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Edited by
Bernd Crasemann

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Foreword

The 1982 International Conference on X-Ray and Atomic Inner-Shell Physics, "X-82," was held on the University of Oregon campus in Eugene on August 23-27. The Conference succeeded meetings held in Stirling, Scotland, in 1980 and in Sendai, Japan, in 1978. The present series has resulted from the coalescence of two earlier series of conferences: on x rays (from Ithaca and Leipzig in 1965 through Washington in 1976), and on inner-shell ionization (Atlanta, 1972, and Freiburg, 1976).

The five-day Conference was attended by 222 participants from 26 countries. The truly international character of the meeting, its size, the high quality of the carefully prepared presentations, and the sunny Oregon summer weather all contributed to making X-82 a very fruitful scientific gathering.

The program incorporated an even representation of x-ray physics and atomic inner-shell physics. Each day, plenary sessions were followed by two parallel sessions pertaining to the two major areas covered by the Conference. There were invited Reviews and Progress Reports, and contributed papers presented in poster sessions.

These Proceedings contain the texts of invited papers presented at the Conference. The material has been reproduced directly from camera-ready copy provided by the authors. The papers have been grouped by subjects, in somewhat different order than in the Conference program. We have attempted to make the Proceedings available as soon as possible after the Conference, and are grateful to AIP Conference Proceedings Series Editor Hugh C. Wolfe for his help in attaining this aim. G. B. Armen kindly assisted with the compilation.

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Bernd Crasemann

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INNER SHELLS AS A LINK BETWEEN ATOMIC AND NUCLEAR PHYSICS

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ABSTRACT

Nuclear decay and reaction processes generally take place in neutral or partially ionized atoms. The effects of static nuclear properties (size, shape, moments) on atomic spectra are well known, as are electronic transitions accompanying nuclear transitions, e.g. K capture and internal conversion. Excitation or ionization of initially filled inner shells, really or virtually, may modify nuclear Q values, will require correction to measured beta-decay endpoint energies, and can permit the use of inner-shell transitions in the determination of nuclear widths Improvements in resolution continue to enhance the importance of these effects. There is also beginning to appear experimental evidence of the dynamical effects of atomic electrons on the course of nuclear reactions.

The dynamics of a nuclear reaction, which influences and may in turn be influenced by atomic electrons in inner shells, offers instructive examples of the interplay between strong and electromagnetic interactions and raises interesting questions about coherence properties of particle beams. A variety of significantly different collision regimes, depending on the atomic numbers of the collision partners and the collision velocity, will be discussed and illustrated.

INTRODUCTION

The border between atomic collision and nuclear reaction physics is at present a developing region, with a number of scattered successes to its credit and a future potential that has yet to be fully assessed. This lecture is intended to provide a survey of some of the major accomplishments and of the basic concepts underlying the experiments that have been carried out so far.

The reasons for the recent upsurge of interest in collision processes at the interface of atomic and nuclear physics are easily appreciated: Particle accelerators in the MeV range, especially single-ended and tandem Van de Graaff accelerators, have found increasing use for experiments involving atomic excitation and ionization; nuclear physicists are turning more and more toward such experiments, repaying a debt to atomic physics that was incurred fifty years ago when, following the discovery of the neutron, many experimental atomic physicists became nuclear physicists almost overnight; the energy resolution of beams and detectors in accelerator-related atomic and nuclear physics is now approaching

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the eV level, making atomic energy differences discernible in nuclear reactions; and - last but not least - theoretical atomic physicists are prepared to deal with the complications that must be faced when the relatively weak and long-range atomic and the stronger short-range nuclear interactions are simultaneously considered in a many-body problem.

Inner shells of atoms constitute a natural bridge between nuclear interactions, which correspond to energies in the MeV and cross sections in the millibarn to barn range, and the bulk of atomic electrons with interaction energies in the eV and cross sections in the 10^{-16} cm^2 range. Although the cross sections for atomic inner-shell processes are generally far smaller than this - but still very large in comparison with nuclear cross sections - the energy transfers and transition rates involving inner-shell electrons are often more nearly comparable to characteristic nuclear quantities, accounting for the role that inner shell electrons play in the processes which are the subject of this lecture. In the interest of simplicity, the symbol K will, in this paper, be used as a generic subscript denoting any inner shell.

NUCLEAR REACTION WIDTHS

The issues are conveniently introduced by a brief review of an imaginative idea put forward by Gugelot[1] for measuring the width, Γ_n, of a compound nuclear resonance, or its reciprocal, the time $\tau(\text{sec}) = 0.658\times10^{-15}/\Gamma_n$, by the use of an "atomic clock." Assuming that in the ("in" part of the) collision of a nuclear projectile Z_1 with a target nucleus Z_2, which leads to the formation of a compound nucleus Z_1+Z_2, an inner-shell electron vacancy is formed with known probability P_K^{in}, the nuclear reaction width Γ_n can be compared with the width or decay rate, Γ_K, of the excited atomic state, if the two rates are of similar magnitude. This method relies on the possibility of experimentally identifying the decay of the atomic vacancy state by the decay energy characteristic of the transient "united" atom (Z_1+Z_2) rather than the target atom (Z_2), and it assumes that the two decay branches, atomic and nuclear, for a compound nuclear state with a vacancy in its atomic K shell are independent of each other. Several recent experiments which have used this technique to determine, by coincidence measurements of x rays (or Auger electrons) from the united atom and purely nuclear scattering, are reviewed in this volume by W. Meyerhof.[2] The collision is schematically depicted in Fig.1. If $N_{\mathbf{p}'}$ is the "singles" rate for the nuclear reaction and $N_{\mathbf{p}',K(Z_1+Z_2)}$ the coincidence rate, then the relation between nuclear and atomic widths is given by

$$\frac{N_{\mathbf{p}',K(Z_1+Z_2)}}{N_{\mathbf{p}'}} = P_K^{in}\ \frac{\Gamma_{K(Z_1+Z_2)}}{\Gamma_{K(Z_1+Z_2)} + \Gamma_n} \qquad (1)$$

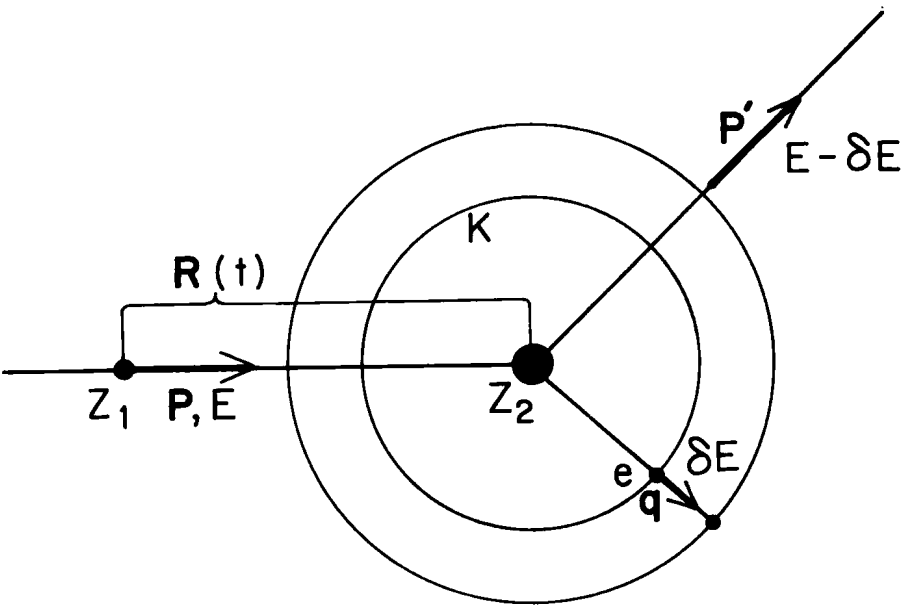

Fig.1. Schematic sketch indicating a nuclear collision with near-zero impact parameter between projectile Z_1, with momentum **P** and energy E, and target Z_2. Straight-line trajectories are assumed, and momentum **q** and energy δE are transferred to an atomic K-shell electron. The nuclear ejectile has final momentum **P'** and energy E-δE. The internuclear vector is **R**(t).

ATOMIC AND NUCLEAR ENERGY AND TIME SCALES

In judging the usefulness of equation (1) for a practical determination of nuclear widths, one must bear in mind that the atomic width Γ_K, which is of order 10^8 sec^{-1} for hydrogen, is proportional to Z^4, whereas Γ_n depends on the mass number A of the nucleus and its excitation energy, E_n, roughly as $\exp[-(A/E_n)^{1/2}]$, and P_K^{in} has values between 10^{-5} and 10^{-1}, depending on the strength of the vacancy-producing atomic interactions. In practice, it has been possible with this method to verify that compound nuclear states in medium-A nuclei at excitation energies of 10-15 MeV have $\Gamma_n \sim 10$ eV. In Fig.2, the approximate range of atomic and nuclear widths, to which this comparison method may be applicable, has been indicated.[3] Since the overlap is limited, Γ_K can serve as an atomic yardstick for Γ_n only under rather favorable circumstances.

Fig.2 also shows the approximate ranges of other relevant atomic and nuclear energy parameters (or their reciprocal time equivalents). These include typical nuclear excitation energies, E_n, atomic collision times T_{coll}, and atomic excitation energies ω_K,

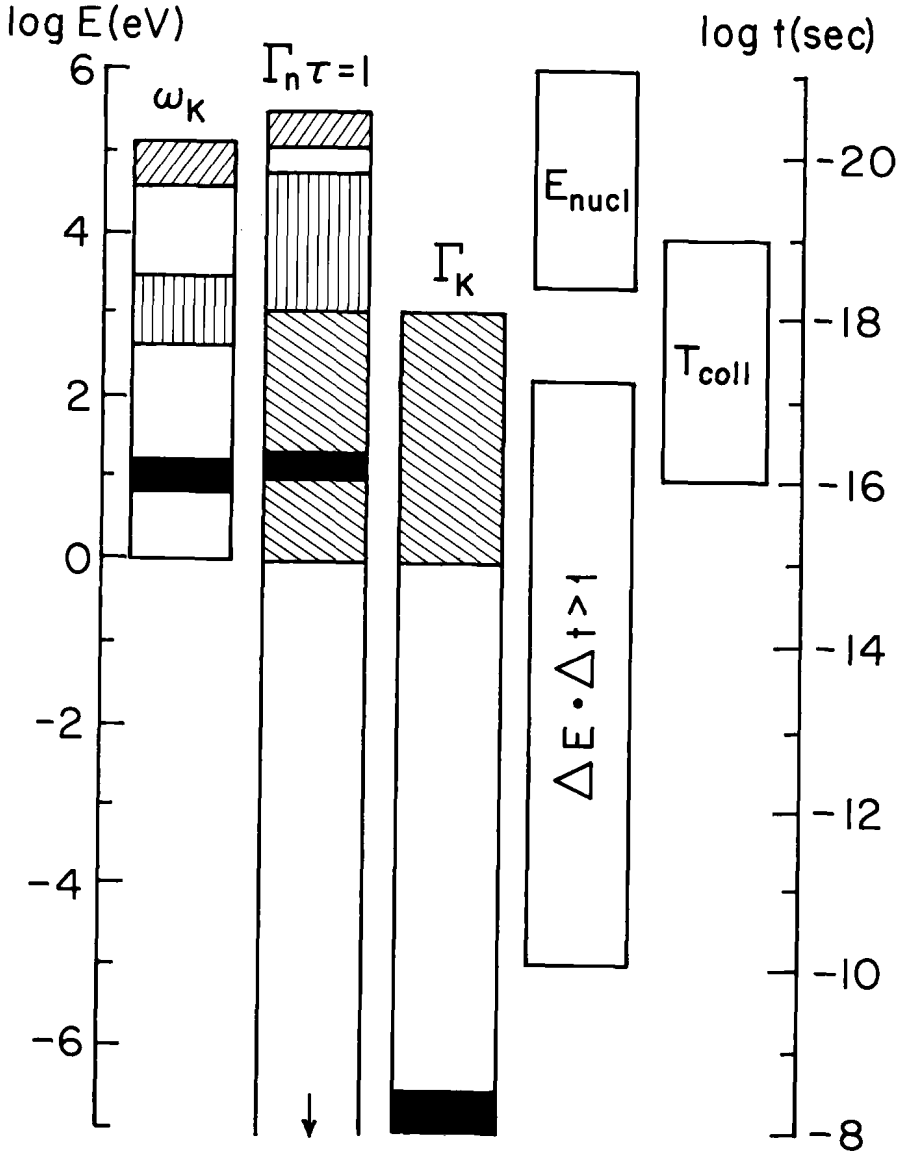

Fig.2. Relation between characteristic energies and times in nuclear reactions and ion-atom collisions. The symbols are explained in the text. The four shaded regions on the Γ_n column refer, starting from the bottom, respectively to the Gugelot-type experiments (Refs. 1, 2), Staub's experiment (Ref. 13), Blair's experiment (Ref. 7), and the proposed heavy-ion experiments (Ref. 5). The diagram is adapted from Ref. 3.

which are in the eV range for hydrogen and proportional to Z^2. Also indicated are some crudely estimated limits for the energy spread, ΔE, and time resolution, Δt, of the wave packets which describe the projectile motion in the usual experimental situation, but it should be remembered that usually for such wave packets $\Delta E \times \Delta t$ is much greater than unity. It is interesting to speculate on the possibility of observing physical effects which require a more detailed understanding of the structure of these wave packets.[4]

EFFECTS OF NUCLEAR REACTIONS ON ATOMIC COLLISIONS

If a nuclear reaction is initiated in a particular collision, the impact parameter on the atomic scale is obviously very small, and it is usually (except for very high-Z collision partners) permissible to assume that $b = 0$. The occurrence of the nuclear reaction signals that an atomic head-on collision has taken place!

For purposes of orientation, it is useful to think of a narrow compound nuclear resonance state as quasistationary with a lifetime $\tau \sim \Gamma$ and to describe the atomic collision by a semiclassical treatment. The prescribed classical orbital motion of the heavy collision partners is responsible for the time-dependent perturbations which cause transitions of the atomic electrons, and it is reasonable to inquire how the atomic transition amplitudes are affected by the time delay introduced into the heavy-particle motion by the nuclear reaction. The atomic target electrons are subject to the time-varying Coulomb fields of the projectile and the recoiling target nucleus. In first-order perturbation theory, the amplitude $a_n(+\infty)$ for an atomic transition to an excited (discrete or contiuum) state n from an initial ($t=-\infty$) state K is, except for some irrelevant constants, given by

$$a_n(+\infty) \sim \int V(\mathbf{q})\, F_{nK}(\mathbf{q})\, d^3q \int_{-\infty}^{+\infty} \exp\{i[\omega_{nK}t - \mathbf{q}\cdot\mathbf{R}(t)]\}\, dt \qquad (2)$$

where $V(\mathbf{q})$ represents the Fourier transform of the perturbation and $F_{nK}(\mathbf{q})$ is an inelastic atomic form factor. In the high-velocity limit, the collision is impulsive, and $\mathbf{q}$ is the momentum transfer from the heavy collision partners to the electron. Most important for the present discussion is the classical orbital Fourier integral,

$$I(\omega_{nK},\mathbf{q}) = \int_{-\infty}^{+\infty} \exp\{i[\omega_{nK}t - \mathbf{q}\cdot\mathbf{R}(t)]\}\, dt \qquad (3)$$

The orbital integral depends on the atomic energy transfer ω_{nK} and the moving position vector $\mathbf{R}(t)$ which describes the time variation of the nuclear configuration. If there is a time delay τ, as in the case of a compound nuclear reaction, this will affect the t-dependence of $\mathbf{R}(t)$. In the particular case of charged-particle capture or decay, only a "half-collision" occurs, and $\mathbf{R}(t)$ is set equal to zero after or before the nuclear process.

These considerations make it evident that atomic transition amplitudes can be significantly influenced by the time delay which a nuclear reaction between so-called "sticky" nuclei introduces into the Fourier integral of equation (3). The observation of such effects on the amplitudes implies the use of the atomic transition energies ω_K, rather than the widths Γ_K, as yardstick for the nuclear width parameter to be determined. Fig.2 shows that this approach to the problem extends considerably the potential range of values of Γ_n that is accessible to determination by atomic collision techniques.

For example, it has been suggested that oscillations in the energy spectrum of the emitted delta electrons might convey information about compound nuclear delay times in heavy-ion reactions.[5] Similar oscillations, with a period comparable to Γ_n, in the energy spectrum of positrons from heavy-ion collisions are currently under investigation.[6] In these instances, the dependence of the transition amplitude (2) on the energy of the final state of ionization of the atom is studied.

Blair et al[7] have shown that one may also study the dependence of the transition amplitude for atomic inner-shell vacancy production in the course of a nuclear resonance reaction on the energy of the incident particle. A consistent analysis in terms of stationary states of total energy E shows that the amplitude for K-shell excitation to a final atomic state n can be expressed as[8]

$$T_{nK} \sim \frac{1}{E-\delta E-E_r+i(\Gamma_n/2)} \; a_{nK}^{in} + a_{nK}^{out} \; \frac{1}{E-E_r+i(\Gamma_n/2)} \qquad (4)$$

The structure of this expression is suggestive: The first term describes atomic excitation (or ionization) on the "in" leg of the reaction, followed by the nuclear resonance scattering, with the incident energy reduced by the energy transfer δE to the atom, and the second term corresponds to atomic excitation on the "out"leg, following the nuclear reaction. The details of the pioneering proton-x ray coincidence experiment by Blair et al[7] verifying the interference between the two terms of equation (4) are reviewed in Meyerhof's lecture in these Proceedings.[2]

THE EFFECTS OF ATOMIC EXCITATION ON NUCLEAR REACTIONS

Since nuclear reaction experiments usually involve ions and atoms, rather than bare nuclei, one expects in nuclear reaction experiments to observe effects caused by real or virtual excitations of the atomic electrons, provided that the experimental resolution is good enough. Many years ago, following the prediction by Lewis[9], evidence of energy transfer to atoms was observed in the thick-target yields of certain narrow nuclear resonances produced by incident charged particles, such as the familiar $^{27}Al(p,\gamma)^{28}Si$ resonance at 992 keV.[10] This so-called "Lewis effect" consists of

slight oscillations of the thick-target yield, above the threshold and the sharp initial rise, as a function of the energy of the incident projectile. The oscillations occur because the reaction yield is lowered when the incident projectile energy exceeds the resonance energy by an amount that is less than (a multiple of) the minimum energy lost by the charged particle in inelastic collisions to the atoms of the target medium. Thus, the Lewis effect is a manifestation of the quantum nature of the atomic energy transfers during the passage of the projectile through the target, as it slows down until it reaches the resonance energy.

The Lewis effect is distinctly different, however, from the process considered in this lecture, because in the case of the Lewis effect the atomic energy losses are mostly due to so-called "distant" collisions at large impact parameters to outer electrons, and these collisions do not occur in the same atom as the nuclear reaction. When Christy[11] inquired whether atomic excitation effects had to be taken into account in the experimental determination of nuclear reaction Q values [which are equivalent to the change in the total masses of the reactants, $Q=(M_{before}-M_{after})c^2$], he concluded that such effects would be difficult to notice unless the resolution were to reach the 100 eV level. Contemporary accelerator beam and particle detection technology has brought atomic and nuclear collision experiments into this range.

For example, precision measurements of endpoints in beta ray spectra are of great current interest (e.g. for determining limits on the neutrino mass). An accurate method for obtaining the endpoint energies of positron spectra consists of measuring the Q values of the inverse nuclear transformations, such as (p,n) and (^{3}He,^{3}H) reactions, which tend to be endoergic ($Q<0$) and therefore have a threshold energy. In such nuclear reactions, several mechanisms can be invoked to describe atomic excitation, although the underlying forces are of course the electrostatic particle interactions in all instances. The energy transfer can be attributed to Coulomb excitation of the atomic electrons by the charged projectile as well as by the recoiling target nucleus, but the excitation can also be considered as arising from the rather abrupt change in nuclear charge and the ensuing shake-off and shake-up processes. In some common examples among light nuclei, these atomic effects require cumulative corrections of nuclear Q values by amounts of the order of 100-300 eV.[12]

Since a compound nuclear state is in reality a quasistationary state of an entire compound nuclear atom, one expects that in a nuclear collision it might be possible to observe replicas of very sharp nuclear resonances, displaced in energy by the atomic excitation energies. A very difficult early heroic experiment by Staub et al[13] was the first attempt to exhibit such atomic replicas, or satellites, or echoes[14], of a very narrow nuclear resonance. The particular reaction chosen was resonant elastic scattering of alpha particles on ^{4}He in the neighborhood of 184 keV. For this resonance in the ^{4}He(α,α)^{4}He reaction, the width ($\Gamma_n\sim$15 eV) is comparable to and generally smaller than the atomic transition energies $\omega_K\sim$100 eV

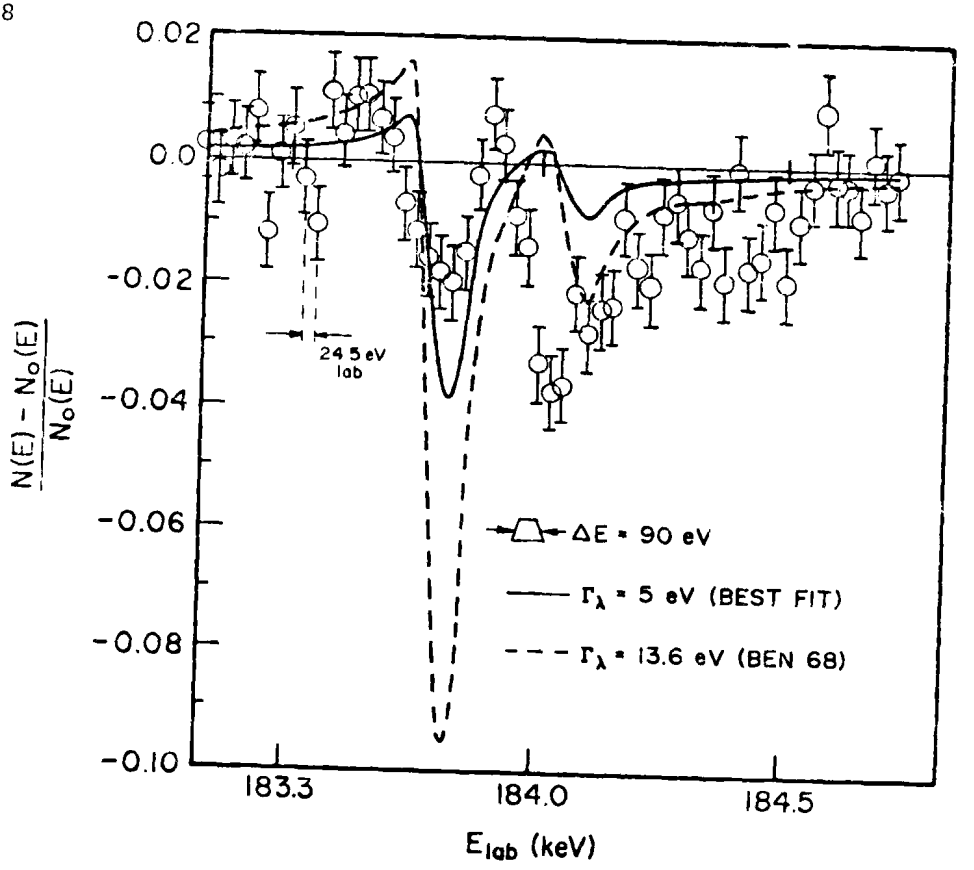

Fig.3. Relative yield of elastic scattering of α particles from ^{4}He near the resonance at 184 keV. The yield N(E) is plotted relative to the yield $N_o(E)$ from Rutherford scattering and shows anomalies attributed to atomic excitation. The data and the dotted theoretical curve are from Ref.13. The solid curve is a recent analysis (Ref. 15).

(in the compound ion $^8Be^+$). The atomic excitations to the first few levels in Be show up as anomalies in the nuclear excitation function. These anomalies are displayed in Fig.3.[13,15]

Quite recently, Duinker et al[16] have found indications of a weak K-shell excitation satellite accompanying the same narrow $^{27}Al(p,\gamma)^{28}Si$ resonance at 992 keV that was mentioned above in the discussion of the Lewis effect. The resonance is narrow (about 100 eV) and the K-shell binding energy is substantially greater (1.6 keV), providing favorable conditions for the observation of such a satellite, but the experimental resolution is not good enough for a clean separation of the two lines. From the results, shown in Fig.4, Duinker estimated $P_K^{in} \sim 10^{-2}$.