Lifetime of the $2\,^3P_0$ state of He-like ^{197}Au

S. Toleikis,[1,*] B. Manil,[2] E. Berdermann,[1] H. F. Beyer,[1] F. Bosch,[1] M. Czanta,[1] R. W. Dunford,[3] A. Gumberidze,[1] P. Indelicato,[4] C. Kozhuharov,[1] D. Liesen,[1] X. Ma,[1] R. Marrus,[5] P. H. Mokler,[1] D. Schneider,[6] A. Simionovici,[7] Z. Stachura,[8] T. Stöhlker,[1] A. Warczak,[9] and Y. Zou[10]

[1]*Gesellschaft für Schwerionenforschung (GSI), Planckstrasse 1, D-64291 Darmstadt, Germany*
[2]*CIRIL-GANIL, rue Claude Bloch, F-14070 Caen Cedex 5, France*
[3]*Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Illinois 60439, USA*
[4]*École Normale Supérieure et Université Pierre et Marie Curie, 4 place Jussieu, F-75252 Paris Cedex 5, France*
[5]*Department of Physics, University of California, Berkeley, California 94720-7300, USA*
[6]*Lawrence Livermore National Laboratory, 7000 East Avenue, Livermore, California 94550-9234, USA*
[7]*European Synchrotron Radiation Facility (ERSF), Boîte Postale 220, F-38043 Grenoble Cedex, France*
[8]*Institute of Nuclear Physics, ulnicka Radzikowskiego 152, 31-342 Kraków, Poland*
[9]*Institute of Physics, ulnicka Reymonta 4, 30-059 Kraków, Poland*
[10]*Max-Planck-Institute für Kernphysik, Saupfercheckweg 1, D-69117 Heidelberg, Germany*

(Received 4 November 2003; published 20 February 2004)

An experiment has been performed at the Gesellschaft für Schwerionenforschung accelerator facility using a beam-foil time-of-flight technique with a newly developed chemical vapor deposition diamond particle detector to measure the lifetime of the $2\,^3P_0$ state, $\tau(2\,^3P_0)$, of the two-electron ion $^{197}Au^{77+}$ (He-like gold) with the result $\tau(2\,^3P_0)=22.16(0.81)$ ps. The mechanism for the decay of this state is by a hyperfine-induced radiative transition to the $1\,^1S_0$ ground state (hyperfine quenching). The lifetime is therefore determined by a number of fundamental atomic and nuclear parameters not normally involved in radiative decay of allowed transitions. The experimental result is compared to several theoretical calculations.

DOI: 10.1103/PhysRevA.69.022507 PACS number(s): 32.10.Fn, 21.10.Ky, 32.30.Rj, 32.70.Cs

I. INTRODUCTION

The radiative decay of the $2\,^3P_0$ state of He-like ions with nonzero nuclear spin is mainly to the $1\,^1S_0$ ground state and occurs by a rare mechanism in atomic physics often referred to as hyperfine quenching [1]. Normally, this $J=0\rightarrow J=0$ transition is rigorously forbidden by the angular-momentum selection rules, and in ions with zero nuclear spin this state will decay by a fully allowed electric dipole transition to the $2\,^3S_1$ state. However, in ions with nonzero nuclear spin the hyperfine interaction will mix a small amount of the $2\,^3P_1$ state into the $2\,^3P_0$ wave function. Because the decay rate of the $2\,^3P_1$ state to the ground state $1\,^1S_0$ is relatively large, the radiative decay of the mixed state is dominated by the hyperfine-quenching mode (see Fig. 1).

The calculation of the decay rate of the mixed state to the ground state involves several atomic parameters, including the decay rate of the $2\,^3P_1$ state and the $2\,^3P_0$-$2\,^3P_1$ fine-structure splitting. The fine-structure splitting is of particular interest, because it is determined by the electron-electron interaction and the two-electron ion is the simplest atomic system in which it can be studied. Because of the rapid scaling of the relativistic part of this interaction with atomic number Z, measurements at high Z provide a particularly sensitive test of the relativistic theory. Calculations of the fine-structure generally include the effects of relativity by a perturbation expansion in the parameter $(Z\alpha)^2$. The problems associated with this approach for two-electron ions at high Z are illustrated by the fact that in helium $(Z=2)$ the calculations [2–4] are accurate at the ppm level whereas the most elaborate calculations at high Z [5–9] claim accuracy of only a few percent. Accurate experimental measurements performed at high Z can therefore provide benchmark values for theoretical work. In addition to the fine structure and the $2\,^3P_1$ decay rate, the lifetime of the $2\,^3P_0$ state depends also on an exotic E1M1 two-photon decay mode. While this decay rate is extremely small at low Z, the rate scales approximately as Z^{12} and contributes about 2% to the total rate at $Z=79$ [9,10]. Thus accurate high-Z measurements of the $2\,^3P_0$ lifetime will be also sensitive to this two-photon decay mode.

Finally, the lifetime depends importantly on nuclear parameters. In the case of ^{197}Au, the situation is particularly interesting for two reasons. First, there exist in the literature two highly precise, but discrepant values for the nuclear magnetic moment [11]. In units of the nuclear magneton, these are $\mu_I=0.145\,746(9)$, experimental method is atomic beam magnetic resonance (original work, Ref. [12]), and $\mu_I=0.148\,158(8)$, experimental method is nuclear magnetic resonance (original work, Ref. [13]). This difference of about 1.7% leads to a difference in the hyperfine-quenched lifetime of about 2.8% because of the quadratic dependence on the nuclear magnetic moment [14]. Second, because of the high value of Z, the decay rate is sensitive to the distribution of nuclear magnetism (Bohr-Weisskopf effect). It has been estimated [8] that at $Z=79$ this effect will contribute 3% to the decay rate. Therefore lifetime measurements of hyperfine-quenched atomic states in the high-Z range offer an alternative method to investigate these nuclear properties.

With respect to fine-structure measurements, we note that direct measurements of the $2\,^3P_0$-$2\,^3P_1$ fine-structure split-

*Electronic address: s.toleikis@gsi.de

 ©2004 The American Physical Society

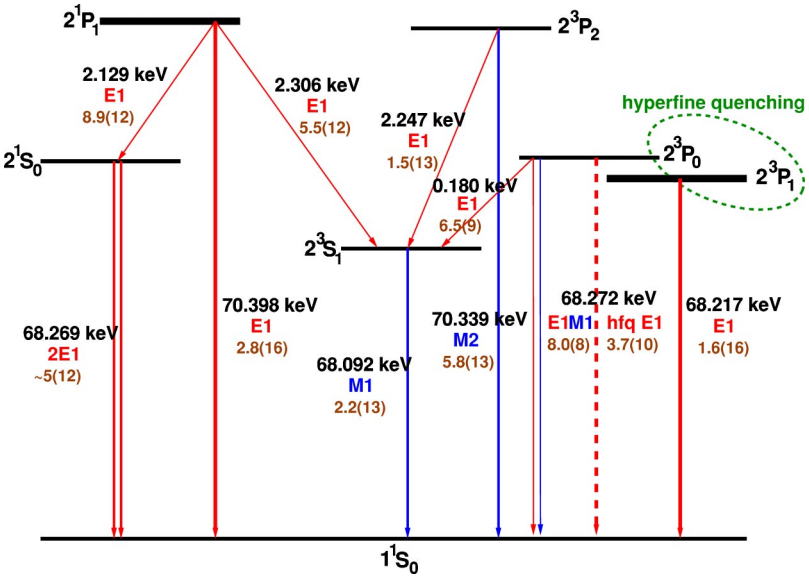

FIG. 1. Level scheme of He-like gold with transition energies, decay modes, and transition probabilities indicated. Numbers are taken from Refs. [5–9]. The transition probabilities are in 1/s with numbers in brackets indicating powers of 10.

ting using radio-frequency spectroscopy or laser spectroscopy have been performed in He [15], Li^+ [16], and F^{7+} [17]. However, extension of direct methods to higher Z is experimentally not feasible and indirect methods must be used. Measurements using UV and x-ray spectroscopy in which the fine structure is inferred as the difference between measured levels have been performed and summarized in review articles by Martin [18] and Desesquelles [19]. In the experiment we report here, the fine structure can be inferred from the measured decay rate of the hyperfine-quenched decay of the $2\,^3P_0$ state. The use of this method to make precise measurements of the fine-structure splitting was first demonstrated in Ag^{45+} [20,21] and subsequently applied to Ni^{26+} [22] and Gd^{62+} [23]. The measurement described in this paper extends the method to the highest Z ion so far investigated, Au^{77+}.

II. EXPERIMENT

The experiment has been performed at the Gesellschaft für Schwerionenforschung (GSI) heavy-ion synchrotron facility located in Darmstadt, Germany. We have used the same basic beam-foil time-of-flight technique employed in previous experiments [21,23]. A schematic of the setup is shown in Fig. 2. The 200 MeV/u gold ion beam emerging from the SIS accelerator is passed through an Al stripper foil of thickness 46.3 mg/cm^2. This stripper foil removes the residual electrons, producing an appreciable fraction of H-like gold which is separated from unwanted charge states with a dipole magnet and collimators. The H-like beam emerging from the dipole then passes through a Ni target foil of thickness 1.5 mg/cm^2 thereby producing excited He-like ions by single-electron capture. Our estimation is that about 1% of the He-like ions are in the $2\,^3P_0$ state of interest.

The velocity of the ions is determined by their circulation frequency in the heavy-ion synchrotron SIS. The final velocity of the ions has to be corrected for energy losses in the stripper and in the target foil. These energy losses have been calculated with a computer code called ATIMA, which was developed at GSI [24,25]. Table I summarizes all contributions which lead to the final energy of the gold ions of $E_{ion} = 194.770(0.520)$ MeV/u.

A pair of Ge(i) x-ray detectors are located outside the vacuum chamber on opposite sides of the ion beam behind the Ni target foil. The x rays emitted by the decay of the excited He-like ions are viewed by the detectors through a

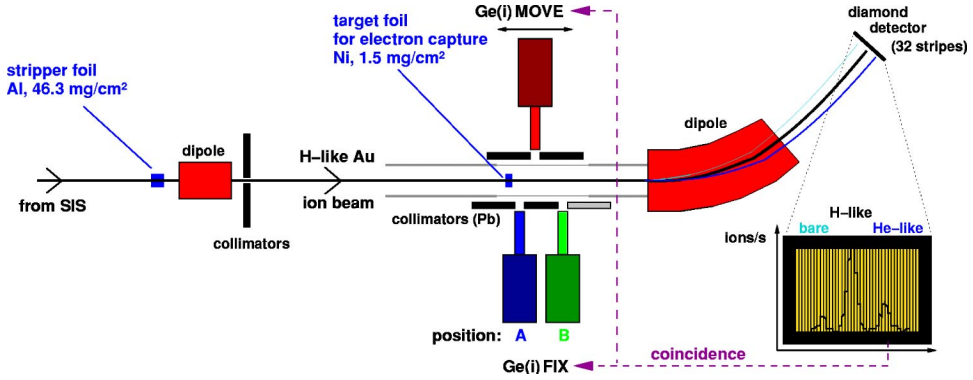

FIG. 2. Schematic of the experimental setup. For a better overview the two quadrupoles of the charge-state spectrometer are not shown.

TABLE I. Velocity determination of the gold ions. The energy values are given in (MeV/u).

Extraction energy (SIS)	200.0	± 0.5
Energy loss in Al stripper[a]	5.079	± 0.520
Energy straggling[a]		± 0.508
Target inhomogeneity		± 0.051
Theory dE/dx[b]		± 0.102
Energy loss in Ni target[a]	0.151	± 0.520
Energy straggling[a]		± 0.520
Target inhomogeneity		± 0.001
Theory dE/dx[b]		± 0.003
Final energy	194.770	± 0.520
β	0.5621	± 0.0006
γ	1.2091	± 0.0006

[a]Calculated with ATIMA based on Refs. [24,25].
[b]Uncertainty $\leqslant 2\%$ [25].

pair of collimators. These collimators prevent the detectors from viewing prompt x rays emitted by the beam at the target. The position of one detector is fixed while the other detector is movable. A precision translator is used which establishes the change in the position of the detector with an accuracy $\leqslant 1$ μm. The raw data are obtained by varying the distance between the target foil and the movable detector and by measuring the ratio of counts from the $2\,^3P_0$-$1\,^1S_0$ transition in the movable detector to the counts in the fixed detector. Measuring the ratio allows normalization directly to the ion population in the excited state of interest and eliminates many systematic errors associated with the normalization to the integrated beam current. Thereby, a decay curve can be traced out and a measurement of the decay length can be obtained.

In this experiment we have employed a particle detector mounted downstream of a charge-state spectrometer consisting of a quadrupole doublet and a bending magnet. This allows us to separate the different charge states of the gold ion beam [26] which are present after the beam passes the Ni target foil. The particle detector is a newly developed 32-fold strip chemical vapor deposition diamond detector with a detection area of 60×40 mm^2. The advantages of this new type of particle detector are its time resolution below 50 ps and its single-particle count rate capability of up to 10^8 ions/s [27,28]. Using this detector in connection with the charge-state spectrometer, in a beam-foil time-of-flight experiment we have been able to measure the x rays in coincidence with He-like ions counted in the diamond detector. This enables us to eliminate spurious x rays observed from a variety of other sources. This is shown in Fig. 3(a) which shows a raw sample x-ray spectrum of the movable detector. Besides the line of interest the x-ray spectrum contains a lot of background, especially the $K\alpha$ lines from the lead collimator material. Due to the coincidence method, one can almost get rid of the background with appropriate condition

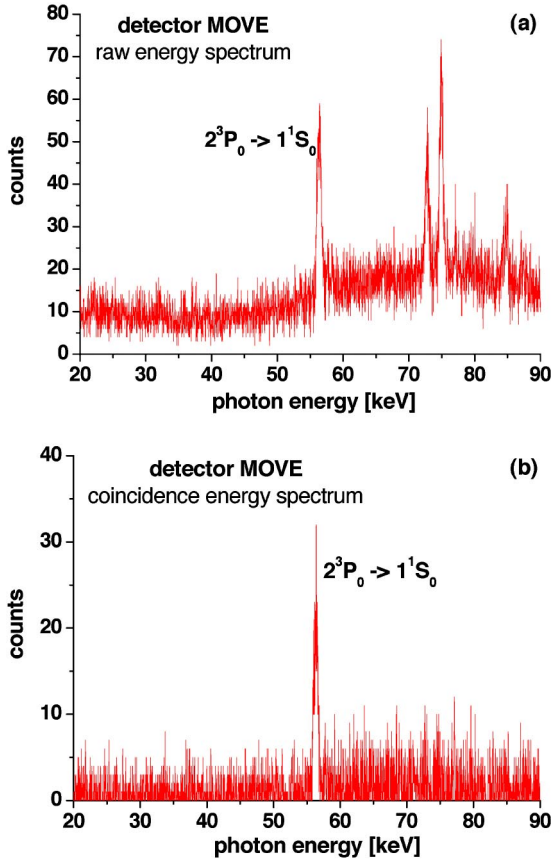

FIG. 3. Sample energy spectra of the detector MOVE.

cuts. The significant background reduction is shown in Fig. 3(b).

III. ANALYSIS AND RESULTS

For each position of the normalization detector, the ratio of counts from the peak of interest ($2\,^3P_0$-$1\,^1S_0$ hyperfine-quenched transition) in the movable detector to the counts in the normalization detector is calculated for several positions of the movable detector. The count rates of these peaks are determined by fitting a Gaussian shape plus linear background to the peak. From these ratios the decay curves can be extracted and are plotted as a function of the position of the movable detector for two different positions of the fixed detector [see Figs. 4(a) and 4(b)]. The decay curves cover just more than two decay lengths. This fact clearly limits the achievable accuracy. The error bars come from the uncertainty due to the fitting procedure of the x-ray spectra and are of statistical nature at the 1σ level. In order to extract the decay length, both decay curves are fitted with a single exponential without background. The statistical errors of the fit parameters are estimated by a bootstrap method [29,30]. This method, which can be assimilated for a Monte Carlo–type simulation, provides a rigorous way to calculate the statistical errors of the fit parameters (as our present fit), which are not well represented by the square root of the diagonal elements of the correlation matrix, as expected for a least-square-fit method. In our case, we calculate the statistical

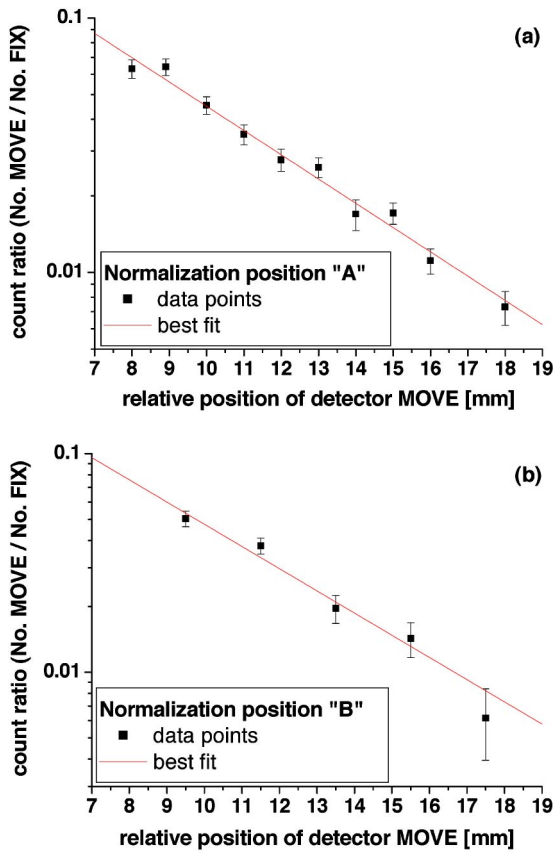

FIG. 4. Measured decay curves for two normalization positions.

error of the decay length as the standard deviation of the mean error extracted from a series of 20.000 fits of 20.000 synthetic decay curves, elaborated from the fitted function where we add randomly the normalized residuals between each interaction. This fitting procedure gives for both positions of the normalization detector the following values of the decay length l: at position A, $l=4.55(0.18)$ mm with a reduced $\chi^2=1.13$ and at position B, $l=4.26(0.49)$ mm with a reduced $\chi^2=1.22$. The extracted decay lengths of both normalization positions are in agreement with each other. A careful analysis of the fitting procedure has shown that the data can be described best using a single exponential without background. This is underlined by the fact that no position-dependent background effects could be found. The counting rate of the movable Ge(i) detector was almost independent of the position and both Ge(i) detectors had comparable counting rates. This indicates that the two Ge(i) detectors have seen a lot of ion-beam dependent background despite, and maybe because of, the collimators [see Fig. 3(a)]. Here the possibility of using coincidences in order to reduce the background was a crucial improvement in comparison to previous experiments. Also, no evidence of possible cascade contributions could be found. If there are any cascades into the $2\,^3P_0$ state we would expect cascades into the $2\,^1P_1$ state. This would show up as a resolved line which results from decay to the ground state. We see no evidence for such a line. This fact is also in good agreement with recent theoretical calculations [31].

TABLE II. Comparison of the lifetime τ of the $2\,^3P_0$ state between experiment and theory. Our experimental value is the weighted mean of the two decay curves.

	$\mu_I(^{197}\mathrm{Au})$	τ (ps)	Reference
Experiment		22.16 ± 0.81	
Theory (Johnson)			[8,9]
No BW,[a] no E1M1	0.148158	23.04	
No BW,[a] with E1M1[b]	0.148158	22.62	
With BW,[a] with E1M1[b]	0.148158	23.31	
With BW,[a] with E1M1[b]	0.145746	23.95	
Theory (Indelicato)			[14]
No BW,[a] with E1M1[b]	0.148158	22.23	
With BW,[a] with E1M1[b]	0.148158	22.92	
With BW,[a] with E1M1[b]	0.145746	23.55	

[a]Bohr-Weisskopf effect.
[b]Value taken from Ref. [9].

With the measured decay length l, the lifetime τ is then determined by

$$\tau=\frac{l}{c\beta\gamma}, \tag{1}$$

where c denotes the speed of light, β the velocity of the ions, and γ the Lorentz factor (cf. Table I). The final result for the lifetime of the $2\,^3P_0$ state $\tau(2\,^3P_0)$ and a comparison with different calculations are summarized in Table II. The given error for the lifetime is associated with the fitting procedure and is the only major contribution to the total error. Other possible errors such as the uncertainty of the velocity of the ions (see Table I), delayed cascade feeding, misalignment of the setup, and dead time effects of the readout electronics are assumed to contribute to $\leqslant 0.1$ ps to the total error.

IV. DISCUSSION AND CONCLUSION

Here the lifetime of the $2\,^3P_0$ state in He-like gold has been measured with an accuracy of 3.7%. The limiting factor in this measurement has been low statistics. But in a beam-foil time-of-flight experiment here this measurement has taken advantage of using coincidences between He-like ions and x rays emitted from the excited metastable state in order to clarify the x-ray spectra. Unfortunately, the reached accuracy is not sensitive enough to the different contributions such as the nuclear magnetic moment, the Bohr-Weisskopf effect, and the two-photon decay mode E1M1 as each of them contributes at the 2–3 % level to the lifetime of the $2\,^3P_0$ state (see Table II). Due to these uncertainties, it is not possible to extract a value for the $2\,^3P_0$-$2\,^3P_1$ fine-structure splitting. On the other hand, under the assumption that the atomic calculations [5–9] are accurate at the 1–2 % level, it could be possible to determine these nuclear parameters if one improves the experimental accuracy by one order of magnitude. This improvement should be possible as the limiting factor up to now has only been low statistics.

[1] A review of the earliest work on hyperfine-quenched transitions in heliumlike ions can be found in R. Marrus and P.J. Mohr, Adv. At. Mol. Phys. **14**, 181 (1978).
[2] M.L. Lewis and P.H. Serafino, Phys. Rev. A **18**, 867 (1978).
[3] A.N. Jette, T. Lee, and T.P. Das, Phys. Rev. A **9**, 2337 (1974).
[4] K. Aashamar and L. Hambro, J. Phys. B **10**, 553 (1977).
[5] G.W.F. Drake, Can. J. Phys. **66**, 586 (1988).
[6] P. Indelicato, F. Parente, and R. Marrus, Phys. Rev. A **40**, 3505 (1989).
[7] W.R. Johnson, D.R. Plante, and J. Sapirstein, Adv. At., Mol., Opt. Phys. **35**, 255 (1995).
[8] W.R. Johnson, K.T. Cheng, and D.R. Plante, Phys. Rev. A **55**, 2728 (1997).
[9] I.M. Savukov and W.R. Johnson, Phys. Rev. A **66**, 062507 (2002).
[10] G.W.F. Drake, Nucl. Instrum. Methods Phys. Res. B **9**, 465 (1985).
[11] *Table of Isotopes*, 8th ed., edited by R.B. Firestone (Wiley, New York, 1995).
[12] H. Dahmen and S. Penselin, Z. Phys. **200**, 456 (1967).
[13] A. Narath, Phys. Rev. **163**, 232 (1967); **175**, 696(E) (1968).
[14] P. Indelicato (unpublished).
[15] S.A. Lewis, F.M.J. Pichanick, and V.W. Hughes, Phys. Rev. A **2**, 86 (1970).
[16] A. Kpanow, V.W. Hughes, C.E. Johnson, S.A. Lewis, and F.M.J. Pichanick, Phys. Rev. Lett. **26**, 1613 (1971).
[17] E.G. Myers, P. Kuske, H.J. Andra, I.A. Armour, N.A. Jelley, H.A. Klein, J.D. Silver, and E. Trabert, Phys. Rev. Lett. **47**, 87 (1981).
[18] W.C. Martin, Phys. Scr., T **T24**, 725 (1981).
[19] J. Desesquelles, in *Proceedings of the Symposium on Atomic Spectroscopy and Highly-Ionized Atoms*, edited by H.G. Berry, R. Dunford, and L. Young (North-Holland, Amsterdam, 1988), p. 30.
[20] R. Marrus, A. Simionovici, P. Indelicato, D.D. Dietrich, P. Charles, J.P. Briand, K. Finlayson, F. Bosch, D. Liesen, and F. Parente, Phys. Rev. Lett. **63**, 502 (1989).
[21] B.B. Birkett, J.P. Briand, P. Charles, D.D. Dietrich, K. Finlayson, P. Indelicato, D. Liesen, R. Marrus, and A. Simionovici, Phys. Rev. A **47**, R2454 (1993).
[22] R.W. Dunford, C.J. Liu, J. Last, N. Berrah-Mansour, R. Vondrasek, D.A. Church, and L.J. Curtis, Phys. Rev. A **44**, 764 (1991).
[23] P. Indelicato, B.B. Birkett, J.P. Briand, P. Charles, D.D. Dietrich, R. Marrus, and A. Simionovici, Phys. Rev. Lett. **68**, 1307 (1992).
[24] C. Scheidenberger, H. Geissel, Th. Stöhlker, H. Folger, H. Irnich, C. Kozhuharov, A. Magel, P.H. Mokler, R. Moshammer, G. Münzenberg, F. Nickel, M. Pfützner, P. Rymuza, W. Schwab, J. Ullrich, and B. Voss, Nucl. Instrum. Methods Phys. Res. B **90**, 36 (1994).
[25] H. Geissel and C. Scheidenberger, Nucl. Instrum. Methods Phys. Res. B **136-138**, 114 (1998).
[26] H. Bräuning *et al.*, GSI Scientific Report No. GSI 2000-1, 1999 (unpublished), GSI Scientific Report No. 91, 2000 (unpublished).
[27] E. Berdermann, K. Blasche, P. Moritz, H. Stelzer, and B. Voss, Diamond Relat. Mater. **10**, 1770 (2001).
[28] P. Moritz, E. Berdermann, K. Blasche, H. Stelzer, and B. Voss, Diamond Relat. Mater. **10**, 1765 (2001).
[29] B. Efron, Stat. Sci. **1**, 54 (1986).
[30] G. Simpson, Astron. Astrophys. **162**, 340 (1986).
[31] S. Fritzsche, Th. Stöhlker, O. Brianzanescu, and B. Fricke, Hyperfine Interact. **127**, 257 (2000).