Brief Reports

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Reanalysis of nuclear level widths from particle-x-ray coincidence experiments

Per Amund Amundsen
Physik Department T30, Technische Universität München, D-8046 Garching, West Germany

Martin Dost
Institut für Kernphysik, Universität Köln, D-5000 Köln 41, West Germany

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Using new theoretical values for the ionization probabilities during the incoming part of a collision, we have reanalyzed the mean nuclear level widths obtained by the particle-x-ray coincidence method. We find that the deduced level widths are substantially reduced.

At present, two experimental methods are used for obtaining mean nuclear level widths, Γ_N, below 100 eV, namely, the crystal blocking technique[1] and the particle-x-ray coincidence method, which can be used both for levels populated in electron capture[2] and in particle induced reactions.[3-5] Of these methods, the latter is, in principle, the more versatile, being neither dependent on single crystals, nor on the existence of particular β-delayed transitions. It does, however, require knowledge of two atomic parameters, namely, the total decay width Γ_A of an atomic (mostly K-shell) vacancy, and the probability, $P_{1/2}$, of creating this vacancy in a collision prior to the formation of a compound nuclear system (the ionization probability in "half a collision"). While Γ_A is well known, the only value available for $P_{1/2}$ has been the calculation by Ciocchetti and Molinari,[6] based on nonrelativistic hydrogenic wave functions and certain other simplifying assumptions. Recently, however, the first experimental determination of $P_{1/2}$ has been reported.[7] The result, $P_{1/2}=(0.90\pm0.15)10^{-4}$ for 10 MeV protons impinging on ^{138}Ba, is in excellent agreement with a new improved theoretical value ($P_{1/2}=0.89\times10^{-4}$).[8] These results imply considerable corrections to the values of Γ_N previously reported,[3-5] and in this Brief Report we present a reanalysis of the experiments based upon the new calculations of $P_{1/2}$.

The principle of the coincidence method is simple. One considers collisions where the projectile simultaneously excites both the nucleus and the atom, the latter by creating an inner-shell vacancy, and monitors if the atomic vacancy decays by an x-ray characteristic of the compound nucleus (united atom, UA) or of the daughter nucleus (separated atom, SA). In the former case, the vacancy has decayed before the nucleus, in the latter case after it, so that in the absence of other sources of x rays, and assuming that the SA and UA fluorescence yields are the same, the ratio Γ_N/Γ_A would just be the ratio of the SA to UA x-ray intensities (McVoy, Tang, and Weidenmüller[9] have shown that this is true independently of assumptions about the nuclear level structure). In order to circumvent the problem that there are other sources of SA x rays, one instead assumes $P_{1/2}$ to be known, and monitors (in coincidence) the number of vacancies per nuclear reaction which decay in the UA, P^{UA}. One then has[3-5]

$$\Gamma_N/\Gamma_A=RP(\Theta)/P^{\mathrm{UA}}-1,\quad R=P_{1/2}/P(\Theta)\ , \tag{1}$$

where $P(\Theta)$ is the ionization probability in an elastic collision at the scattering angle Θ, which may be determined in the same experiment. The ratio R is introduced in order to cancel systematic errors in $P_{1/2}$. In the actual experimental situations there may be further corrections to Eq. (1), but these are irrelevant for the following analysis.

The theory for the calculation of $P_{1/2}$ is the same as for the time-reversed process, ionization during particle decay,[10] and is based upon a first order distorted wave approach. However, since we are interested mainly in collisions at or above the Coulomb barrier, the theory simplifies considerably,[8] and, in fact, becomes identical to the semiclassical approximation of Ciocchetti and Molinari,[6] where the projectile is assumed to follow a classical constant-velocity path until it hits the nucleus. If Z_T is the target charge, Z_P the projectile charge, and $|n;Z\rangle$ an atomic wave function for an atom of charge Z, we get (atomic units, $e=\hbar=m_e=1$, are used throughout)

$$\begin{aligned} P_{1/2}&=|a_{fi}|^2\ ,\\ a_{fi}&=\langle f;Z_T+Z_P|i;Z_T\rangle\\ &\quad-i\int_{-\infty}^{0}dt\,e^{i\Delta Et}\langle f;Z_T+Z_P|(V_P+V_R)|i;Z_T\rangle\ , \end{aligned} \tag{2}$$

where ΔE is the energy transferred to the electron, V_P the projectile Coulomb potential, and V_R the recoil "potential" induced because the nucleus is being accelerated during the collision, while the atomic wave functions refer to an inertial system.[11] To first order in Z_P/Z_T the overlap in Eq. (2) can be rewritten ($f\neq i$)

$$\langle f;Z_T+Z_P|i;Z_T\rangle=\langle f;Z_T|\Delta V|i;Z_T\rangle/\Delta E\ , \tag{3}$$

where ΔV is the difference in the atomic potentials between the SA and UA. To the same order, we may neglect the difference between the SA and the UA wave functions in the t integral of Eq. (2), and the evaluation of $P_{1/2}$ then becomes identical to the one outlined in Ref. 8, to which we refer for further details. The final result for R (for $\Theta = 0$) can be written

$$R = \frac{\sum_f \sum_l (P_l^{fi2} + Q_l^{fi2})}{4 \sum_f \sum_l P_l^{fi2}} , \tag{4}$$

where, except for a trivial phase, P_l^{fi} and Q_l^{fi} are the real and imaginary parts of the 2^l-pole component of a_{fi} of Eq. (2). The phase is chosen to make the real part only contribute to forward scattering at zero (i.e., very small) impact parameters. The overlap and recoil terms are included in Q_0^{fi2} and Q_1^{fi2}, respectively.[8]

We have calculated R for all systems known to us where Γ_N has been determined by the coincidence method. We have used the code described in Ref. 8, with relativistic electron wave functions derived from an optimized effective atomic potential.[12] The purely numerical accuracy of the calculations is better than 2%. The code reproduces measured[7,13] K-shell ionization probabilities at near zero impact parameters to within about 20% in the collision energy range under consideration, and since errors partly cancel in calculating R, the absolute accuracy of this quantity should be at least as good.

From Eq. (4) one sees that R can, in principle, take on any value larger than $\frac{1}{4}$, depending upon the relative importance of the real and imaginary parts of the ionization amplitudes. A result of Ref. 8 is that the ratios Q_l^{fi2}/P_l^{fi2} depend strongly both on ΔE and on the collision energy, E_p. In Fig. 1 we illustrate the consequence of this for the value of R in K-shell ionization of ^{112}Sn by proton impact. At low energies, where $l = 0$ is almost completely dominant, R reaches a value close to the theoretical minimum of $\frac{1}{4}$, since $Q_0^{fi2} << P_0^{fi2}$. At very low E_p, the imaginary part increases in importance, as do dipole transitions,[11] but in this region (below about 2 MeV in the Sn case) the neglect of the Coulomb distortion of the projectile trajectory is no longer warranted. The main reason for the slowly rising value of R at high energies is the increasing importance of dipole transitions, for which the difference in magnitude between the real and the imaginary parts of the amplitude is much less than in the monopole case. We find that R continues to rise at energies above those shown in the figure, considerably exceeding 1 in near-relativistic collisions. In this limit the imaginary amplitude dominates the real one even for monopole transitions. We notice that the classical value $R = \frac{1}{2}$, which has been used in previous analyses, does not seem to have any special significance in the quantal case. The results shown in Fig. 1 remain qualitatively correct for any target, when interpreted in terms of the scaled energy E_p/Z_T^2. For cases of current experimental interest, $R = 0.28$–0.30 will be appropriate.

We illustrate the consequences of the improved knowledge of R by reanalyzing the x-ray data from elastic and inelastic proton scattering on ^{112}Sn (Refs. 3 and 5) and ^{106}Cd (Ref. 4) in terms of the average compound nuclear level width at high excitation energy, E^*. The experimental intensities needed to obtain $P(\Theta)/P^{UA}$ in Eq. (1) are taken from Ref. 5 for the ^{112}Sn measurement, and from Ref. 4 for ^{106}Cd (see Ref. 14). In Table I we compare the resulting values of the ratio Γ_N/Γ_A with those obtained in the original publications, where the classical value $R = 0.5$ was used. The improved values of R change Γ_N/Γ_A by a factor of 3 for ^{113}Sb and by factors 5–9 for ^{107}In. We also give the corresponding values of Γ_N. For ^{113}Sb, they are based upon a K-vacancy decay width $\Gamma_A = 9.16$ eV from the recent compilation of Krause and Oliver,[15] which was also used in the original analysis.[5] In the case of ^{107}In, we give for comparison values of Γ_N derived from both using $\Gamma_A = 7.91$ eV, from Ref. 15, and $\Gamma_A = 10.8$ eV, employed in the original analysis of these measurements.[4] As is evident from Table I, substantial changes in the deduced values for Γ_N are obtained when the assumption $R = 0.5$ is replaced by a realistic calculation. Given that the intensities reported in the compound nuclear x-ray experiments[3–5] are correct, we believe that the new results for Γ_N are realistic, as the value $R = 0.28$ used in the present reanalysis is consistent with the measured value of $P_{1/2}$ reported in Ref. 7 for proton scattering on ^{138}Ba. The new values of Γ_N continue to fit into the general trend of nuclear level widths in the 10^{-1}–10^3 eV range compiled in Ref. 5, the ^{107}In widths be-

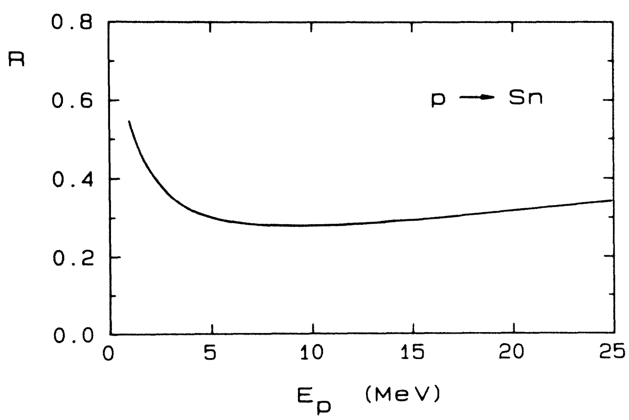

FIG. 1. Relative ionization probability during the incoming part of a collision, $R = P_{1/2}/P(0°)$, as a function of collision energy E_p for proton impact on ^{112}Sn.

TABLE I. Derived nuclear level widths $\Gamma_N(E^*)$ of ^{113}Sb and ^{107}In.

Nucleus	E^* (MeV)	R	Γ_N/Γ_A	Γ_N (eV)
^{113}Sb	15	0.50	2.09	19.1[a]
		0.28	0.72	6.6[a]
	13	0.50	1.81	16.6[a]
		0.28	0.57	5.2[a]
^{107}In	15.6	0.50	1.26	10.0[b] (13.6[c])
		0.28	0.26	2.1[b] (2.8[c])
	13.6	0.50	0.98	7.8[b] (10.5[c])
		0.28	0.11	0.9[b] (1.2[c])

[a] $\Gamma_A = 9.16$ eV from Ref. 15.
[b] $\Gamma_A = 7.91$ eV from Ref. 15.
[c] $\Gamma_A = 10.8$ eV from Ref. 4 (original analysis).

ing somewhat narrower than the trend indicated by the bulk of the data.

We conclude that a major theoretical uncertainty in the interpretation of compound-x-ray-particle coincidence measurements has been removed, and that reasonably accurate nuclear level width determinations in the electronvolts range by this method are feasible.

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