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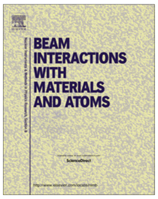

X-ray production with heavy post-accelerated radioactive-ion beams in the lead region of interest for Coulomb-excitation measurements

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ABSTRACT

Characteristic K X-rays have been observed in Coulomb-excitation experiments with heavy radioactive-ion beams in the lead region ($Z = 82$), produced at the REX-ISOLDE facility, and were used to identify the decay of strongly converted transitions as well as monopole $0_2^+ \rightarrow 0_1^+$ transitions. Different targets were used, and the X-rays were detected by the Miniball γ-ray spectrometer surrounding the target position. A stable mercury isotope, as well as neutron-deficient mercury, lead, polonium, and radon isotopes were studied, and a detailed description of the analysis using the radioactive ^{182,184,186,188}Hg isotopes is presented. Apart from strongly converted transitions originating from the decay of excited states, the heavy-ion induced K-vacancy creation process has been identified as an extra source for K X-ray production. Isolating the atomic component of the observed K X-rays is essential for a correct analysis of the Coulomb-excitation experiment. Cross sections for the atomic reaction have been estimated and are compared to a theoretical approach.

1. Introduction

Coulomb-excitation experiments in inverse kinematics using heavy post-accelerated radioactive-ion beams have been initiated at the REX-ISOLDE facility [1], located at CERN. Beams of even-mass neutron-deficient mercury [2], lead [3], polonium [4,5], radon [5,6], and neutron-rich radium and radon [7] isotopes at energies around ~2.85 MeV/u were sent onto different targets like tin, silver, cadmium, palladium, and molybdenum. As a result, low-lying excited states of the beam and/or the target are populated via Coulomb excitation. The Miniball γ-ray spectrometer was used for the detection of γ rays originating from electromagnetic transitions in the nuclei of interest. The nuclear levels populated via Coulomb excitation do not only decay to a lower-lying energy level by emitting a γ ray, but also by internal conversion. Especially $E0$ components of mixed multipolarity transitions (e.g. $2_2^+ \rightarrow 2_1^+$ transitions), as well as $E0$ $0_2^+ \rightarrow 0_1^+$ de-excitations are important in this region of the nuclear chart, due to the high proton number Z and nuclear-structure arguments. The occurrence of these transitions are characteristic for the neutron-deficient even–even nuclei in the lead region where shape coexistence occurs at low-excitation energy [2]. Different coexisting nuclear shapes give rise to energy levels with the same spin and parity but corresponding to dissimilar shapes. These states can mix, generating an enhanced $E0$ transition rate between the levels [8]. Moreover, in even–even nuclei featuring shape coexistence, low-lying 0_2^+ states have been identified (even becoming the first excited state in the nucleus in certain cases) decaying to the 0_1^+ ground state via an $E0$ transition. Hence, observed γ-ray intensities do not suffice to analyze Coulomb-excitation data in a proper way: the inclusion of the decay from populated levels involving electrons is crucial in order to determine their correct population.

Internal conversion is accompanied by the emission of characteristic X-rays. The Miniball γ-ray spectrometer can be used to detect the more energetic K X-rays, and after correction for the relative branching for K_α emission at 69 keV (≈74%) and the fluorescence (≈96%) of the transition (the relative intensity of X-ray

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emission after the creation of a K vacancy), the total number of decays via electrons can be estimated. However, other atomic processes also give rise to K-vacancy creation and thus to the production of X-rays. This paper reports on the determination of X-rays from converted and *E*0 transitions after Coulomb excitation of the even–even $^{182-188}$Hg isotopes. The data allowed the cross section for the atomic process to be estimated. The same analysis procedure was applied to beams of stable mercury, and neutron-deficient lead, polonium and radon.

2. Experimental details

Two Coulomb-excitation experiments were performed at the REX-ISOLDE radioactive-beam facility on neutron-deficient mercury isotopes. A molten lead target was bombarded by 1.4-GeV protons to produce the isotopes of interest. After diffusion and effusion out of the ion source, the ions were mass separated, bunched employing a Penning trap (REX-trap) and charge bred by REX-EBIS to a higher charge state to insure an efficient post-acceleration by the REX-LINAC [1]. Pure mercury beams with an energy of 2.85 MeV/u were guided to the collision chamber. After the reaction with the stable target, the scattered particles were detected by a double-sided silicon strip detector (DSSSD) [9], and the X-rays and γ rays were registered by the Miniball γ-ray spectrometer [10]. The photons were emitted in flight introducing a Doppler shift and broadening of the photon energy peaks. This effect can be corrected for, since the direction and the energy of both particle and γ ray (or X-ray) are known. Data were acquired during the first experiment on the ^{184,186,188}Hg isotopes using two different targets for each isotope: a ^{120}Sn target of 2.3 mg/cm^2 and a ^{107}Ag target of 1.1 mg/cm^2. In the second experiment ^{112}Cd was employed as the target for ^{182,184}Hg and ^{114}Cd for ^{186,188}Hg. Both targets had a thickness of 2.0 mg/cm^2. The details of both experiments are summarized in Table 1.

Random-subtracted γ-ray energy spectra collected in coincidence with scattered mercury-beam and cadmium-target ions are shown in Fig. 1. A Doppler correction has been applied using the velocity of the mercury projectile.

In these four spectra, K X-rays are clearly present at 69 keV and 80 keV, and correspond to holes created on the K shell of the mercury atoms as these give rise to a K$_\alpha$ line and a K$_\beta$ line at these energies [11]. Since they are in prompt coincidence with two scattered particles, and a Doppler correction for the projectile velocity needs to be applied, they must originate from the projectile in flight. The number of X-rays compared to the $2_1^+ \rightarrow 0_1^+$ is significantly higher in ^{182,184}Hg than in ^{186,188}Hg. The X-rays originating from electron vacancies created in higher-lying orbitals are too low in energy to be detected by the Miniball γ-ray spectrometer. After correction for the relative branching for K$_\alpha$ emission at 69 keV and the fluorescence of the atomic transition, the total number of electronic decays can be gauged.

3. Heavy-ion induced K-vacancy creation

The total cross section for K-shell ionization of a target atom by a projectile ion was described by a universal form [12], given by

$$\sigma = \frac{Z_p^2}{I_K^2} f(E_p/I_K) \tag{1}$$

where E_p and Z_p are respectively the energy and proton number of the incoming ion, I_K the binding energy of the K electron in the target and f the universal curve.

Romo-Kröger et al. deduced a phenomenological curve from this theoretical approach, based on the proton-induced K-vacancy created in any target atom [13]. The cross section σ for K ionization by an incident proton is estimated by a fifth-order polynomial:

$$\ln(\sigma I_K^2) = \sum_{i=0}^{5} b_i (\ln(E_{\text{proton}}/I_K))^i \tag{2}$$

where $\{b_i\} = \{11.122, 0.6564, -0.5981, 0.0091, 0.0285, 0.006\}$. Here, E_p is given in MeV, I_K in keV, and the cross section σ in barn. The cross section for K-vacancy creation of a target atom irradiated by a heavy projectile with proton number Z_p and atomic number A_p is derived from the proton-induced cross section by a scaling factor Z_p^2:

$$\sigma_{\text{proj}}(E_p) = Z_p^2 \sigma_{\text{proton}}(E_p/A_p) \tag{3}$$

Only the energy per nucleon of the beam appears in the calculation of the cross section for creating a K-vacancy in the target atom. Since the cross section is sensitive to the incident energy, it should be integrated over the target thickness, taking into account energy losses when the projectile penetrates through the target. Also a correction of replacing I_K by $I_K^{0.95}$ on both sides of Eq. (2) is suggested, corresponding to an effective charge for the target being lower for heavier targets [14].

In order to infer the cross section for K-vacancy production in the mercury projectile of interest in the Coulomb-excitation experiment, a change of frame of reference is needed. An incoming cadmium projectile should be considered, incident on a mercury target at rest, inducing a K vacancy. In both frames of reference the total energy in the center-of-mass-frame should be equal. When the reference frame of projectile and target are interchanged, this leads to the following equation:

$$\frac{E_{lab,\text{Cd}}}{m_{\text{Cd}}} = \frac{E_{lab,\text{Hg}}}{m_{\text{Hg}}} \tag{4}$$

Table 1
The properties of the mercury beams and employed targets. The half lives, measured beam intensities, energies and charge states are given for different projectiles. The target isotopes with thicknesses are also presented. The last column lists the duration of each measurement.

Isotope	$T_{\frac{1}{2}}$	I_{beam} [ions/s]	Energy [MeV]	Charge state	Target (s)	Thickness [mg/cm^2]	Duration [h]
^{182}Hg	10.83 s	3.5×10^3	518.7	44^+	^{112}Cd	2.0	110.53
^{184}Hg	30.87 s	2.2×10^4	524.4	44^+	^{112}Cd	2.0	12.82
		4.8×10^3	524.4	43^+	^{107}Ag	1.1	18.3
		4.8×10^3	524.4	43^+	^{120}Sn	2.3	58.73
^{186}Hg	1.38 min	3.0×10^4	530.1	44^+	^{114}Cd	2.0	5.77
		2.1×10^5	530.1	43^+	^{107}Ag	1.1	1.42
		2.1×10^5	530.1	43^+	^{120}Sn	2.3	3.03
^{188}Hg	3.25 min	1.0×10^5	535.8	45^+	^{114}Cd	2.0	15.95
		1.6×10^5	535.8	44^+	^{107}Ag	1.1	1.62
		1.6×10^5	535.8	44^+	^{120}Sn	2.3	11.43