Nuclear Instruments and Methods in Physics Research A 338 (1994) 419–424
North-Holland

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH
Section A

Calibration of CsI(Tl) scintillators for heavy ions ($3 \leqslant Z \leqslant 54$) in a wide energy range ($E/\mathrm{u} \leqslant 60$ MeV/u)

P.F. Mastinu, P.M. Milazzo, M. Bruno *, M. D'Agostino, L. Manduci

Istituto Nazionale di Fisica Nucleare, Sezione di Bologna e Dipartimento di Fisica dell'Università di Bologna, Via Irnerio 46, 40126 Bologna, Italy

(Received 19 July 1993)

The light output response of CsI(Tl) scintillators, photodiodes readout, has been investigated for heavy ions with atomic number $3 \leqslant Z \leqslant 54$ for energies up to 45 MeV/u. The detectors have been calibrated with particular attention to the dependence on the atomic number of the ions. The expression obtained with this procedure was applied to the calibration of the CsI(Tl) detectors of the MULTICS array, on the basis of only one renormalization coefficient. A complete compatibility has been found with recent data at energies up to 60 MeV/u.

1. Introduction

The simultaneous detection of large number of fragments emitted in intermediate energy heavy ion reactions needs new arrays of several detectors [1–4], covering 4π in the center of mass system. The detectors have to be thick enough to stop the ions in order to evaluate the charge by means of the ΔE–E technique.

The CsI(Tl) is a good scintillation material [5] to be used as detector since it has a high stopping power ($\rho = 4.51$ g/cm^3), no limits in the geometrical shape, negligible radiation damage, low cost and good resolution. However, since the light output strongly depends both on the energy deposited in the crystal and on the atomic number and mass of the incident ion, an accurate calibration of these detectors is needed. This is also true since the CsI(Tl) scintillators are commonly used as counters of light particles and γ rays and the studies to understand the scintillation mechanism are not able to quantitatively describe the light output response for heavy ions [6–8].

In this paper we present a procedure to relate the light output to the deposited energy with an expression containing few parameters. These parameters have been obtained by a least squares fit to the data collected in two different measurements performed at the 88 in. Cyclotron at Lawrence Berkeley Laboratory and at the Cyclotrons of the GANIL Laboratory (Caen/France). The experimental data collected with the CsI(Tl) scintillators of the MULTICS [#1] array [4] have been calibrated with the expression obtained by the fitting procedure.

A recent measurement extending the range of energy up to 60 MeV/u shows excellent agreement with our parametrization.

2. Experimental measurements

The characteristics of the CsI(Tl) scintillator [#2] used in these tests have been described in detail elsewhere [4]. A first measurement has been performed at the LBL 88 in. Cyclotron where the CsI(Tl) have been exposed directly to low intensity beams (100 particle/s) at energies up to 25.5 MeV/u and ions with atomic number up to the Kr ($Z = 36$) [9]. The energy resolution of CsI(Tl) scintillators was found of the order of $\approx 1\%$, independent of the ion charge and energy (see for instance Fig. 1 of ref. [9]).

In order to check the extrapolation of these results to higher energies and higher atomic numbers, i.e. in the expected range of the measurements with the MULTICS array [10], we performed additional tests at GANIL with beams of ^{40}Ar at 44 MeV/u and ^{132}Xe at 35 MeV/u on a target of ^{197}Au. Two different tele-

* Corresponding author.

[#1] INFN collaboration: Sections of Bari, Bologna, Milano, Trieste, Laboratori Nazionali di Legnaro and GANIL.

[#2] Chosen from a set of 48 detectors of the MULTICS array.

SSDI 0168-9002(93)E0766-L

scopes were used; the first consisted in a 200 μm solid state silicon detector used as ΔE and in a CsI(Tl) scintillator as stopping detector (E); the second telescope had another 200 μm solid state silicon detector as ΔE and a 3.5 mm lithium drifted silicon detector [Si(Li)] as E detector. The telescopes were placed at the same scattering angle, near the grazing angle, in order to collect with comparable cross sections either reaction fragments or elastically scattered ions.

The calibration of the silicon detectors can be obtained straightforwardly, since their response is linear with respect to the energy independent of the incident ion.

It is then possible to get informations on the light output of the CsI(Tl) scintillator by comparing the two ΔE–E matrices. A new set of data points (280), where the light output has been determined for different atomic number and energies, has been added to the data collected at LBL. In this way the total set of data has been extended to higher energies and atomic numbers. The normalization of the data collected at LBL and at GANIL was done comparing the data in the common range of measurements. A unique normalization coefficient allows for making all the data consistent in the common range of energies and atomic numbers.

3. Scintillation response

The curves evaluated in ref. [9] from the data collected in the experiment at LBL, extrapolated to higher energies ($E > 30$ MeV/u) and heavier ions ($Z \geqslant 36$), did not agree with new experimental data collected at GANIL. It was then necessary to examine more in detail the calibration procedure.

We studied the light output keeping the function, used for other kinds of scintillators [11,12]:

$$L = \gamma E + \beta(e^{-\alpha E} - 1). \tag{1}$$

This function contains a linear contribution, expressing the linear behaviour of the light output for high values of energy deposited in the crystal, and an exponential part (with the parameter α positive) for low energy incident ions, which takes into account quenching effects in the induced luminescence.

In previous approaches [9,11,12] the calibration procedure consisted in a first step where the data collected for each ion were separately fitted with some free parameters and in a second step where these parameters were fitted as a function of the atomic number. Since this procedure has the great disadvantage of introducing noncorrelated parameters (consequently the extrapolation to higher Z values is out of control) we decided to study the parameters α, β and γ, investigating their sensitiveness on the charge of the

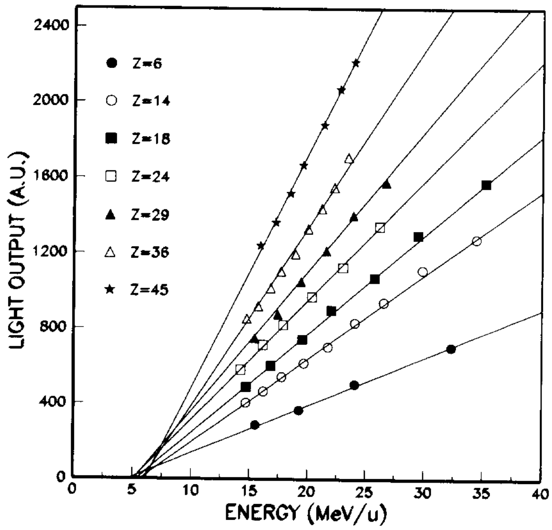

Fig. 1. Light output as a function of the energy per nucleon for different incident ions. The solid lines are the fit of the data for energy above 15 MeV/u.

incident ion, carrying out a unique fit on the whole set of the data.

The light output is presented in Fig. 1 as a function of E/A. The parametrization [13,14]

$$A = 2.08Z + 0.0029Z^2$$

has been used for the data where only the charge was known. From Fig. 1 an almost linear region can be seen above 15 MeV/u, independently from the considered ions:

$$L(E) = \gamma E - \beta \tag{2}$$

consistent with the asymptotic behaviour of Eq. (1). As it appears from Fig. 1 the coefficients β and γ must be positive.

This is in agreement with the theory proposed by Meyer and Murray [15] according to the hypothesis of the existence of a threshold in E/A for the production of energetic electrons (δ rays, $E_\delta > 1.5$ keV) being this process very efficient in producing the induced luminescence. The lines for different ions, if extrapolated to vanishing light output, intercept the E/A axis in a narrow region around $E_i/A \simeq 6$ MeV/u.

A similar linear behaviour can be extracted from the theoretical expression of the specific scintillation $\mathrm{d}L/\mathrm{d}E$ as formulated by Birks [16]:

$$\frac{\mathrm{d}L}{\mathrm{d}E} = \frac{S}{(1 + \mathrm{kB}(\mathrm{d}E/\mathrm{d}x))}, \tag{3}$$

where $\mathrm{d}E/\mathrm{d}x$ is the specific energy loss, S the scintillation efficiency and kB the scintillation quenching factor accounting for nonradiative deexcitation. For sufficiently high energies one can neglect the contribution of quenching effects to the total induced luminescence since quenching effects are negligible before the ion reaches a low energy ($dE/dx \ll 1$), and since the energy lost in the region where the quenching is relevant is a small fraction of the total energy. In this limit, integrating Eq. (2) and neglecting quenching effects, one gets a linear dependence of the light output of the energy of the ion. This linear dependence can be written as a function of E/A:

$$L(E) = (\gamma A)(E/A) - \beta. \quad (4)$$

The angular coefficient (γA) of the straight line increases with the atomic number, as it is clearly seen in Fig. 1. In addition, neglecting the weak dependence of E_i/A from the ion characteristics, with the constraint $L(E_i) = 0$ for a constant value of E_i/A the following condition should hold:

$$\gamma E_i = \beta;\ \gamma/\beta = 1/E_i. \quad (5)$$

If one assumes that in Eq. (1), $L(E)$ monotonically increases for increasing energy, i.e. if a minimum exists

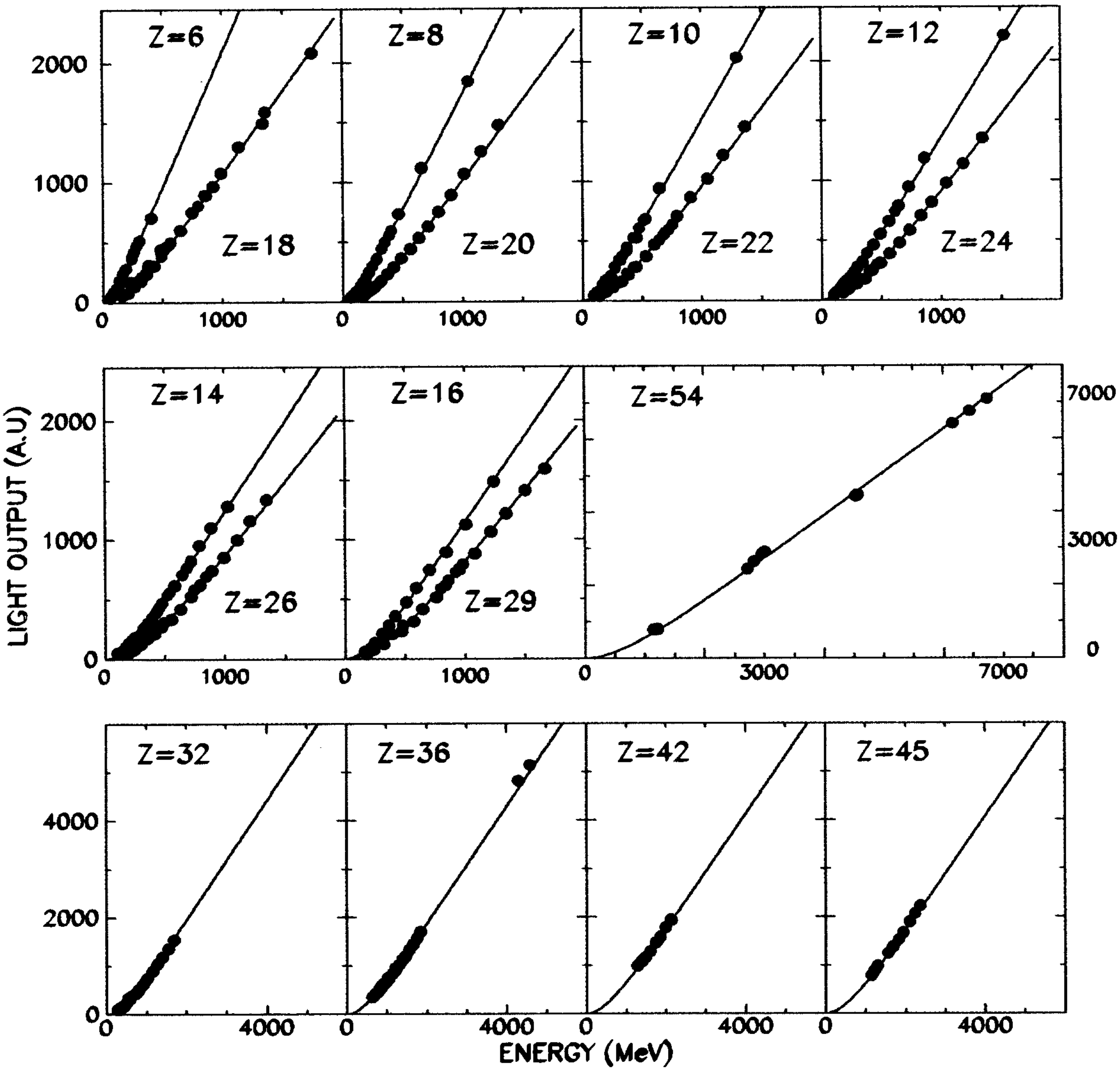

Fig. 2. Light output of the CsI(Tl) as a function of energy for some ions. The solid lines are the results of fit with Eq. (16). Uncertainties in the measured channel number and ion energy are smaller than the size of the points. The points in black are the data collected at Lawrence Berkeley Laboratories, in red at GANIL Laboratories and in green at NSCL of the Michigan State University.

it has to be at zero or negative energy values, one gets a unique solution:

$$dL/dE = \gamma - \alpha\beta e^{-\alpha E}, \tag{6}$$

$$dL/dE = 0 \text{ at } E' = -\frac{1}{\alpha} \ln \frac{\gamma}{\alpha\beta}, \tag{7}$$

with the condition

$$\gamma \geqslant \alpha\beta \tag{8}$$

where the equal sign holds true for $E' = 0$ in the Eq. (7).

From Eqs. (8) and (5) one gets

$$\alpha \leqslant 1/E_i. \tag{9}$$

A stronger constraint can be obtained if one considers the ion with a relatively low energy (1–5 MeV/u) and consequently a high specific energy loss, where Eq. (2) can be approximated as:

$$dL/dE \simeq S/kB(dE/dx). \tag{10}$$

Taking into account the Bethe–Bloch formula [17] and neglecting the logarithmic part one has:

$$|dE/dx| \approx AZ^2/E, \tag{11}$$

and consequently:

$$dL/dE \approx \text{constant } E. \tag{12}$$

Expanding Eq. (6) in Taylor series one obtains:

$$dL/dE = (\gamma - \alpha\beta) + \alpha^2\beta E + O(E^2). \tag{13}$$

To keep the same behaviour of Eq. (12) in this low energy region it is necessary to introduce the constraint:

$$\gamma = \alpha\beta, \tag{14}$$

and consequently from Eq. (5) one gets:

$$\alpha = 1/E_i. \tag{15}$$

Eqs. (5) and (15) show strong constraints among the parameters of the fit; these indications allow for a better definition of the parameters as a function of the atomic characteristics.

4. Calibration procedure

The strong correlations among the parameters α, β and γ allow for a single fit on the whole set of the data, contrary to previous works [9,11,12].

Taking into account the fact that the straight lines of Fig. 1 seem to originate by a unique focus (Eq. (5)) and using the constraints that the functions $L(E)$ have to monotonically increase for positive values of energy with its minimum value in $E = 0$ (Eq. (15)) it is now possible to rewrite Eq. (1) in the form:

$$L(E) = \gamma\left(E + E_i(e^{-E/E_i} - 1)\right). \tag{16}$$

Starting from the considerations of section 3 we fitted the experimental data with four free parameters, using for E_i a simple linear dependence on Z:

$$E_i = d_1 Z, \tag{17}$$

and for γ the parametrization:

$$\gamma = d_2/Z + d_3 + d_4 Z, \tag{18}$$

assuming for the angular coefficient (γA) of the straight lines in Fig. 1 a quadratic dependence on Z. A simple linear dependence on Z is not able to reasonably fit the experimental data, a cubic dependence has to be negligible as suggested by the small value of the parameter d_4.

The values of the parameters d_1, d_2, d_3 and d_4 were determined using the minimization code Minuit [#3] on a set of 400 data (120 collected in the first measurement at LBL and 280 new experimental points collected at GANIL). It has to be noted that the experimental points are well spread over the whole range of charges and energies. The results are:

$$\begin{cases} d_1 = 12.9 \pm 0.1, \\ d_2 = 8.17 \pm 0.08, \\ d_3 = 0.89 \pm 0.01, \\ d_4 = 0.0025 \pm 0.0002. \end{cases} \tag{19}$$

The validity of Eq. (15) has been checked by repeating the fitting procedure with an additional parametrization:

$$\alpha = d_5/E_i.$$

The result has been $d_5 \approx 1$ in good agreement with Eq. (15) without any appreciable improvement in the value of χ^2.

The results of this fitting procedure are shown in Fig. 2; an excellent consistency of the full set of data collected in both measurements has been achieved. The curves are in a very good agreement with experimental data and a normalized χ^2 of ≈ 1.8 corresponds to the values of the parameters d_1, d_2, d_3 and d_4 given in Eq. (19). The residuals from calculated values are of the order of $\approx 1\%$ and are nearly independent of the atomic number and energy of the ion.

All the procedure has been repeated for other detectors of the MULTICS apparatus and the results show that the light response can be parametrized in the same way and that only one normalizing factor is enough to account for different detectors keeping the same values for the parameters d_1, d_2, d_3 and d_4. No effects due to differences in scintillation efficiency have been found within the experimental errors, suggesting that the normalization factor can be ascribed to different electronic chains, or that the differences can be accounted for by a simple factor.

[#3] D506 of the CERN library.

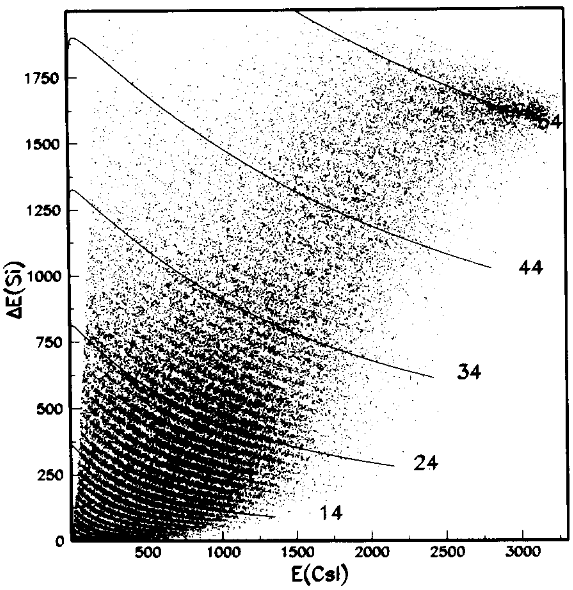

Fig. 3. Calibrated $\Delta E-E$ (Si–CsI(Tl)) matrix. The curves were calculated with the energy loss code ENLOSS [18,19].

5. Results and conclusions

The results were applied to the calibration of several CsI(Tl) scintillators of the MULTICS array.

The procedure can be described as follows:

a) selection of the charges of the fragments, from the matrix ΔE–E (ΔE given by a silicon detector and E by the CsI(Tl) scintillator;

b) calculation of $E_l(Z)$ and $\gamma(Z)$ from Eqs. (18) and (19);

c) determination of the normalization factor from points of known charge and energy (for instance from elastically scattered ions).

It has been checked that this simple normalization factor is sufficient to account for differences in the output signals and this result is very important because it allows the use of Eq. (1) together with the evaluated coefficients d_1, d_2 d_3 and d_4 for the calibration of all the CsI(Tl) of the MULTICS array, once this normalization factor has been determined.

The energy loss in the detectors can be calculated from Eq. (16). A simple numerical inversion of Eq. (16) is preferable to the analytic inversion of Eq. (1): due to the experimental errors, several numerical problems can arise, since one has to deal with logarithms.

The calibrated ΔE(Si 200 μm)–E(CsI(Tl)) matrix is shown in Fig. 3; the curves superimposed to the experimental data are energy loss calculations performed with the code ENLOSS, based on the parametrization of Anderson and Ziegler optimized by Hubert et al. [18,19]. A very good agreement between calculated values and calibrated data up to the atomic number $Z = 54$ can be observed.

In Fig. 4 the overlap of 20 calibrated scatter plots (ΔE – Si 500 μm, E – CsI(Tl)) is shown; excellent results in the definition of the energy of the fragments have been achieved. We want to stress that the calibration procedure described in this paper can obtain very fast and accurate results when extended to a large number of identical detectors.

A further check has been made to test the reliability of the parameters obtained in the fit, extrapolating the results to heavier ions and higher energies. A very good agreement has been found for all the collected data, as it is clearly shown in Fig. 2 for some of them. The data have been collected during the calibration of an experiment on Xe + Au at 70 MeV/u carried out at NSCL of the Michigan State University and correspond to beams of ^{16}O, ^{20}Ne, ^{24}Mg, ^{44}Ca, ^{48}Ti, ^{52}Cr,^{56}Fe, ^{60}Ni, ^{64}Zn, ^{68}Zn, ^{80}Kr, ^{84}Kr, ^{128}Xe, ^{132}Xe, ^{136}Xe at very low intensity, impinging directly in the telescopes.

Summarizing, we have investigated the response function of CsI(Tl) detectors to heavy ions as a function of the energy and the charge number. This study covers energies up to 60 MeV/u for ions in the range $3 \leqslant Z \leqslant 54$. Satisfactory results were obtained in the fit of the response function. We have also shown the application of this parametrization to other experimental data. We would like to stress that for the calibration

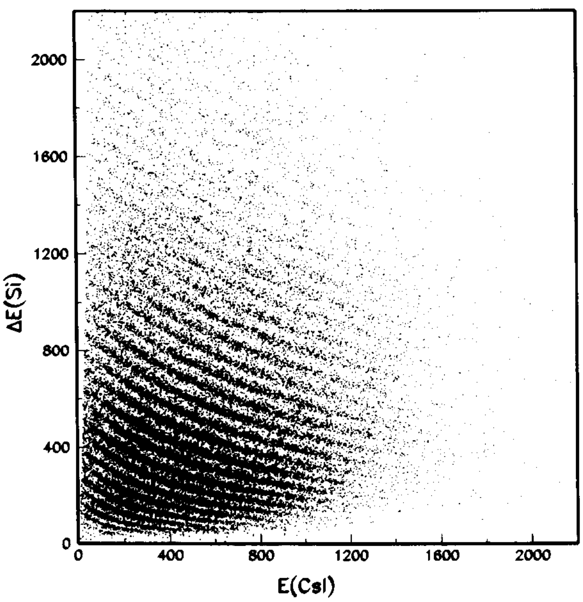

Fig. 4. Overlap of 20 $\Delta E-E$ matrices for the data from reaction Xe+Cu at 45 MeV/u collected by the MULTICS apparatus.

of several detectors only one normalization factor has to be evaluated.

This calibration procedure of CsI(Tl) detectors allows the use of these detectors with performances similar to the ones typical of solid state detectors, but with the advantage of the larger thicknesses and low cost, i.e. to use the CsI(Tl) as high resolution heavy ion detectors.

Acknowledgements

The authors would like to thank the MULTICS group for the collaboration in the measurements and for generously making recent data available. The authors are indebted to A. Moroni and N. Colonna for stimulating discussion and suggestions. The technical assistance of R. Bassini, C. Boiano, S. Brambilla, G. Busacchi, A. Cortesi and M. Malatesta is gratefully acknowledged. This work was supported in part by the Italian Ministry of University and Scientific Research.

References

[1] M. Bruno, M. D'Agostino, P.M. Milazzo, S. Ostuni, E. Fuschini and A. Moroni, Nucl. Instr. and Meth. A 305 (1991) 410.
[2] R.T. De Souza et al., Nucl. Instr. and Meth. A 295 (1990) 109.
[3] E. Plagnol, INDRA: a new detector for heavy ion reaction studies, IN2P3-RIKEN Symp. on heavy ion collisions 2, Obernai, France (1990).
[4] I. Iori et al., Nucl. Instr. and Meth. A 325 (1993) 458.
[5] H. Grassmann, E. Lorenz and H.G. Moser, Nucl. Instr. and Meth. A 234 (1985) 122.
[6] G. Viesti, G. Prete, D. Fabris, K. Hagel, G. Nebbia and A. Menchaca-Rocha, Nucl. Instr. and Meth. A 252 (1986) 75.
[7] D.W. Stracener, D.G. Sarantites, L.G. Sobotka, J. Elson, J.T. Hood, Z. Majka, V. Avenante, A. Chbihi and D.C. Hensley, Nucl. Instr. and Meth. A 294 (1990) 485.
[8] C.J.W. Twenhöfel, P.F. Box, P. Schotanus, T.M.V. Bootsma, G.J. Van Nieuwenhuizen, P. Decowski and R. Kamermans, Nucl. Instr. and Meth. B 51 (1990) 58.
[9] N. Colonna, G.J. Wozniak, A. Veeck, W. Skulski, G.W. Goth, L. Manduci, P.M. Milazzo and P.F. Mastinu, Nucl. Instr. and Meth. A 321 (1992) 529.
[10] M. Bruno et al., Phys. Lett. B 292 (1992) 251.
[11] E. Valtonen, J. Peltonen and J.J. Torsti, Nucl. Instr. and Meth. A 286 (1990) 169.
[12] M. Buenerd, D.L. Hendrie, U. Jahnke, J. Mahoney, A. Menchaca-Rocha, C. Olmer and D.K. Scott, Nucl. Instr. and Meth. 136 (1976) 173.
[13] A. Gavron, Phys. Rev. C 21 (1986) 230.
[14] R.J. Charity, M.A. McMahan, D.R. Bowman, Z.H. Liu, R.J. Mcdonald, G.J. Wozniak, L.G. Moretto, S. Bradley, W.L. Kehoe, A.C. Mignerey and M.N. Namboodiri, Phys. Rev. Lett. 56 (1986) 1354.
[15] A. Meyer and R.B. Murray, Phys. Rev. 128 (1) (1962) 98.
[16] J.B. Birks, The Theory and Practice of Scintillation Counting (Pergamon, Oxford, 1964).
[17] H.A. Bethe, Ann. Physik 5 (1930) 325.
[18] H.H. Anderson and J.F. Ziegler, Stopping Power and Ranges in All Elements (Pergamon, 1977).
[19] F. Hubert, R. Bimbot and H. Gauvin, Nucl. Instr. and Meth. B 36 (1989) 357;
H. Breuer, Phys. Lett. C 26 (1982) 178.