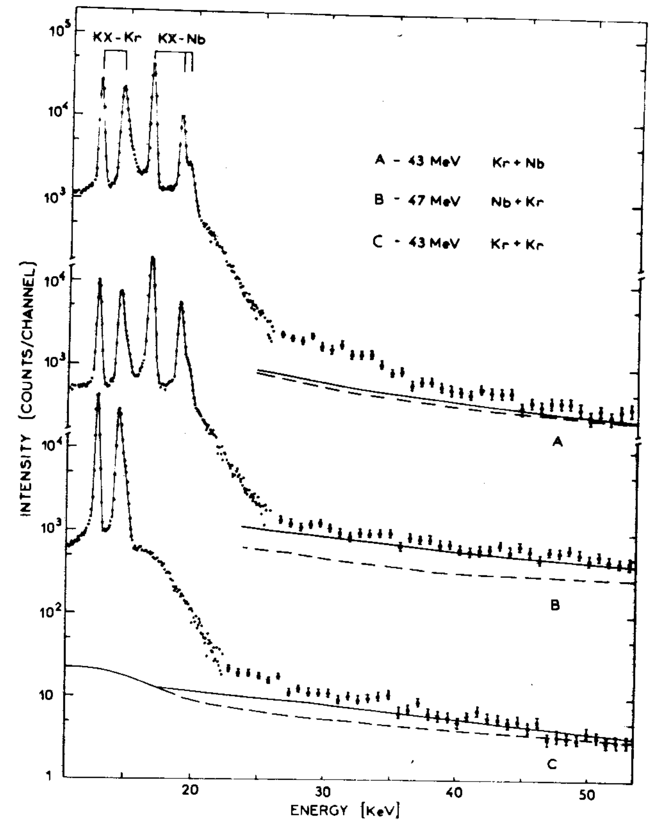

Fig.2. The X-ray spectra measured by bombarding the metallic Nb target with 43 MeV Kr ions (A) and the Kr gas target with 47 MeV Nb ions (B) and 43 MeV Kr ions (C). The dashed lines represent the measured background and the solid lines are the summed spectra of background and bremsstrahlung radiations.

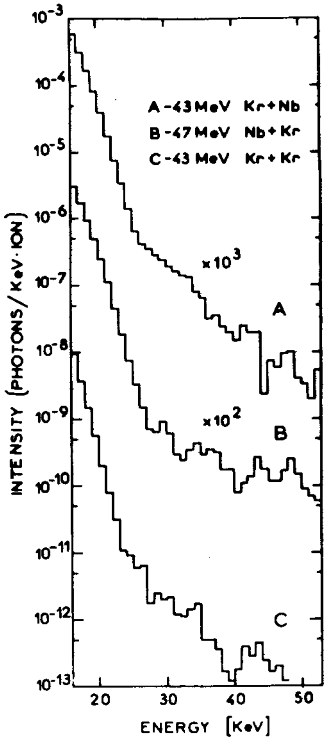

Fig.3. The absolute X-ray intensities corrected for absorption, background and detector efficiency.

of more than 20 in the Kr gas target experiment. Not only the yield ratio for both MO components but also the C2 yield per K-vacancy of the higher-Z collision partner are affected by the target density. Since a value of Y_{C2}/Y_K (Nb)= $=3.2\cdot10^{-4}$ was obtained with the Nb target, this ratio is a factor of about 30 smaller in the one-collision case involved in experiments with the gas target. This confirms that multiple collision processes dominate for the C2 production in solid targets with Z_1, $Z_2 \leq 41$.

The symmetric collision systems 43 MeV Kr+Kr and 67 MeV Nb+Nb

The comparison of the C1 and C2 yields in symmetric collisions with solid and gas targets should provide information on the dominating influence of the one- and two-collision processes on this MO-radiation. For this reason the symmetric systems 43 MeV Kr + Kr and 67 MeV Nb + Nb were investigated using targets 185 μg cm^{-2} and 200 μg cm^{-2} thick, respectively. From earlier studies /9/ it is known that the relative MO yields Y_{MO}/Y_K do not depend considerably on the projectile energy, so that in spite of the different c.m. energy, one can obtain an adequate information.

The X-ray spectra measured in the Kr + Kr studies are presented in figs.2c and 3c. They show that the intensity lying above the C1 continuum cannot be interpreted as wholly due to the bremsstrahlung and background radiations. The total intensity is about 10^{-10} photons per ion in the X-ray energy region of 24 to 60 keV. From the consideration of the bremsstrahlung and background radiation the MO yield is obtained to be $Y_{C2}=(5\pm2)10^{-11}$ photons per ion.

The yields for the 67 MeV Nb+Nb collision system are given in the table. The X-ray spectrum observed with a 200 μg cm^{-2} target is qualitatively in agreement with the earlier published spectra for thick targets /10/. The comparison of the MO yields in the Kr + Kr, Ge+Ge and Nb + Nb systems with solid targets shows that the Y_{C2}/Y_K values for the monatomic gas target are considerably smaller while the C1 values are independent of the target density. Finally the results of the symmetric collision systems investigated confirm the above-mentioned conclusion that the C1 continuum is the quasimolecular 2pσ radiation and that the 1sσ radiation is produced predominantly in two-collision processes.

Properties of the quasimolecular 2pσ-radiation

In what follows several properties of the 2pσ-radiation will be analysed such as the

Table

Z_1 (MeV) + Z_2	TARGET $\mu g/cm^2$	ABSOLUTE K-RAY YIELDS $Y_K(Z_1)$	$Y_K(Z_2)$	PHOTONS/ION Y_{C1}	Y_{C2}	$E_{max}(C1)$ keV	$H_{1/2}(C1)$ keV	$H_{1/2}(C2)$ keV
Ni (39 MeV) + Ni	1000	1.8 (-2)	-	1.6 (-5)	2.0 (-7)	11.7	0.47	2.77
Ge (54 MeV) + Ge	500	3.6 (-2)	-	4.3 (-5)	6.3 (-7)	18.7	0.70	3.42
Kr (43 MeV) + Kr	185	2.0 (-5)	-	6.0 (-8)	5 (-11)	24.0	0.728	-
Nb (47 MeV) + Kr	135	5.4 (-7)	2.3 (-5)	1.9 (-7)	6 (-12)	26.0	0.945	-
Kr (43 MeV) + Nb	200	1.9 (-4)	2.8 (-6)	1.4 (-6)	9.0 (-10)	26.0	0.945	3.0
Nb (67 MeV) + Nb	200	2.0 (-4)	-	9.7 (-7)	3.5 (-9)	32.0	0.96	5.76
Nb (67 MeV) + In	> 10^4	1.1 (-4)	7.0 (-7)	2.8 (-6)	2 (-11)	38.0	1.16	-
Xe (150 MeV) + La	> 10^4	4.3 (-6)	2.0 (-6)	1.3 (-6)	2.5 (-9)	55.5	2.18	19
La (115 MeV) + La	> 10^4	9.6 (-6)	-	3.7 (-6)	4.0 (-10)	56.0	2.38	15

absolute and relative yields, the upper limit of the continuum energy and the slope of the spectra for all the investigated collision systems with Z_1, $Z_2 \geq 28$ with the purpose of stimulating further studies of this quasimolecular radiation.

The spectra corrected for the detector efficiency and background show an exponential shape for both MO continua above the atomic K-lines. Therefore by fitting the continua to the exponential functions $N_0 \cdot e^{-E_x/H}$ one can obtain the half-width H of the spectra and the MO yields after integration. To determine the yields the upper limit of the C1 continuum was taken to be the crossing point of both exponential functions, which is also the lower limit for the C2 continuum. The lower C1 limit is arbitrary since only the spectrum shape above the K-lines is known. Because of the correlation of the $2p\sigma$ orbital with the $1s_{1/2}$ level of the lower-Z collision partner, the K_β -energy was used as the energy limit.

The upper limit of the C1 energy $E_{max}(C1)$ as a function of the sum of the atomic numbers $Z = Z_1 + Z_2$ is given in the table and shown in fig.4. Theoretically the limit of the C1-energy should increase proportionally to Z^2, i.e., $E_{max}(C1)/Z^2 =$ const. The experimental values correspond well to the expected dependence: $4.3\ eV \leq E_{max}(C1)/Z^2 \leq 4.7\ eV$. These few experimental values do not so far permit any conclusions on deviations from Moseley rule.

The yields ratio Y_{C1}/Y_K can provide an important information on the probabilities of transition between the MO orbitals and on the dominant mechanism of the collision

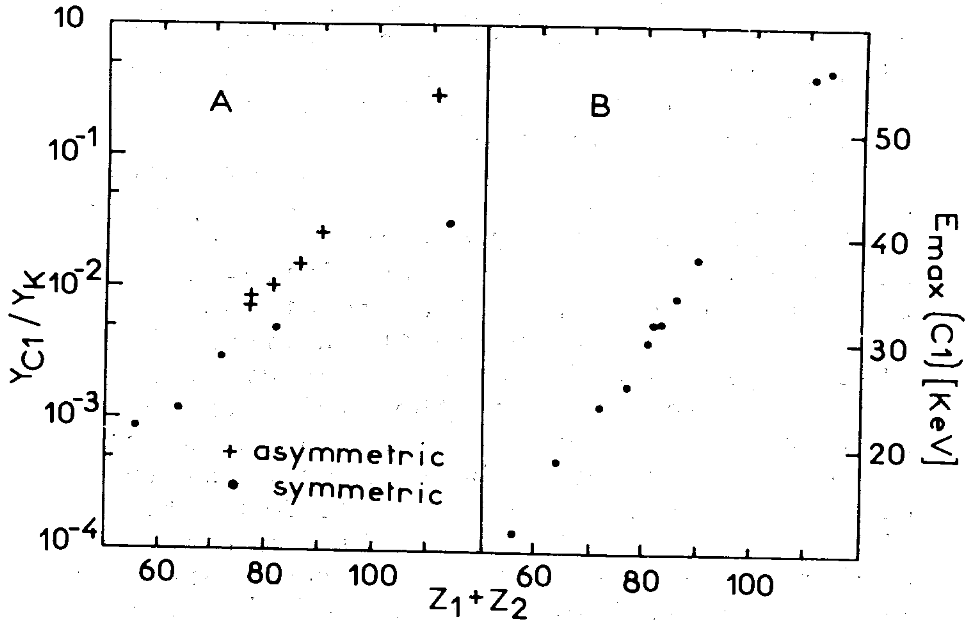

Fig.4. The yield ratio Y_{C1}/Y_K for symmetric and asymmetric collision systems (A) and the upper energy limit of the C1 continuum (B), plotted as functions of the summed atomic number $Z = Z_1+Z_2$.

process. The target density following from the experiments with solid and gas targets does not influence the ratio Y_{C1}/Y_K. The obtained Y_{C1}/Y_K values for symmetric collision systems in the atomic region $28 \le Z_1, Z_2 \le 57$ increase proportionally to $(Z_1+Z_2)^n$ with $n \approx 6$. From this result it cannot be concluded that the relative yield of the total C1 spectrum behaves in this way, since the lower energy limit was chosen to estimate the MO yields arbitrarily. Rather the

observed behaviour of the Y_{C1}/Y_K ratio must be interpreted in such a way that the portion of the C1 spectrum above the K_β -energy increases with increasing Z. Contrary to the C1 yields, the ratio Y_{C2}/Y_K for the C2 radiation increases only at $n \approx 2$ in agreement with simple theoretical estimations/11/.

The half-widths of the MO continua have also the Z-dependence shown in fig. 5. In this

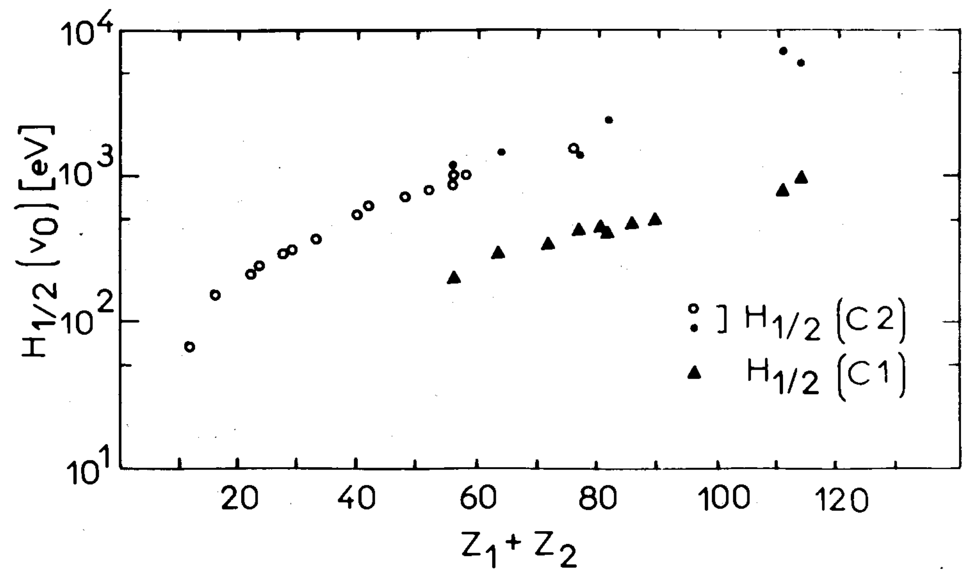

Fig.5. The normalized half-widths $H(v_0)$ of the C1 and C2 continua as functions of the summed atomic number.

figure, the half-widths $H_{1/2}(v_0)$ corrected for the ion velocity are confronted to the values of the table. According to Betz et al./12/ the half-widths are proportional to the square root of the ion velocity v. Therefore all the experimental values of $H(v)$ were normalized to the ion velocity $v_0 = 2.8 \cdot 10^8$ cm s^{-1} using the formula $H(v_0) = H(v)\sqrt{v_0/v}$. The deduced $H_{C2}(v_0)$ -values for a collision system with Z_1, $Z_2 \geq 28$ follow the known Z-dependence of the lighter collision systems observed by Betz et al.[12], the values for the C1 continua being about a factor of 5 smaller.

CONCLUSIONS

The intensive C1 continuum observed in experiments with a gas target provides evidence for the fact that this component cannot be caused by radiative electron capture. On the other hand, the comparison of the C1 yields obtained in Kr + Nb asymmetric collisions with gas and solid targets shows that the C1 continuum is associated with the formation of vacancies in the lower-Z collision partner and can be interpreted as quasimolecular radiation to the $2p\sigma$ orbital. The strong suppression of the C2 component in the gas target experiments indicates that the MO radiation to the $1s\sigma$ orbital is emitted preferentially in the two-collision process in symmetric and near symmetric systems with Z_1, $Z_2 \leq 41$.

The authors wish to express their gratitude to Academician G.N.Flerow for his interest in and support of the work and to the cyclotron staff for their fruitful cooperation.

REFERENCES

1. P.Gippner, K.-H.Kaun, F.Stary, W.Schulze, Yu.P.Tretyakov. Nucl.Phys.,A230,509(1974).
2. W.Frank, P.Gippner, K.-H.Kaun, H.Sodan, Yu.P.Tretyakov.Phys.Lett.,59B,41(1975).
3. K.-H.Heinig,H.-K.Jäger,H.Richter,H.Woittenek.Phys.Lett.,60B,249(1976).
4. K.-H.Heinig,H.-K.Jager,H.Richter,H.Woittenek, W.Frank,P.Gippner,K.-H.Kaun,P.Manfrass.JINR,E7-9862,Dubna,1976.
5. W.E.Meyerhof,T.K.Saylor,R.Anholt.Phys. Rev.,A12,2641 (1975).
6. W.E.Meyerhof,T.K.Saylor,S.M.Lazarus, A.Littles,B.B.Triplett,L.F.Chase,R.Anholt. Phys.Rev.Lett.,32,1279(1974).
7. P.Gippner.JINR,E7-8843,Dubna,1975.
8. S.Datz,C.D.Moak,H.O.Lutz,L.C.Northcliffe, L.B.Bridwell.Atomic Data,2,273,(1971).
9. W.Frank,P.Gippner,K.-H.Kaun,H.Sodan, W.Schulze, Yu.P.Tretyakov.JINR,E7-8616, Dubna,1975.
10. K.-H.Kaun,W.Frank,P.Manfrass.Proc. 2nd Int. Conf. on Inner Shell Ionization Phenomena, Freiburg 1976, Invited Papers, p.68.
11. P.Armbruster,G.Kraft,P.Mokler,B.Fricke, H.J.Stein.Physica Scripta, 10A,175(1974).
12. H.-D.Betz,F.Bell,H.Panke,W.Stehling, E.Spindler,M.Kleber.Phys.Rev.Lett., 34, 1256 (1975), Book of Abstracts,2nd Int. Conf. on Inner Shell Ionization Phenomena, Freiburg, 1976,p.11.

Received by Publishing Department
on April 21, 1977