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By V.A. Vukolov, F.E. Chukreev
I.V. Kurchatov Atomic Energy Institute

Translated by A. Lorenz for the IAEA

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Abstract

Recommended cross-sections together with their uncertainties for the $^{12}C(p)^{11}C$, $^{12}C(p)^{7}Be$, $^{27}Al(p)^{24}Na$, $^{27}Al(p)^{22}Na$ and the $^{63}Cu(p)^{63}Zn$ reactions for proton energies up to 100 MeV are presented in tabular form. The cross-sections for these reactions are designed to be used as flux monitors in experiments using proton beams. The evaluation of these cross-sections was performed on the basis of an analysis of experimental data which have been published up to the year 1986. The international EXFOR data library served as the principal source of information.

Introduction

The experimental technique to measure particle beams using well known monitor reaction cross-sections has been widely used not only in basic research but also in a number of practical applications such as activation analysis, investigations of the resistance of materials to radiation damage, radioactive isotopes production, etc... Under normal circumstances experimental results obtained in such applications consume the least time and effort.

The monitor reactions most often used in the application of proton beams are $^{12}C(p)^{11}C$, $^{27}Al(p)^{24}Na$, $^{27}Al(p)^{22}Na$, $^{12}C(p)^{7}Be$ and $^{63}Cu(p)^{63}Zn$. Such a set of cross-sections allows one to monitor a particle beam of different energies and to perform experiments of varying lengths of time. However, the use of these reactions for beam flux measurements relies on measurements of cross-sections of these reactions performed in other experiments; this very often precludes taking full account of all of the pertinent data of these experiments. Another aspect of this work, which is based on the analysis of experimental data published in the open literature up to the year 1986, is the evaluation of reaction cross-sections for protons energies up to 100 MeV.

Evaluation methodology

The method used in the evaluation of these cross-sections is the same used by the authors in the evaluation of (α,n) reaction cross-sections described in reference [30]. Following is a brief description of the steps in the evaluation procedure:

1. The different sets of experimental data are plotted over comparable energy intervals yielding an approximation of the excitation function curve. The function is defined by the following expression:

$$\sigma(E) = \sum_{i=0}^{n} B_i (1-E_n/E)^{i}$$

2. Corrections to eliminate systematic inconsistencies were made when necessary. For those cross-sections which were measured by activation, which is used in most experiments, the corrections involved considerations of improved decay data published in reference [48]; these are also given in Table I.

TABLE I. DECAY CHARACTERISTICS OF RADIOACTIVE ISOTOPES PRODUCED IN MONITOR REACTIONS

Monitor Reaction	A	B	C	D	E	F
$^{12}C(p)^{11}C$	-16.5	20.3	20.39 m	β^+	0.961	99
$^{63}Cu(p,n)^{63}Zn$	-4.15	4.2	38.1 m	γ	0.670	8.4
				β^+	2.340	93
$^{27}Al(p)^{24}Na$	-23.7	32.6	15.026 h	β^+	1.390	99.91
				γ	1.360	99.99
				γ	2.754	99.84
$^{12}C(p)^{7}Be$	-22.6	28.4	53.23 h	γ	0.478	10.38
$^{27}Al(p)^{22}Na$	-18.8	24.3	2.603 y	β^+	0.546	90.50
				γ	1.274	99.94

A - Reaction energy
B - Threshold energy (MeV)
C - Decay half-life
D - Type of decay
E - Particle energy (MeV)
F - Intensity (%)

3. Values for the weighted average cross-sections and their corresponding uncertainties were determined for each energy interval, namely:

$$\bar{\sigma} = \frac{\sum_{i=1}^{n} w_i \sigma_i}{\sum_{i=1}^{n} w_1}$$

the fractional standard deviation $$\Delta\sigma_{FSD} = \frac{1}{\sqrt{\sum_{i=1}^{n} w_1}}$$

and the standard error $$\Delta\sigma_{SD} = \sqrt{\frac{1}{(n-1)} \frac{\sum w_i (\sigma_i - \bar{\sigma})^2}{\sum w_i}}$$

and where $$w_i = \frac{1}{(\Delta\sigma_i)^2}$$

is the weight given to the experimental value.

4. Birge's criterion was then calculated:

$$\mathbf{K} = (n-1)\ \frac{|(\Delta\sigma_I)^2 - (\Delta\sigma_E)^2|}{(\Delta\sigma_I)^2\sqrt{2}}$$

For K<2, the value of the weighted average cross-section was taken to be σ-bar with an uncertainty equal to the larger of the two uncertainty values $\Delta\sigma_I$ and $\Delta\sigma_E$. For those cases where K>2, and there is no reason for its reduction, then the recommended value of the cross-section was taken to be equal to the arithmetic mean of all of the experimental data (n) with an uncertainty equal to:

$$\Delta\sigma = t_p(n) \cdot \sqrt{\frac{1}{n(n-1)} \sum_i (\sigma_i - \bar{\sigma})^2}$$

where t_p is the Student's distribution coefficient for (n-1) degrees of freedom and the probability to obtain the actual value for the limits of the uncertainty p is 0.3.

Experimental data and evaluation results

The $^{12}C(p)^{11}C$ reaction is probably the most studied reaction, and the accuracy of the experimental data characterizing this reaction is better than 5%. All cross-section measurements were made by the activation method. The principal source of systematic error may be due to an inadequate accounting of the leakage of the radioactive ^{11}C isotope from the irradiated target. The magnitude of this effect has been investigated experimentally for a number of different thicknesses of different target materials [8]. It was shown that for target thicknesses smaller than 10 mg/cm^2, the extent of this effect could be as high as 15%.

The evaluation of this reaction included values of the absolute measurements reported in references [2-5], and the relative measurements published in references [1,8,16]. The values reported in reference [1] were normalized to the value of 63.3±0.3 mb at a proton energy E_p=98.1 MeV reported in reference [12] which brought about a change in their values by a factor of 0.894. The data reported in reference [2], at 62.5 and 97.5 MeV, were not included in this analysis because of the large differences between these values and those of the other authors.

The $^{27}Al(p)^{24}Na$ reaction has been investigated with the use of the activation method as well, except that for most experiments the measurements of the relative dependence of the excitation function were normalized to the values of known cross-sections of reactions such as $^{12}C(p)^{11}C$ reported in [1,17,20] and others [16,19]. This method was used because of the difficulty to account for the contribution of secondary particles from the $^{27}Al(n,\alpha)^{24}Na$ reaction, whose ^{24}Na reaction product yield is larger by an order of magnitude. Particularly in those experiments in which the target consists of a stack of individual foils, which could attain total a thicknesses of 5 g/cm^2, the contribution of this effect is reflected in an increasing degree of uncertainty, (namely 0.4±0.4 mb [45], 0.51±0.26 mb [41] and 0.61±0.30 mb [19]), which is the source of the largest part of the measurement error. The only measurement which has been excluded from the bulk of the data that are included in this analysis is the one reported in reference [16]. The large cross-section values obtained in this experiment may have been due to the inadequate consideration given to the contribution of secondary particles; however, because of the lack of information given on the technical details of the measurement, it is difficult to make the necessary corrections. In the evaluation, these results were given a lower weight by assigning an uncertainty of 15% instead of the reported 7%.

The $^{27}Al(p)^{22}Na$ reaction, because of its characteristics, is used as flux monitor in experiments requiring longer irradiation times. It can also serve as an alternative to the $^{27}Al(p)^{24}Na$ reaction, but it is less sensitive to low energy secondary particles. Because of the significant differences between results, Reference [23], which contains evaluated data derived from results published in references [7] and [5], as well as from unpublished results reported in LBL-3650, by Lind-Stream et al., and LBL-2680, by Radin et al., was also taken into consideration. The excitation function given in reference [46], which was taken as the basis in the evaluation of this reaction for energies up to 100 MeV range, was normalized to the value of 12.2±1.2 mb reported in reference [23]. The normalization coefficient used in this normalization was equal to 12.2/9.4; the recommended uncertainty of the evaluated data was based on the 10% value of the normalizing factor.

The $^{63}Cu(p)^{63}Zn$ reaction is a convenient and often used monitor for proton energies below 20 MeV. This energy range is of particular interest to the development of the proton accelerator technology to generate proton beams for medical applications. With the exception of data reported in references [19,33], the experimental data for this reaction was obtained with the use of two methods: data reported in references [19,34,31,38,35,33,43 and 32] were measured by activation, and data reported in references [39,40 and 32] were measured by the neutron counting technique. Notable systematic discrepancies between the results of these two methods have not been observed. The following correction factors have been used in order to take the current decay characteristics of ^{63}Zn into account: 0.914 for [31] and

[32], 1.20 for [35], 0.960 for [37], 0.968 for [42]. As in the procedure mentioned above, data from reference [33] were corrected by the factor 0.894 derived from the cross-section data of references [1] and [2]. The corrections which were made are justifiable for most of the data sets with the exception of the data reported in reference [35]. The 20% increase of these results made them considerably larger than the rest of the data, which prompted us to exclude them from this analysis.

The experimental data which have been included in this evaluation are shown in Figures 1a to 1f, and the values of the evaluated cross-sections, and associated uncertainties, for the $^{12}C(p)^{11}C$, $^{27}Al(p)^{24}Na$, $^{27}Al(p)^{22}Na$, $^{12}C(p)^{7}Be$ and $^{63}Cu(p)^{63}Zn$ reactions are listed in Tables IIA, IIB and IIC.

A comparison of these evaluated data with results that had been published earlier shows the following:

- for the $^{12}C(p)^{11}C$ reaction, the recommended accuracy has improved from 5% (given in reference [7]) to 3%, which is due to the new measurements [8 and 12], whereas the evaluation published in [7] relies primarily on data from reference [1] normalized to values at E_p=50 MeV published in reference [4];

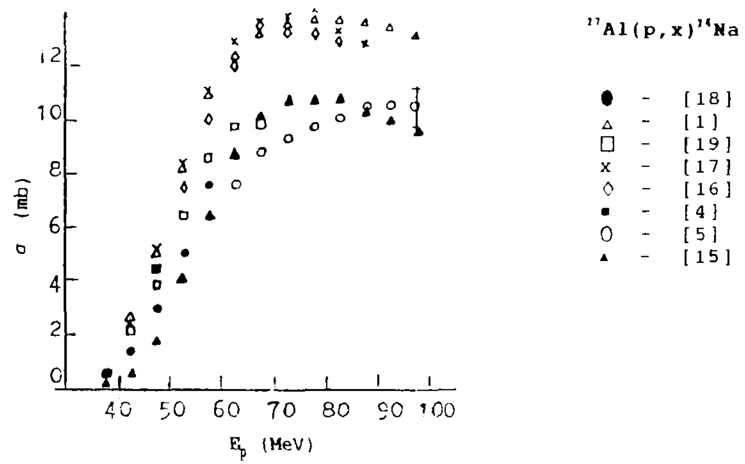
- although the 6% accuracy of the evaluated data for the $^{27}Al(p)^{24}Na$ reaction is comparable to the data accuracy claimed in reference [7], the data values of this evaluation are a good 5% larger, which is due primarily to the inclusion of five new sets of data out of a total of nine considered measurements;

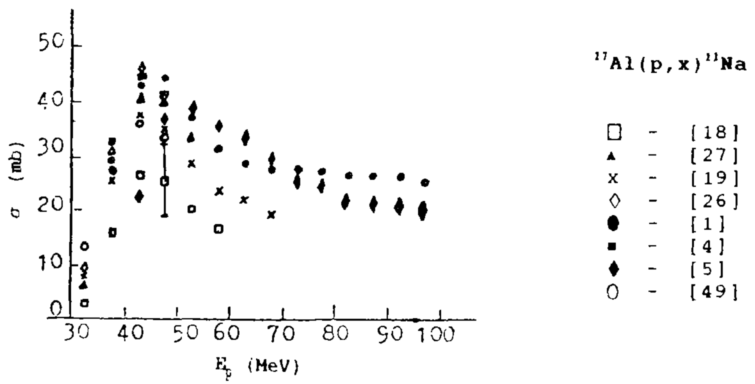
- the accuracy of the $^{27}Al(p)^{22}Na$ reaction data ranges from 7% to 10%, which is due primarily to new experimental results;

- the 10% accuracy of the evaluated $^{11}C(p)^{7}Be$ reaction data is on the average 10% lower than the earlier data published in [7] and is closer to the evaluation published in [23];

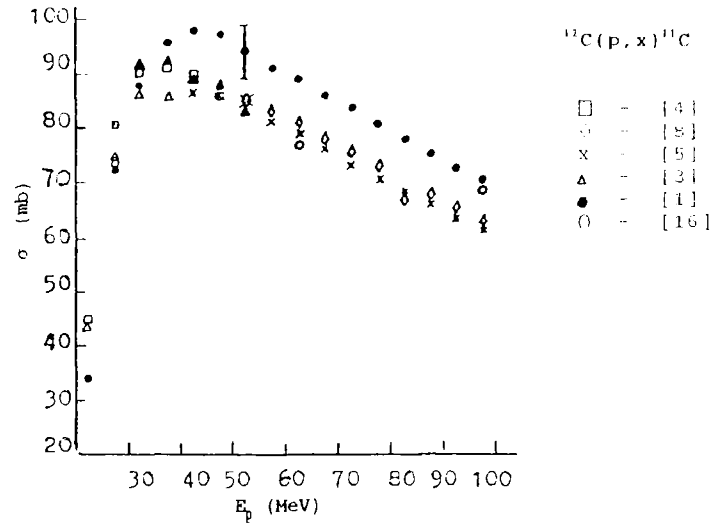
- for the $^{63}Cu(p,n)^{63}Zn$ reaction, the recommended accuracy is 5% in the most interesting energy range of 6 to 12 MeV.

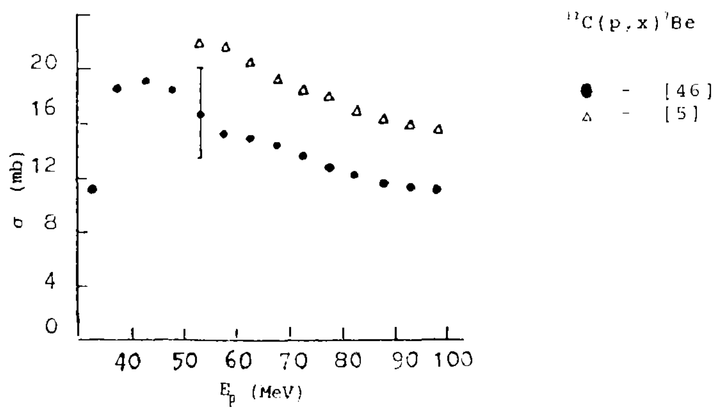
Figures 1a and 1b. Experimental Data



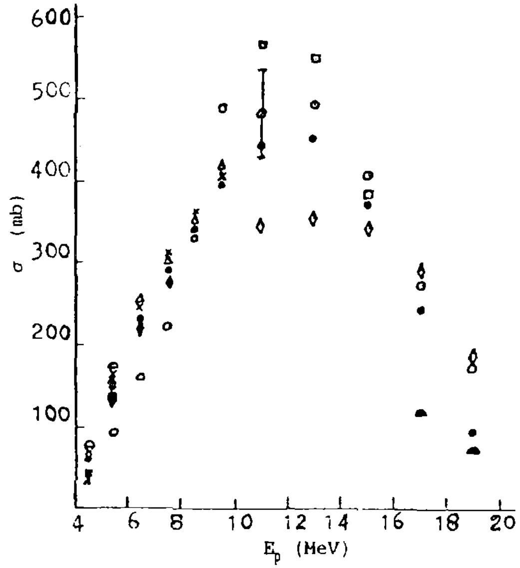


Figures 1c and 1d. Experimental Data



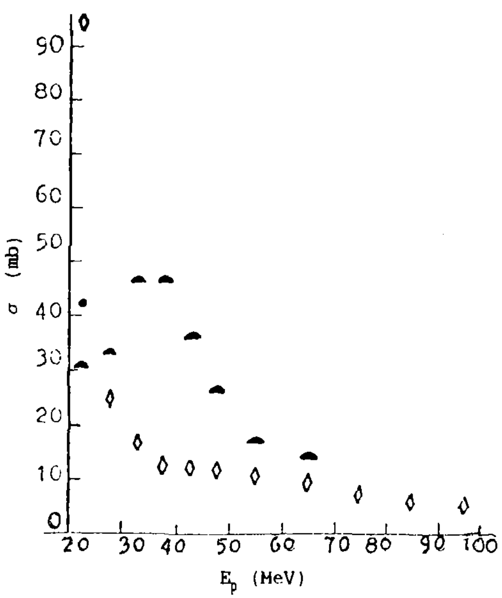


Figures 1e and 1f. Experimental Data



$^{63}Cu(p,n)^{63}Zn$

- [19]
- [34]
- [31]
- [38]
- [35]
- [39]
- [33]
- [40]
- [43]
- [37]
- [32]



$^{63}Cu(p,n)^{63}Zn$

(same captions as above)

TABLE IIA. RECOMMENDED MONITOR REACTION CROSS-SECTIONS

E (MeV)	$^{12}C(p)^{11}C$		$^{27}Al(p)^{24}Na$	
	σ (mb)	Δσ (mb)	σ (mb)	Δσ (mb)
22.5	44.2	1.7	-	-
27.5	76.2	2.7	-	-
32.5	88.9	2.2	-	-
37.5	89.2	2.0	0.60	0.03
42.5	88.9	2.0	2.10	0.08
47.5	87.3	2.0	4.4	0.2
52.5	85.1	1.9	6.7	0.4
57.5	83.0	2.0	9.3	0.6
62.5	79.2	1.5	9.4	0.7
67.5	78.0	1.9	10.1	0.5
72.5	75.6	1.8	10.6	0.6
77.5	72.8	1.8	10.7	0.6
82.5	68.4	1.6	10.7	0.4
87.5	67.5	1.6	10.5	0.4
92.5	65.1	1.6	10.4	0.4
97.5	64.7	1.8	10.3	0.4

TABLE IIB. RECOMMENDED MONITOR REACTION CROSS-SECTIONS

E (MeV)	$^{27}Al(p)^{22}Na$		$^{12}C(p)^{7}Be$	
	σ (mb)	Δσ (mb	σ (mb)	Δσ (mb)
22.5	-	-	-	-
27.5	-	-	-	-
32.5	7.6	0.7	14.3	1.4
37.5	28.8	1.7	23.9	2.4
42.5	41.5	1.3	24.8	2.5
47.5	39.7	1.0	23.9	2.4
52.5	33.9	1.5	21.6	2.2
57.5	30	4	20.3	2.0
62.5	29	3	19.5	2.0
67.5	28	3	18.7	1.9
72.5	27.0	2.1	17.7	1.8
77.5	24.0	1.7	16.6	1.7
82.5	21.8	1.5	15.9	1.6
87.5	21.2	1.5	15.1	1.5
92.5	20.7	1.4	14.8	1.5
97.5	20.0	1.4	14.6	1.5

TABLE IIC. RECOMMENDED MONITOR REACTION CROSS-SECTIONS

E (MeV)	$^{63}Cu(p,n)^{63}Zn$	
	σ (mb)	Δσ (mb
4.6	45	5
5.5	142	13
6.5	225	16
7.5	290	12
8.5	348	14
9.5	403	16
11.0	455	25
13.0	464	26
15.0	381	21
17.0	251	18
19.0	77	4
22.5	30	4
27.5	25	4
32.5	17	2
42.5	12.6	1.9
47.5	12.0	1.8
55	11.0	1.6
65	9.6	1.4
75	7.8	1.2
85	6.0	0.9
95	5.6	0.8

In concluding, it must be noted that the use of the evaluated cross-section data for the reactions considered in this analysis makes it possible to monitor a proton beam flux with an accuracy of 3 to 5% in a proton energy range of up to 100 Mev in experiments of various time duration.

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