A capacitance servo control plunger for accurate lifetime measurement *

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Abstract: The recoil distance Doppler shift method has been widely used in the study of nuclear structure to determine the level lifetime and absolute transition probabilities. A capacitance servo control plunger based on this method has been successfully developed by the Nuclear Structure Group of the China Institute of Atomic Energy. Three microscopes were employed to check the parallelism and can therefore guarantee a delicate measurement of the distance between the target and the stopper. This new plunger made a successful performance in the test experiment and the measured lifetime of the $2^+\rightarrow0^+$ transition in ^{78}Kr is in agreement with the previous value.

Key words: lifetime, RDDS, plunger, capacitance method, servo control

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1 Introduction

Transition probabilities are very sensitive to the details of the wave functions of the states involved. Lifetime measurements are therefore of special interest for understanding the structure of excited nuclear states. Many methods have been applied for different ranges of lifetime. The recoil distance Doppler shift (RDDS) method has been well developed in the past five decades and has become a classic method in γ ray spectroscopy for lifetime measurements in the range of 10^{-12} s to 10^{-9} s [1–5]. Many kinds of devices called plunger have been developed. These works have made a great contribution to nuclear physics [6–33]. This paper will introduce a brand new capacitance servo control plunger developed at the China Institute of Atomic Energy (CIAE), which promises a higher precision and easier operation.

This article is structured in five sections. After the introduction, the following section describes the basic theory of the RDDS method. The third part is dedicated to the developments, including model design and control software. Several new skills such as three microscopes checking the parallelism are presented to guarantee the accurate distance measurement. Section 4 is focused on the test experiment and results. This paper ends with a summary including work planned for this plunger.

2 The recoil distance Doppler shift method

Figure 1 describes the basic principle of the RDDS method. The target and the stopper foils are mounted parallel to each other at different distances (D). The beam impacts the thin target, then the produced excited nucleus recoils with the velocity of a few percent of the light speed in the direction of the stopper foil in the vacuum chamber. The recoiling nucleus de-excites by emitting a cascade of γ rays which are detected by the surrounding detectors. The Doppler shifted energy is determined by Eq. (1),

$$E_{\gamma}^{1}=E_{\gamma}\left(1+\frac{v}{c}\cos\theta\right), \tag{1}$$

where E_{γ}^{1} is the Doppler shifted component, θ is the angle with respect to the beam axis at which the γ ray is observed. The effect of Doppler shift increases when θ gets close to 0° or 180°. Here v is the recoil speed and c is the speed of light in a vacuum. The rest of the excited nuclei surviving for a time greater than $t=D/v$ stopped in the stopper foil, de-excite the unshifted γ rays and the energy is E_{γ}. The intensities of the Doppler shifted ($I_{\rm s}$) and unshifted (I_0) peaks are determined by the equa-

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tions:

$$I_s = I[1-e^{-D/(v\tau)}], \quad (2)$$

$$I_0 = Ie^{-D/(v\tau)}. \quad (3)$$

The lifetime τ can be determined by Eq. (4) [1],

$$\tau=\frac{-D}{v\ln R}, \quad (4)$$

where $R=I_0/(I_0+I_s)=e^{-D/(v\tau)}$ obtained from the spectrum varies according to different target/stopper distances (D).

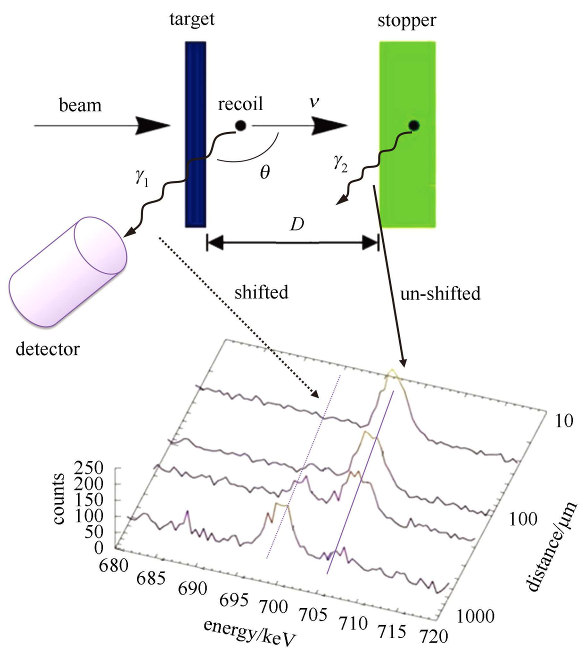

Fig. 1. (color online) Principle of the RDDS method.

3 The capacitance servo control plunger

This new plunger is a delicate instrument equipped with a servo control and its algorithm is based on the capacitance method. A novel optical detection system is applied to guarantee a better accuracy for the distance measurement between the target and stopper foils.

3.1 The structure design

Figure 2 shows the optimized original design by UG and the assembled plunger apparatus. Before the manufacture, some FEM (Finite Element Method) and motion simulations are applied to optimize the structure.

From the bottom to the top, the main parts of the plunger are an aluminium base, miniature linear stage and supporting frames. On the base there are airtight rubber rings for the vacuum and the connector for the miniature linear stage.

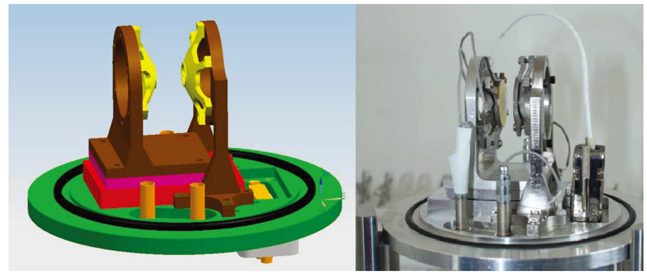

Fig. 2. The structure design and assembled plunger.

In order to measure the lifetime accurately, the structure design must reach four goals. 1) The miniature linear stage can move freely in the target chamber at the range of 20 mm with 20 nm resolution; 2) the main material is aluminium which can guarantee the stability during online experiment with a low γ ray stopping power; 3) the chamber must guarantee a vacuity better than 4×10^{-4}Pa; 4) under 1)–3), the whole device should be simple and light.

The plunger apparatus is the core part of the measurement system, but for the sake of lifetime measurement, some other components are necessary.

3.2 The capacitance servo control

During the online experiment, disturbances such as mechanical shock and deformation of the target caused by heat from beam bombardment may affect the precision and stability, especially when the distance is in a short range. Thus the plunger needs a servo control to keep high resolution and robustness. The control system has been developed as Fig. 3.

The servo control is quite simple: D_0 is the commanded distance between the target and the stopper foils while the real value is D, if the deviation $\Delta D=D-D_0$ is larger than 0.1 μm, the controller will give the command to the stage motor to move back, otherwise the controller will hold on which means the distance already meets the precision requirement.

The key problem is to obtain the real distance D. The capacitance method has been proved to be a good choice, as the electrically insulated target and stopper foils can form a parallel plate capacitor themselves. Thus, the control does not need other sensors [2]. The basic equation of the capacitance method is Eq. (5),

$$C=\varepsilon_0\frac{A}{D}, \quad (5)$$

where A is the area of the stretched foil, D is the target-to-stopper separation and ε_0 is the vacuum permittivity. A novel algorithm has been developed to realize the servo control, which can be called the capacitance servo control algorithm, described in Fig. 4.

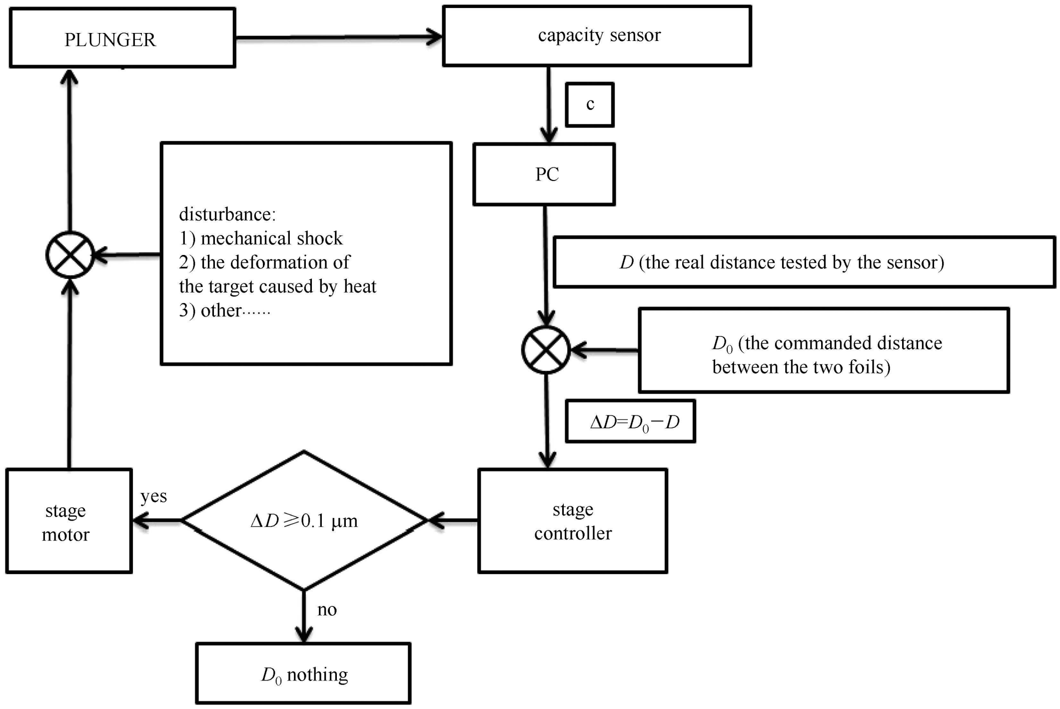

Fig. 3. The control flow chart.

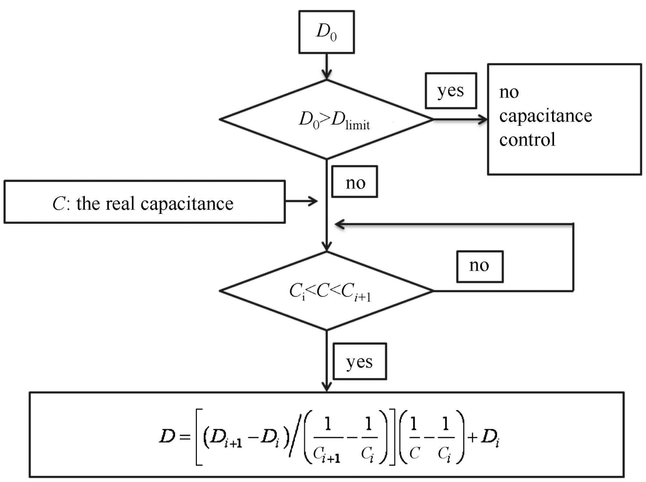

Fig. 4. The capacitance servo control algorithm.

A standard database is built up with a series of C_i and D_i in a subtle way when both the plunger and environment are stable and quiet enough, of course, the capacitance resolution must be better than 0.05 pF, which can distinguish the smallest distance step 20 nm. There is a limited distance for the capacitance method, usually D_{limit}=300–400 μm, but for different targets and structures, it may deviate from this value. Only in the limited range the capacitance servo control can perform a good work. When the distance exceeds this limit, the precision can be relaxed, at the same time the miniature stage can guarantee a high resolution itself, then the plunger can work without the capacitance servo control.

During the experiment, if the commanded distance is in the limited range, the algorithm will search the standard database for every realtime capacitance to find its interval and calculate the realtime distance D through the equation in Fig. 4. According to this realtime D, the whole servo control can flow smoothly, as in Fig. 3.

The corresponding softwares have been developed based on Labview, including the servo control software and the calibration software. To optimize the operation, all these functions are combined into one frame called Plunger Application Software.

Figure 5 is the main control window containing the corresponding results, where the distance is 1 μm and the accuracy reaches 0.05 μm, which is much better than the 0.1 μm precision introduced in Ref. [6].

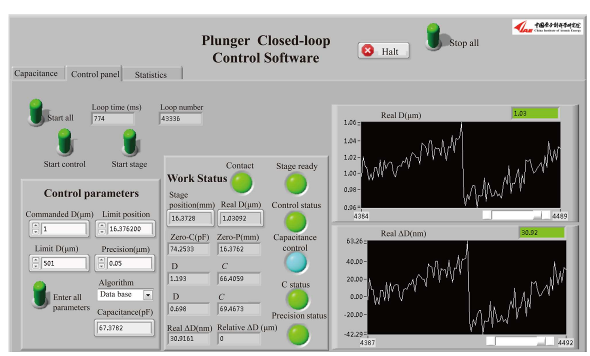

Fig. 5. (color online) The servo control software.

The control window shows that the controller pulls the distance back to 1 μm when the foils deviate from this value more than 0.05 μm. There are five functions in Plunger Application Software, as shown in Fig. 6, to make the measurement easy to operate.

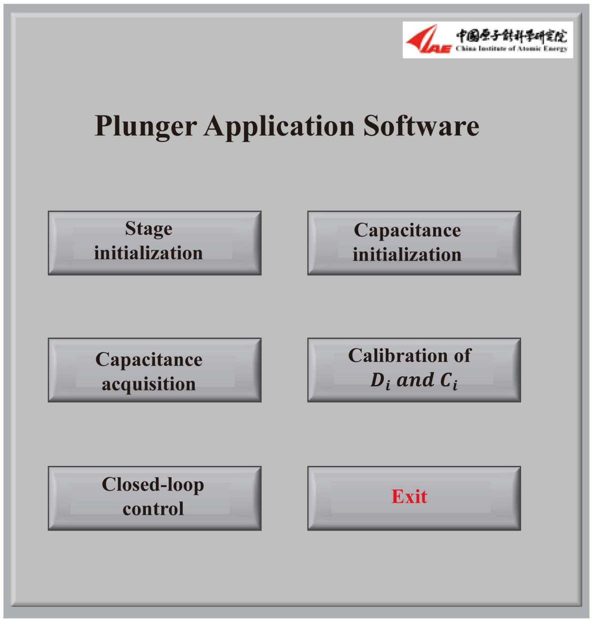

Fig. 6. (color online) The plunger application software.

3.3 The promises for high accuracy

The minimum separation of the target and the stopper is an important quantity of the RDDS technique, especially when one deals with very short effective lifetimes (below 2 ps). The effective minimum separation depends on the surface roughness of the foils and the precision of the parallel alignment of the target and the stopper foils.

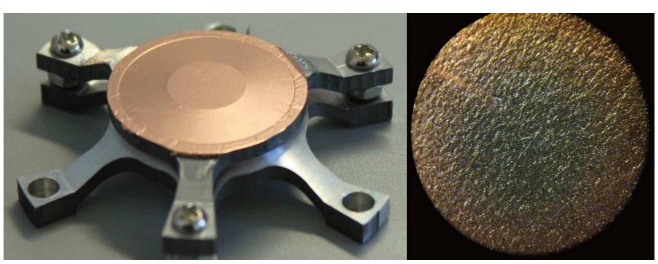

Fig. 7. The flat and smooth target.

There are three aspects to promise the accuracy of the measurement. First, the miniature linear stage can realize a motion with 20 nm resolution. This high resolution promises reliable D_i in the standard database. Second, the target and stopper should have smooth and flat surfaces to form a stable capacitor, which can guarantee reliable C_i. The right photo in Fig. 7 taken through a 100X magnification microscope indicates that the frame in the left can stretch the foils well. Third, before the calibration of C_i–D_i three video microscopes are applied to check the parallelism of the target/stopper plane and some adjustments can be made at the same time. The idea of utilizing three video microscopes comes from the common sense that three points can determine a plane and all the microscopes giving the same separation can guarantee a high parallelism.

Fig. 8. The optical detection system.

Figure 8 shows the optical detection system working in monochromatic light. Adjusting the three screws to yaw or pitch the stopper can obtain better parallelism. Then the parallelism can be checked in different separations. The data in Table 1 prove that this method is reliable. Each microscope (M-scope A, M-scope B and M-scope C) reads the separation at every distance listed in the first three columns, the fourth and the fifth column give the average distance and standard error respectively.

Table 1. The detection data of parallelism.

M-scope A/μm	M-scope B/μm	M-scope C/μm	average distance/μm	standard error/μm
7.2	8	8.7	7.97	0.61
11.6	10.9	12.4	11.63	0.61
24.8	20.3	21.8	22.30	1.87
42.3	40.0	42.3	41.53	1.08
84.6	81.4	86.1	84.03	1.96
164.9	167.2	166.4	166.17	0.95
335.7	337.4	340.8	337.97	2.12

In fact, it is not absolute parallelism, but 1 μm deviation only deduces 2×10^{-4} rad un-parallelism with 10 mm diameter target/stopper foils. However, it is enough for the measurement request.

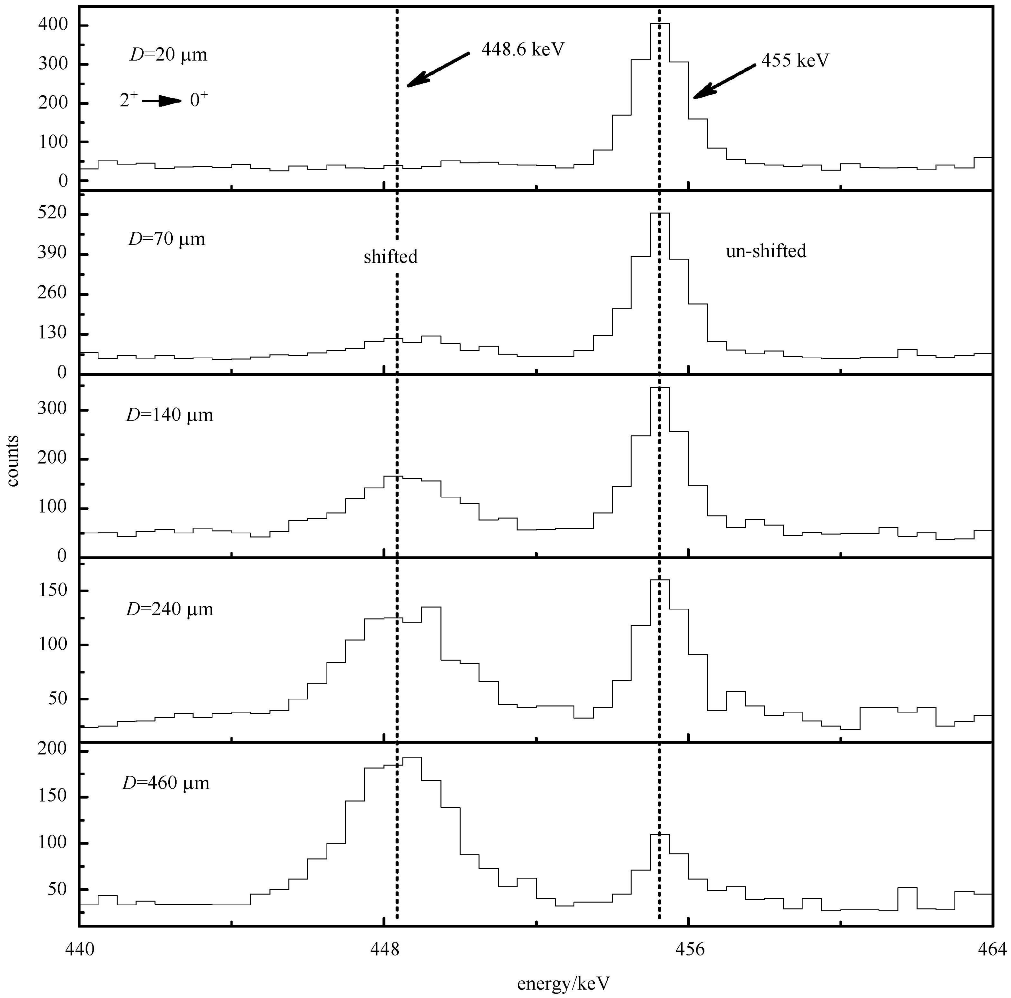

Fig. 9. The Doppler γ ray spectra show the shifted and un-shifted components of the $2^+ \rightarrow 0^+$ 455 keV transition in ^{78}Kr for different target/stopper distances.

4 The test experiment and results

The test experiment for this new plunger has been carried out by measuring the lifetimes of low spin states of the nucleus ^{78}Kr at HI-13 Tandem Accelerator at CIAE. Previous studies [8, 9] show that the lifetimes of low excited states are very suitable for the plunger test. The high spin states of ^{78}Kr were populated by the ^{63}Cu(^{19}F, 1p3n)^{78}Kr reaction at a beam energy of 77 MeV. The thickness of the ^{63}Cu target and the Au stopper are 800 μg/cm^2 and 14.5 mg/cm^2 respectively. The recoil velocity v/c=2.1% was determined by the reaction kinematics. In the test experiment, five different target-to-stopper distances (20, 70, 140, 240 and 460 μm) were set. The detector array consisted of 11 HPGe detectors and two planer-type HPGe detectors. Four of these detectors were placed at 90°, two at 140° and 150°, and one each at 42°, 45°, 50°, 122°, and 145° respect to the beam direction.

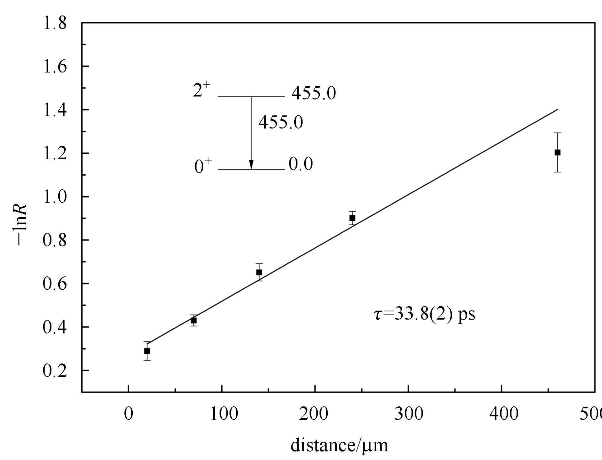

Fig. 10. The fitted lifetime of the $2^+ \rightarrow 0^+$ 455 keV transition in ^{78}Kr.

Figure 9 illustrates the spectra obtained under different distances by the detector at 150°. It is obvious that the intensity of the stopped peak decreases as the foils depart away with each other, while the shifted peak increases simultaneously.

The lifetime was fitted with Eq. (4) and the result is shown in Fig. 10. As compared with Table 2, this result is in agreement with the previous one in Ref. [9] and has a better accuracy.

Table 2. The lifetimes in different work.

transition energy/keV	previous work τ/ps	this work τ/ps
455.0	32(2)	33.8(2)

5 Summary

The RDDS technique is a versatile method to determine the level lifetimes of excited nuclei. The test experiment has proved that this new capacitance servo control plunger was capable in the lifetime measurement and its closed-loop control realized a high precision of 50 nm at 1 μm distance. The measured lifetime was in agreement with the previous work and promised a better accuracy.

However, for the sake of pursuing a better plunger there is much work to do. The foils (target/stopper) will be a permanent working field inherent to the RDDS technique. Aside from the production of specific targets, it is the behavior under beam bombardment which has to be investigated, especially when different materials (target with backing) are used. The optical detection system has considerable room for improvement if the video microscopes have a larger magnification. The whole control system is sensitive to capacitance, so the choice of material and the manufacture including assemble process need an in-depth study. More attention should be paid to the data analysis and its source code development.

References

1 Jones K W, Schwarzschild A Z et al. Phys. Rev, 1969, **178**: 1769
2 Alexander T K, Bell A. Nucl. Instum. Methods, 1970, **81**: 22
3 Fossan D B, Warburton E K. Pure and Applied Physics, 1974, **40**-C: 307
4 Dewald A, Sala P et al. Nucl. Phys. A, 1992, **545**: 822–834
5 Rother W, Dewald A et al. Nucl. Instrum. Methods A, 2011, **654**: 196–205
6 Dewald A, Moller O, Petkov P. Nucl. Instrum. Methods A, 2012, **67**: 786–839
7 Dewald A, Harissopulos S, von Brentano P. Z. Phys. A, 1989, **334**: 163
8 Hellmeister H P et al. Nucl. Phys. A, 1979, **332**: 241
9 Joshi P K et al. Nucl. Phys. A, 2002, **700**: 59
10 Rother W et al. Nucl. Instrum. Methods Phys. Res. A, 2011, **654**: 196
11 Kanbe M, Kitao K. Nucl. Data Sheets, 2001, **94**: 227
12 Morrissey D J et al. Nucl. Instrum. Methods Phys. Res. B, 2003, **204**: 90
13 Mueller W F et al. Nucl. Instrum. Methods Phys. Res. A, 2001, **466**: 492
14 Bazin D et al. Nucl. Instrum. Methods B, 2003, **204**: 629
15 Taylor M J et al. Nucl. Instrum. Methods Phys. Res. A, 2009, **606**: 579
16 Chester A et al. Nucl. Instrum. Methods Phys. Res. A, 2006, **562**: 230
17 Pullanhiotan S et al. Nucl. Instrum. Methods Phys. Res. A, 2008, **593**: 343
18 Page R D et al. Nucl. Instrum. Methods B, 2003, **204**: 634
19 Grahn T et al. Nucl. Phys. A, 2008, **801**: 83
20 Lieb K P, Uhrmacher M, Dauk J, Kleinfeld A M et al. Nucl. Phys. A, 1974, **223**: 445
21 Altmann J, Dewald A, Zell K O, von Brentano P. Nucl. Instrum. Methods Phys. Res. A, 1992, **321**: 59
22 Rascher R, Lieb K P, Uhrmacher M. Phys. Rev. C, 1976, **13**: 1217
23 Krane K S, Steffen R M, Wheeler R M. Nucl. Data Tables, 1973, **11**: 351
24 Petkov P. Nucl. Instrum. Methods Phys. Res. A, 1994, **349**: 289
25 Petkov P, Dewald A, von Brentano P. Nucl. Instrum. Methods Phys. Res. A, 2001, **457**: 527
26 Winter G. Nucl. Instrum. Methods, 1983, **214**: 537
27 Petkov P et al. Nucl. Phys. A, 1998, **640**: 293
28 Adrich P et al. Nucl. Instrum. Methods Phys. Res. A, 2009, **598**: 454
29 Pasternak A A et al. Eur. Phys. J. A, 2000, **9**: 293
30 Srebrny J et al. Nucl. Phys. A, 2001, **683**: 21
31 Pasternak A A et al. Eur. Phys. J. A, 2002, **13**: 435
32 Grodner E et al. Eur. Phys. J. A, 2006, **27**: 325
33 Lieder R M et al. Eur. Phys. J. A, 2011, **47**: 115