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MEASUREMENTS AND CALCULATIONS OF REACTION LOSSES
OF MEDIUM-ENERGY PROTONS IN NaI DETECTORS

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ABSTRACT

Reaction losses of protons in NaI have been directly measured at 86, 133, and 146 MeV. Calculations of the expected tail-to-peak ratios were made over the range 40 to 240 MeV using recent total reaction cross-section data for sodium and iodine. The calculated ratios agree well with the data and are slightly larger than the previously calculated values of Measday and Richard-Serre.

1. INTRODUCTION

An extensive series of elastic and quasi-elastic cross-section measurements are being made at TRIUMF by several experimental groups.¹ These measurements all involve detection of protons in one or more detector telescopes, each composed of a multi-wire proportional counter (MWPC), one or more thin plastic scintillators, and a sodium iodide (NaI) total energy detector.² Because these telescopes will be used to measure absolute cross-sections, it is necessary to accurately know the absolute efficiency of the telescopes for detection of protons (and other particles) in the medium-energy range. The efficiency of the telescopes has been measured for protons over the range of proton energies from 85 to 450 MeV.^{2,3} The NaI detectors are thick enough to stop protons with energies up to 150 MeV, so degraders are not needed as part of the telescopes at the lower energies. For these cases the desired efficiency is determined only by the reaction losses in the NaI total energy detector. These losses may be calculated if the total reaction cross-sections (σ_R) for sodium and iodine are known.⁴ This report summarizes the method used to extract the NaI reaction losses from the efficiency data at three energies below 150 MeV. We compare these measured losses with results of a calculation based on the best currently available reaction cross-section data. We have obtained rather good agreement between the measured and calculated losses, which allows us to use the calculations with confidence at energies where no accurate measurements exist.

2. EFFICIENCY MEASUREMENT TECHNIQUE AND DATA ANALYSIS

The efficiency measurement consisted of detecting proton-proton coincidences from a CH₂ target in two identical detector telescopes. Each telescope contained a cylindrical NaI detector 5 in. in diameter and 3 in. thick viewed by a 5 in. photomultiplier. By selecting the angles to be those appropriate to proton-proton elastic scattering, the scattering from the carbon in the CH₂ was reduced to a small percentage of the hydrogen scattering. The energy incident on the NaI detector was calculated from the known proton bombarding energy and scattering angle, taking into account energy losses in the MWPC and plastic scintillators. The energy at the NaI detector could be conveniently varied by changing the scattering angle.

With a proton bombarding energy of 250 MeV we were able to extract the NaI reaction losses at energies of 86, 133, and 146 MeV. The selection of events to be acquired was done by requiring only a left-right coincidence between the first detectors in the two telescopes. All events satisfying this requirement were recorded on magnetic tape by a computer. The data on tape are analyzed by reading the tapes back into the computer and forming selected events into histograms. The selection of events to be formed into histograms is made by requiring that various of the recorded parameters for each event lie between specified limits. The objective of the selection process is to choose from the events recorded on tape a group which corresponds to a monoenergetic uniform flux of protons incident on the centre of the circular face of the NaI crystal.

All the data recorded on tape do not correspond to such a uniform flux because of the small number of constraints applied by the electronics when the data were acquired. In the acquisition of the data the two telescopes were treated identically. In the later analysis of the data on tape the proton detected in one telescope is used as a tagging signal to define a monoenergetic flux at the other telescope. By interchanging the roles of the two telescopes in the analysis, a measurement at one angle setting can be used to obtain the NaI reaction losses at two different energies.

A typical pulse height spectrum in the NaI from such a selected group of events is shown in Fig. 1. The quantity which conveniently characterizes the reaction losses in the NaI detector is the ratio of the number of counts in the 'tail' region to the number of counts in the full-energy peak. This ratio is a measure of the probability that a proton of a particular energy (146 MeV in the case of Fig. 1) will suffer an inelastic nuclear reaction before being stopped by the normal dE/dx process. To measure this tail-to-peak ratio accurately it is important that the 'incident beam' defined by the apparatus and analysis does not itself contain a low-energy tail. In addition, it is important to avoid any geometrical edge effects in the NaI because this type of loss varies from detector to detector and is more difficult to calculate accurately than is the bulk reaction loss.

To avoid geometrical edge effects the protons incident on the NaI are collimated in the analysis by placing limits on the co-ordinates from the MWPC detector. The accepted protons are required to pass through a

square aperture of size 6.8 cm $\times$ 6.8 cm centred on the 5 in. (12.7 cm) circular face of the NaI crystal. In addition to the collimation requirement in the NaI used for the loss measurement, it is required that events have a detected energy in the other (tagging) NaI which corresponds to elastic hydrogen scattering. These two requirements reduce the incident low-energy contamination from carbon to a fraction of one per cent of the tail from the NaI reactions. This background is then subtracted utilizing data from a similar measurement and analysis with a pure carbon target. A correction is also made for protons which suffer a reaction in one of the thin plastic counters before reaching the NaI. Using the tables of Ref. 4 for NE102 reaction losses we make corrections ranging from 1.15% at 86 MeV to 0.66% at 146 MeV.

The separation of the measured spectra into tail and peak regions is made at a point 7 MeV below the centroid of the full-energy peak, as indicated by the vertical arrow in Fig. 1. This choice of where to make the separation between tail and peak regions is somewhat arbitrary. Because of the small reaction Q-value and the finite detection resolution in the NaI it is not possible to cleanly separate the data into elastic and inelastic regions. However, the effect of changing the position of the cut by a few MeV is small. The tail-to-peak ratios for the three energies measured are given in Table I. The last column in Table I is the absolute amount by which the tail-to-peak ratio changes when the separation point between tail and peak is changed. These numbers may be used to adapt the tabulated value of reaction loss to an energy cut other than the one we used. In addition to the kinematically-determined energy of the protons passing through the centre of the MWPC aperture, the first column of Table I also gives the approximate energy spread due to kinematic broadening and finite target thickness.

Table I. Measured NaI reaction losses

The energy spread quoted in the first column is that due to kinematic broadening and finite target thickness. The uncertainty quoted in the second column is that due to statistics.

E_p (MeV)	Tail/Peak Ratio (%)	$\Delta(\text{Tail/Peak})/\Delta E$ (%/MeV)
86 $\pm$ 4	8.0 $\pm$ 0.2	0.14
133 $\pm$ 4	17.4 $\pm$ 0.3	0.17
146 $\pm$ 4	20.0 $\pm$ 0.3	0.31

3. CALCULATION OF THE EXPECTED TAIL-TO-PEAK RATIO

The method of Measday and Richard-Serre⁴ was used to calculate the expected tail-to-peak ratio for NaI and several other materials. The input to the calculation for NaI are the total reaction cross-sections for sodium and iodine as a function of proton energy, shown in Fig. 2. The curves shown in Fig. 2 are based on recent measurements of reaction cross-sections.⁵ For comparison, the older values of σ_R used by Measday and Richard-Serre are also shown.

The ambiguity of how to separate the reactions into peak and tail regions also makes a small uncertainty in the calculation of the expected tail-to-peak ratio. The calculation performed in Ref. 4 and in this work is an integration of the inelastic cross-section as a function of energy over the range of the proton as it slows down in the material. It is assumed that all inelastic events occurring as the proton slows down contribute to the tail region of the spectrum. To approximately account for the production of 'slightly inelastic' protons which cannot be resolved from the full-energy peak, the integration procedure is stopped when the proton has been degraded to some small energy in the material. In our case we chose this cut-off energy to be 5 MeV.

Fig. 3 shows the calculated tail-to-peak ratios over the energy range $E_p = 40-240$ MeV. Table II contains the same information in tabular form.

4. COMPARISON OF CALCULATED AND MEASURED TAIL-TO-PEAK RATIOS

Fig. 4 shows our data along with other measured data on NaI reaction losses in the energy range we measured. The solid curve is the calculation described in Sec. 3 of this report. The calculation of Measday and Richard-Serre is shown as a dashed curve. Our calculation using the revised values of σ_R fits the NaI reaction loss data slightly better than the earlier calculation.

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Table II. Tail-to-peak ratio protons in NaI as a function of proton energy

Energy (MeV)	Tail/Peak (%)	Energy (MeV)	Tail/Peak (%)
40	2.11	145	19.78
45	2.56	150	21.00
50	3.11	155	22.26
55	3.70	160	23.55
60	4.32	165	24.88
65	4.96	170	26.25
70	5.64	175	27.65
75	6.36	180	29.08
80	7.12	185	30.56
85	7.90	190	32.08
90	8.71	195	33.63
95	9.55	200	35.24
100	10.42	205	36.89
105	11.32	210	38.56
110	12.27	215	40.28
115	13.24	220	42.08
120	14.22	225	43.89
125	15.27	230	45.76
130	16.35	235	47.68
135	17.46	240	49.66
140	18.60		

REFERENCES AND NOTES

1. TRIUMF experiments which propose to use such detector telescopes include Elastic Scattering (proposals 14 and 24), Quasi-elastic Scattering (proposals 16 and 58) and (p,2p) Reactions (proposal 59).
2. The MWPC detectors were designed and built by E.B. Cairns at the University of Alberta. The telescope assemblies were designed by A.W. Stetz at the University of Alberta. A partial description of the telescopes is contained in:
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Fig. 1. A typical NaI energy spectrum. The arrow indicates the division point between tail and peak regions of the spectrum. The tail is taken to be the region to the left of the arrow and the peak to the right.

Fig. 2. Total reaction cross-sections used in the calculations. The solid curves are the cross-sections used in this work to compute the reaction loss in NaI. They are based on the measurements of Ref. 5. The + 's are cross-sections used by Measday and Richard-Serre⁴ at selected values of energy.

Fig. 3. Calculated NaI reaction losses as a function of incident energy. The solid curve is the calculation described in Sec. 3 of this report. The dashed curve is the calculation of Ref. 4.

Fig. 4. Measured and calculated NaI reaction losses as a function of incident energy. The solid and dashed curves are the same as in Fig. 3.