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In-Flight X-Ray Measurements: A Technique for Identification of Superheavy Elements

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In energetic heavy-ion–atom collisions there is an extremely high probability for producing electron holes in inner shells of the collision partners. The resulting high x-ray yield opens the possibility of detecting superheavy elements by their collision-induced characteristic x rays. A Z determination of fast recoils with lifetimes longer than 10^{-6} sec seems to be possible. The applicability of the method is discussed.

In energetic heavy-ion–atom collisions a high cross section for inner-shell vacancy production is observed.[1-3] The mechanism responsible for the high vacancy production is mainly electron promotion in the quasimolecule formed during the collision.[4-6] This holds true as long as the collision velocity v is small compared to the orbital velocity u of the electrons of interest. For such cases the electron promotion may be read from the diabatic molecular orbitals as a function of the internuclear distance. The electrons promoted can be effectively excited either by transitions to empty levels via crossings or asymptotical crossings or by direct ionization.[5] Generally, diabatic correlation diagrams may give a good qualitative explanation of the experimental findings.

Superheavy elements are assumed to be produced with a recoil energy smaller than or comparable to 1 MeV per nucleon. The corresponding velocity v is considerably smaller than the orbital velocities u of the inner- and medium-shell electrons. As an example, for a recoil with $Z = 120$ and an energy of 0.5 MeV per nucleon, the collision velocity v is comparable to the orbital velocities of the 5*d* or 6*s* electrons. That means the quasimolecule formed by a superheavy recoil and a heavy atom during the collision may be well described by a diabatic correlation diagram as long as we are not concerned with the outermost shells.

Such a diagram is given in Fig. 1 for a superheavy recoil ($Z = 120$) colliding with a gold atom ($Z = 79$). The right-hand scale in Fig. 1 shows both the electron levels of the superheavy element and the gold atom; the left-hand scale gives the levels of the united atom ($Z = 199$). The term energies for the gold atoms are taken from Herman and Skillman.[7] The other term energies are a rough extrapolation of the values given in Ref. 7. For our purpose an accurate knowledge of the term energies is not necessary. The presented H_2^+-like correlation diagram includes spin-orbit interaction.[8] A diagram without spin-orbit interaction shows the same main features.

From the correlation diagram we may learn the following:

(i) The two K-shell electrons of the superheavy element are not promoted. Their binding energy is increased and no K-shell ionization will be observed.

(ii) For the L electrons of the superheavy ele-

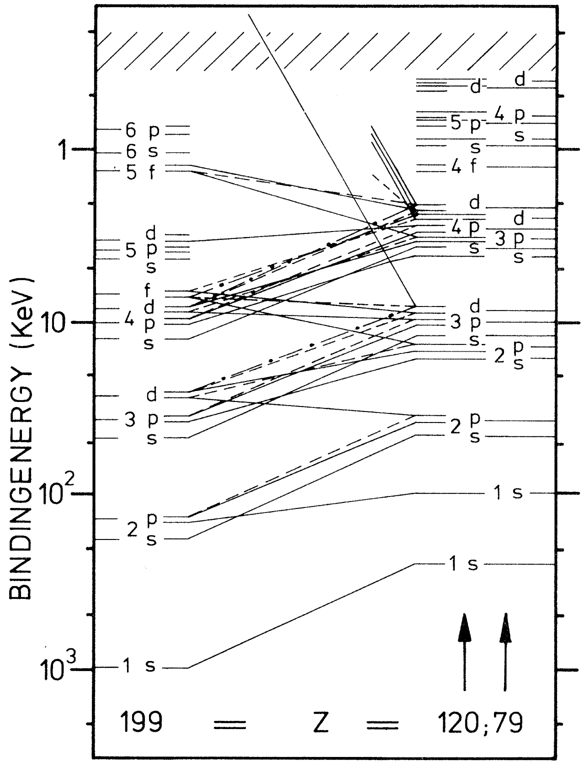

FIG. 1. Diabatic level diagram of the quasimolecule $_{79}$Au-$_{120}Z$. The molecular orbitals are distinguished by the projection Ω of the angular momentum $j=l+\sigma$ on the internuclear axis (solid line, $\Omega=\frac{1}{2}$; dashed line, $\Omega=\frac{3}{2}$; dash-dotted line, $\Omega=\frac{5}{2}$). The region for approximately equal orbital velocities v and collision velocity u for an energy of 0.5 MeV per nucleon is indicated by the shaded band in the top of the diagram.

ment no pronounced promotion in energy occurs. Most of the term energies are increased. Only two $2p_{3/2}$ electrons show a weak promotion in energy; however, the crossed levels will be fully occupied. Hence, there seems to be no chance for an effective L-shell excitation. This will be a general feature in a collision of a superheavy recoil with a heavy atom.

(iii) A very pronounced promotion only occurs for two M electrons ($3d_{5/2}$) of the superheavy element. The level may cross empty ones and rises steeply up to an energy region ($v>u$) where multiple excitation and ionization is expected to be very effective. It may be assumed that both electrons will be lost. On separation of the collision partners these electron holes may be transfered to the M shell of the superheavy element. We have to take into account the possibility that electrons may fill the empty level on crossings and thus may reduce the possible high M-shell excitation of 2. Except for the two $3d_{5/2}$ electrons no efficient M-shell excitation may be expected for superheavy elements.

(iv) A high excitation and ionization is expected for the N shell and for all higher shells of the superheavy element. However, the x-ray energy of these transitions becomes small and the spectrum may be very complicated.

We conclude that only M radiation is suitable for an in-flight detection of superheavy elements. To calculate the ionization cross section for the M shell we need the promotion radius. According to Kessel[9] the promotion radius is expected to be on the order of the M-shell dimension. With an extrapolated M-shell radius of $R=3\times10^{-10}$ cm,[7] an ionization cross section of $\sigma=\pi R^2=3\times10^5$ b is obtained.

This estimated value is supported by an extrapolation of a measurement reported by Specht.[3] For a system of 0.3 MeV per nucleon heavy fission fragments from ^{235}U impinging on U an ionization cross section of $(3-4)\times10^6$ b can be assumed for the M radiation of U. Heavy fission fragments are almost equivalent to I ions. A diabatic correlation diagram of the I-U system, however, can be compared almost exactly with the one shown in Fig. 1. From this U_M cross section, corrected for the different shell radii, an ionization cross section for the superheavy recoils of about 10^6 b may be expected. This value agrees well with the above estimate of 3×10^5 b.

With a supposed fluorescence yield of 0.2, an x-ray production cross section between 5×10^4 and 10^5 b is expected. To get a feeling for the detection efficiency we assume the following geometry: A 1-mg/cm^2 Au foil is placed in the focal plane of a recoil mass spectrometer[10] delivering a beam diameter of 1 cm. The x rays produced in the foil are analyzed by a 80-mm^2 Si-(Li) detector with a solid angle of $\Omega/4\pi=6\%$. With this arrangement a detection efficiency for the superheavy element of 1–3% can be achieved. To reduce the background in the x-ray spectra, coincidences between a following recoil detector and the x-ray detector are possible without any loss in count rate.

We have shown that collision-induced M radiation will be produced with high efficiency. A problem still remaining is determining the nuclear charge of the superheavy element from the spectrum unambiguously. The energy levels of the superheavy elements may be calculated with high accuracy.[11] The energy of the M radiation of a superheavy element is in the region of 6 keV. The distance between corresponding lines of adjacent elements is about 100 eV. The M shell will be excited in a specific way giving rise to simple spectra with only a few, probably two main lines. Using Si(Li) detectors the position of a line may be determined to better than 50 eV. From this point of view there should be no difficulty in determining an exact Z value. However, for colliding heavy ions and atoms an energy shift is observed for the collision-induced L radiation compared with the photon-induced characteristic L radiation.[3,12,13] Such a shift is expected for the M radiation as well. Considering that the M-shell excitation of a superheavy element seems to be quite equivalent to the L-shell excitation in systems investigated,[3,12,13] the shift will be not too large, but has to be taken into account in any Z determination. The shifts of the M lines may be studied using systems like I-U. Preliminary investigations of this system[14] substantiate the presumptions that the collision-induced M spectrum of the superheavy element may be very simple and that the shift may be not too large. Therefore, an unambiguous nuclear-charge determination seems to be possible.

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[10] The beam of recoils has to be free from strong contaminants of the primary accelerator beam in order to limit the counting rate of the x-ray detector. In any case a reduction of the high number of primary-beam particles is necessary before applying the proposed technique. This method seems suitable to determine the nuclear charge of superheavy elements with lifetimes larger than 10^{-6} sec, as discussed in an equivalent case by P. Armbruster, D. Hovestadt, H. Meister, and H. J. Specht, Nucl. Phys. 54, 586 (1964).

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Determination of the Hydrogenic-Carbon Lamb Shift via $2S_{1/2}$ Metastable Quenching

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We have measured the Lamb shift in the $n=2$ state of hydrogenic carbon-12. The result is 780.1 ± 8.0 GHz as compared with the quantum-electrodynamic calculation of 783.7 ± 0.24 GHz. The ratio of the electron-pickup cross section to the $2S_{1/2}$ metastable state to the total electron-pickup cross section has also been determined as 0.022 ± 0.010 in argon at 25 MeV.

Measurements and calculations of the hydrogenic-atom Lamb shift $\mathcal{S}$ (the $2P_{1/2}$-$2S_{1/2}$ splitting) are of fundamental importance to our understanding of quantum electrodynamics (QED) and the values of the fundamental constants. Because of the strong Z dependence of the QED series expansion[1] for $\mathcal{S}$ [terms of order $(\alpha Z)^6$ have been calculated to date] it is important to extend Lamb-shift measurements to high-Z hydrogenic atoms in order to probe the limits of validity of the calculations.

In a previous publication[2] we demonstrated the feasibility of Lamb-shift measurements for the $n=2$ state of $^{12}C^{5+}$ via metastable quenching of the $2S_{1/2}$ state, and reported preliminary results which were about 5% lower than theoretical predictions. Metastable beam intensities have been increased by an order of magnitude, new detec-