NUCLEUS-NUCLEUS BREMSSTRAHLUNG FROM SCATTERING ANGLE
SELECTED Cl - Sn COLLISIONS

CONF-8611124--3

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Continuum X rays above the K lines of Sn were measured at 90° and 0° angle relative to the incident beam direction in coincidence with Cl projectiles scattered at very large laboratory angles between 8° and 164°. By varying the isotope mass of the projectile ions (^{35}Cl and ^{37}Cl) and of the target atoms (^{112}Sn and ^{118}Sn) the radiation at scattering angles $>10^\circ$ could be clearly identified as Bremsstrahlung from the elementary scattering process of the two nuclei. The intensity of the radiation emitted at 0° and 90° relative to the beam direction can be reasonably well described by a quantum mechanical calculation of nucleus-nucleus Bremsstrahlung by Reinhardt et al. [7] which includes the interference between dipole and quadrupole radiation amplitude.

1. Introduction

The emission of continuum X rays like quasimolecular (M0) X rays from slow ion-atom collisions has been the subject of numerous investigations in recent years [1]. The main motivation for these studies was the expectation, that these X rays could give direct information about the dynamics of the collision process and the transiently formed quasimolecular states. Similar information could be obtained from measurements of the ionization electrons. There the results obtained, however, still depended on the model used to interpret the

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*Present address: Oak Ridge National Laboratory, P. O. Box X, Oak Ridge, TN 37831. Research sponsored by the U.S. Department of Energy, Division of Chemical Sciences under Contract No. DE-AC05-84OR21400 with Martin Marietta Energy Systems, Inc.

data. The goal of getting a direct spectroscopic access to the transient quasimolecular states was finally reached by measurements of the interference structure in MO X rays with hydrogen-like projectiles [2]. Another approach to see features in the MO X-ray continuum being characteristic for the united atom transition energy was first tried by Burch et al. [3] and one has still new attempts in this direction coming along. The idea is the reduction of collision broadening in the MO X rays by measuring them in coincidence with backwards scattered projectiles. The reduction of collision broadening could be the case because during scattering with very large angle (close to 180°) the projectile is decelerated to almost zero velocity in the Coulomb potential of the target nucleus. However, as we will see from the results of the present measurements, the shoulder in the X-ray continuum above the K lines of Pb, which was believed to be of evidence for this effect by Burch et al. with Cl ions colliding with Pb, had a different origin.

Because of the small vacancy production probability in the quasimolecular $1s\sigma$ state, the emission probability for MO X-rays above the K lines using projectiles without K vacancies is generally very small. The probability integrated over the X-ray energy can be estimated from the radiative lifetime divided by the transit time through the quasimolecule, multiplied by the $1s\sigma$ vacancy probability, gives values in the order of 10^{-5} per collision, e.g., for the system discussed in ref. 3. With such small probabilities, it is necessary to consider also other processes which could give high energetic continuum X rays. One of these which does not depend on the availability of inner shell vacancies is the nucleus-nucleus Bremsstrahlung [4]. The photons are produced here in an elementary process by the acceleration of the charges during the scattering event. To our knowledge, no experimental studies of

nucleus-nucleus Bremsstrahlung of well-defined scattering events have been performed heretofore, i.e., where the scattering angle of pure Coulomb scattering was known.

Evidence for the importance of nucleus-nucleus Bremsstrahlung was found already in non-coincidence continuum X rays [5,6] for asymmetric collisions. Some data [5] have been used to test a quantum mechanical treatment of this Bremsstrahlung emission [7]. It is evident, that an experiment defining the particle trajectories during the collision should allow a more stringent test of Bremsstrahlung theories than could be done with singles spectra. We also want to point out that background count rates (slit nuclear activation, room background, and Compton scattering of these γ 's), which can be very disturbing in singles measurements of low intensity continuum X rays, are almost completely ruled out in coincidence measurements.

By measuring the continuum X rays at 90° and 0° angle relative to the incident beam direction in coincidence with Cl projectiles scattered from Sn targets at very large laboratory angles, and by varying the isotope mass of the projectile ions (^{35}Cl and ^{37}Cl) and of the target atoms ^{112}Sn and ^{118}Sn) it could be clearly shown that in these collisions Bremsstrahlung photons are produced with a larger probability than MO X rays at nearly zero impact parameters. The results of these measurements are compared with the quantum mechanical treatment of the Bremsstrahlung process given in ref. 7.

2. Experiment

The measurements were performed at the EN tandem accelerator of the Max-Planck Institut für Kernphysik in Heidelberg. The Cl beams of mass 35

or 37 were collimated to about 1 mm^2 size into a Faraday cup. The target foils of pure isotopic ^{112}Sn or ^{113}Sn were self-supporting of about $100 \text{ }\mu\text{g/cm}^2$ thickness and positioned at 45° with respect to the beam axis. The X rays were detected by a $500 \text{ mm}^2 \times 5 \text{ mm}$ Ge(I) detector at 90° in 18 mm distance from the target. The scattered ions were detected by two position-sensitive parallel plate avalanche detectors (PPAD) [8]. In the backward direction the PPAD covered an angular range of 139° to 164° . In some of the measurements a PPAD was also mounted at forward angle to detect particles scattered between 8° and 37° . This PPAD could be replaced by a second Ge(I) detector of $500 \text{ mm}^2 \times 5 \text{ mm}$ in 45 mm distance from the target to measure X rays emitted at 0° . A shielded Faraday cup was mounted in front of this detector to stop the particles. The coincidences were stored in the event mode. The random coincidences were subtracted off-line with a procedure described in ref. 9.

3. Results

An X-ray singles spectrum measured with 44 MeV ^{35}Cl on ^{118}Sn is shown in fig. 1. Above the K lines of Sn there are two continua dropping off with different slopes. The one with the steeper slope can be seen up to about the united atom (u.a.) K_β transition energy. There it merges into a flatter continuum which we think is mainly produced by background pulses, e.g., Compton scattering of room background, or from nuclear Coulomb excited apertures or chamber walls emitting gamma rays. We could observe this fact by measuring without target, with beam and without beam. The steeper decaying continuum, seen up to about 60 keV is produced by beam target

interaction. From the slope of its decay and its intensity we deduce that it is due to quasimolecular X-ray emission. Figs. 2 and 3 shows the photon emission probabilities from coincidences with scattered particles into the angle interval of $139 - 164^\circ$ from 44 MeV ^{35}Cl on ^{118}Sn and 44.5 MeV ^{37}Cl on ^{112}Sn collisions, respectively. Notice that the photon emission probability is more than a factor of ten less for the ^{37}Cl and ^{112}Sn isotopes. This already shows the dominance of nucleus-nucleus Bremsstrahlung over MO X rays, because MO X rays are not expected to show such an isotope effect. In nucleus-nucleus Bremsstrahlung, the dipole amplitude is proportional to $Z_1/A_1 - Z_2/A_2$, and the quadrupole amplitude goes with $Z_1/A_1^2 + Z_2/A_2^2$, where the dipole amplitude is much stronger than the quadrupole amplitude. One should also notice that the steep decaying continuum observed in the single spectrum (fig. 1) is not to be seen in the true coincidence spectra (figs. 2 and 3).

In order to see also possible contributions of MO X rays to this continua, we measured the probability for the $^{36}\text{Cl} - ^{112}\text{Sn}$ isotopes down to smaller scattering angles. Since the nucleus-nucleus Bremsstrahlung is expected to display a very different scattering angle dependence [7] than that for MO X rays (these have roughly the dependence of the Sn K vacancy probability [10]), one can separate the two in a plot of $d^2P/dE_x d\Omega_x$ versus the impact parameter. This is shown in fig. 4.

In all the results the absorption of a Cu and Al absorber, and the efficiency of the Ge(I) detector was corrected. The X-ray detector solid angle was determined separately and taken into account, then the results were multiplied by 4π . The error bars shown in the figures indicate only the

statistical errors. Systematical errors are estimated to be in the order of 30%.

4. Discussion

The full curves in figs. 2-4 represent a calculation of nucleus-nucleus Bremsstrahlung done with the computer code of Reinhardt et al. [7]. As nucleus-nucleus Bremsstrahlung is strongly anisotropic depending on its multipolarity, its emission probability had to be integrated over the acceptance angle of the X-ray detector. So these data and theoretical curves represent emission into an angular region ϑ_x around $90^\circ \pm 25^\circ$ (see also table 1). The full curves include the dipole, the quadrupole and the interference term between dipole and quadrupole nucleus-nucleus Bremsstrahlung. In ref. 7, it was shown that higher order amplitudes in the multipole expansion of the nucleus-nucleus Bremsstrahlung transition operator do not give significant contributions. The dashed curve in fig. 4 shows the dipole nucleus-nucleus Bremsstrahlung alone.

Considering, that this is a comparison in absolute value of the probabilities, the agreement is surprisingly good. The calculations reproduce very well the isotope dependence and the spectral shape of the continuum X-ray emission. Also the predicted dependence of nucleus-nucleus Bremsstrahlung on scattering angle (respectively impact parameter) agrees well with the measured dependence of the continuum X-ray emission probability for X-ray energy intervals of 52 - 144 keV (fig. 4). At larger impact parameters, at the 32 - 52 keV interval the contributions of MO X rays can clearly be seen.

For consideration of background effects, we have estimated the contribution of nuclear Coulomb excitation (e.g. of the 1.26 MeV Sn level) and

following γ -transition and Compton scattering to the continuum X-ray probability in our energy region of interest to be less than 10^{-10} photons/particle, which is negligible. Also, the considerations of inner Bremsstrahlung and secondary electron Bremsstrahlung show that these contributions are negligible. These processes would certainly also strongly contradict with the isotope mass dependence measured.

Further support for our interpretation of the origin of this radiation is found in the angular dependence. For its measurement the PPAD in forward scattering direction was replaced by another Ge(I) detector. However, because of the much lower Bremsstrahlung emission probability at 0° , but also because of the much smaller solid angle, the coincidence rate with backwards scattered particles was extremely low. Therefore, we can only give upper limits for the emission probabilities at $\Theta_x = 0^\circ \pm 10^\circ$, shown in table 1. The upper limits inferred from the data are consistent with the theoretical predictions integrated over the detector acceptance angle (table 1).

5. Conclusion

From the measured isotope, emission angle, and impact parameter dependence of the continuous X-ray probability, we conclude that these X rays are produced by the acceleration of the nuclear charge in the scattering process. A quantum mechanical treatment of nucleus-nucleus Bremsstrahlung up to the quadrupole radiation amplitude was found in very good agreement with the data. The results show that at large scattering angles and certain isotopes nucleus-nucleus Bremsstrahlung can be dominating the quasimolecular radiation emitted in ion atom collisions. This explains also the missing photon

intensity in the singles spectra of ref. 3, when normalizing the coincidence intensity to the characteristic X rays in the singles spectrum.

The authors wish to acknowledge the help of J. Reinhardt for his help in setting up the computer code.

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Figure Captions

- Fig. 1. Singles X-ray spectrum at 90° relative to the beam direction from collisions of 44 MeV ^{35}Cl with ^{118}Sn . The arrow denotes the united atom K_β transition energy.
- Fig. 2. X-ray emission probabilities at 90° relative to beam direction derived from the coincidences with ^{35}Cl particles scattered into $139 - 164^\circ$. The line is calculated nucleus-nucleus Bremsstrahlung according to ref. 7 including dipole, quadrupole, and the interference term.
- Fig. 3. Same as fig. 2, however for ^{37}Cl on ^{112}Sn .
- Fig. 4. Impact parameter dependence of continuum X-ray emission at 90° relative to beam direction. The full line is the same calculation as shown in figs. 2 and 3. The dashed line shows the dipole term alone.

Table 1. Photon emission probabilities from ^{35}Cl on ^{118}Sn collisions at $139^\circ - 164^\circ$ scattering angle in certain energy intervals and emission angles θ_x

	$\theta_x = 90^\circ$		$\theta_x = 0^\circ$	
$\Delta E_x [\text{keV}]$	$\frac{d^2p}{dE_x d\Omega_x}$ (exp.)	$\frac{d^2p}{dE_x d\Omega_x}$ (theor.)	$\frac{d^2p}{dE_x d\Omega_x}$ (exp.)	$\frac{d^2p}{dE_x d\Omega_x}$ (theor.)
	[4 π photons/keV sr]	[4 π photons/keV sr]	[4 π photons/keV sr]	[4 π photons/keV sr]
32 - 44	$(1.4 \pm 0.3) \times 10^{-6}$	1.5×10^{-6}	$< 1.7 \times 10^{-7}$	2.4×10^{-8}
45 - 71	$(9.0 \pm 1.0) \times 10^{-7}$	1×10^{-6}	$< 1.5 \times 10^{-7}$	1.2×10^{-8}
72 - 98	$(4.0 \pm 0.7) \times 10^{-7}$	5×10^{-7}	$< 2.4 \times 10^{-8}$	6.2×10^{-9}

Fig. 4