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Cross Sections for (p,n) and (d,2n) Reactions on ^{79}Br and ^{127}I :
An Evaluation of Literature and Model Calculated Results

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Cross Sections for (p,n) and (d,2n) Reactions on ^{79}Br and ^{127}I :
An Evaluation of Literature and Model Calculated Results

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ABSTRACT

We have evaluated (p,n) and (d,2n) cross sections on ^{79}Br and ^{127}I , and made these cross sections available for test diagnostics. We believe that these interim cross sections are of reasonable accuracy and should be used for diagnostic interpretations until more precise measurements can be made. Our evaluation consisted of a literature search and an examination of the available experimental data. These data were supplemented by statistical model calculations using both the STAPRE and ALICE codes. We found reasonably good measured data (from threshold to the peak of the excitation function) for the (p,n) reaction on both ^{79}Br and ^{127}I . The literature data for the (d,2n) reaction on ^{127}I is questionable and no data were found for the (d,2n) reaction on ^{79}Br . We have, therefore, relied completely on calculations for the (d,2n) cross sections for both ^{79}Br and ^{127}I .

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Because of current interest in ^{79}Br and ^{127}I as charged-particle detectors in nuclear device diagnostics, we have evaluated the relevant cross sections. This evaluation has provided interim cross-section sets for ^{79}Br and ^{127}I , and also the background data necessary for future measurements. Because of the success of our recent measurements of (p,n) and (d,2n) excitation functions on the Eu nuclei, we believe that we have developed a simple but effective target-making technology which we can apply to other difficult materials. Thus, it seems now possible to make very good cross section measurements of the rather difficult halogen species Br and I.

We present here the data obtained from our literature search condensed, edited, and evaluated. These evaluations were aided by our best experience with Ti and Cr and are derived, in part, from statistical-model calculations which incorporate, in particular, our understanding of deuteron breakup as it applies to cross sections at low energies. Our survey of the literature covered the years 1935-1988 via computer search through the National Nuclear Data Center archives which was performed by the LLNL Technical Information Division. Between the years 1976-1988, this information was supplemented by references obtained from the "Charged Particle Nuclear Data Bibliography," published by the Brookhaven National Laboratory.

The results of our evaluations for the (p,n) and (d,2n) excitation functions for ^{79}Br and ^{127}I are given in Tables 1-4. These tables include both experimental and calculated results. In Table 5, we summarize our primary and secondary sources and add some clarifying notes about the experiments and the errors in the data. In Figures 1-4, we show much of the data and plot the results of our statistical-model calculations.

Cross section measurements at low energies, and where the excitation function rises rapidly, are difficult to make and are susceptible to many uncertainties. In our experiments we always make multiple measurements and check our consistency by comparing results at the same energy with thin and thick targets. In general, the measurements currently described in the literature are not done with the same level of care. Thus, although the errors quoted by most authors are realistic when applied to excitation function data at high energies, they tend to be somewhat optimistic when applied to measured values near threshold. Moreover, because modern measurements now tend to emphasize radionuclide production for medical

applications, an accurate cross-section measurement, when such a value is small, is not a particularly important component of that research. For those reasons, and because there simply is not much data on the rising portion of the excitation functions, we have used model calculations to fill in these gaps. Although there are particular uncertainties associated with applying such calculations to Br and I, we believe our calculated values, when combined with existing data, offer a far more palatable "guess" at a cross section than simple extrapolations or other ad hoc numerical manipulations. For the (d,2n) cross sections, we completely relied on the calculations from the STAPRE and ALICE codes with global parameters. In the rising portion of the excitation functions, the two codes gave similar cross sections, although the physics in both is somewhat different.

Virtually all the measurements discussed were done with stacked foils (see Table 5, note c). This is a standard technique but suffers from the drawback that the energy deposited in a foil must be calculated by an energy-loss prescription. Error propagation can be considerably reduced if one uses few foils per stack and if each foil is reasonably thin. The primary references noted deal with experiments in which we believe that some care was taken to minimize this kind of error propagation.

Finally, in Figures 1-4, we have also plotted some of the data from our secondary sources. This is done to emphasize what we believe are essentially consistent results among all the experiments. The plots further emphasize the paucity of data at low energies; for all the isotopes considered here, there are only eight (8) data points for $E < 7$ MeV.

Table 1: $^{79}\text{Br} (p,n) ^{79}\text{Kr}$

No.	E_p (MeV)	$\sigma(p,n)$ (mb)	No.	E_p (MeV)	$\sigma(p,n)$ (mb)
1	2.47	0.11 ^a	9	7.76	442
2	2.97	3.91	10	8.83	545
3	3.48	13.7	11	9.92	626
4	3.98	33.6	12	10.98	724
5	4.33	52 ^b	13	12.13	646
6	5.55	160	14	13.12	521
7	6.70	328	15	14.11	434
8	7.13	394	16	16.69	158

(^a) Cross-section values between 2.47 and 3.98 MeV are taken from STAPRE calculations. These calculations are done with global optical model parameters and fit the existing data between 4.33 and 7.13 MeV quite well. These calculations give -5 mb at 3 MeV while the measurement at this energy gives -1.4 mb. We recommend that the calculated values be taken in place of a simple extrapolation of the data to 3 MeV. The calculations were also done with ALICE code with global parameters. The calculated cross sections from the STAPRE and ALICE codes agree quite well for the threshold region.

(^b) Experimental data given for energies between 4.33 and 16.69 MeV.

Table 2: $^{79}\text{Br} (d,2n)^{79}\text{Kr}$

No.	E_d (MeV)	$\sigma(d,2n)^a$ (mb)	No.	E_d (MeV)	$\sigma(d,2n)^a$ (mb)
1	4.78	0.005	12	6.96	277
2	4.88	0.16	13	7.52	389
3	4.99	0.96	14	7.93	467
4	5.01	1.54	15	8.55	574
5	5.22	7.7	16	8.96	637
6	5.52	32	17	9.57	721
7	5.73	56	18	9.98	769
8	6.04	104	19	11.01	868
9	6.24	140	20	12.03	943
10	6.55	197	21	13.06	999
11	6.75	236	22	14.09	1043

(^a) No data available. The values given here are obtained from a STAPRE calculation, but reduced by 20% to account for deuteron breakup. This reduction is based on our experience with understanding the (d,2n) reaction in Cr and Ti. The STAPRE calculations, at lower energies, agree quite well with those obtained from an ALICE calculation.

Table 3: $^{127}\text{I} (p,n) ^{127}\text{Xe}$

No.	E_p (MeV)	$\sigma(p,n)$ (mb)	No.	E_p (MeV)	$\sigma(p,n)$ (mb)
1	3.01	0.08 ^a	10	7.14	135
2	3.5	0.28	11	7.77	196
3	4.0	0.89	12	8.78	362
4	4.34	1.61	13	8.93	375
5	4.5	3.15	14	9.92	457
6	5.0	8.9	15	10.98	384
7	5.56	20.3	16	12.13	305
8	6.0	42.4	17	13.15	193
9	6.70	86.3 ^b	18	14.12	134

(^a) Cross sections between 3.01 and 6.0 MeV are taken from STAPRE calculations except for the points at 4.34 and 5.56 MeV. At these points, the calculated/measured points agree to better than 3% and, therefore, we have kept the measured values. The STAPRE cross sections near threshold agree quite well with those from the ALICE code.

(^b) Experimental values given for points between 6.70 and 14.12 MeV.

Table 4: $^{127}\text{I}(d,2n)^{127}\text{Xe}$

No.	E_d (MeV)	$\sigma(d,2n)^a$ (mb)	No.	E_d (MeV)	$\sigma(d,2n)^a$ (mb)
1	3.91	0.001	10	8.58	328
2	4.52	0.16	11	8.99	394
3	4.93	1.04	12	9.60	490
4	5.54	7.1	13	10.01	550
5	5.94	18	14	11.02	685
6	6.55	53	15	12.04	796
7	6.96	91	16	13.05	863
8	7.57	169	17	14.07	879
9	7.98	230	18	15.09	878

(^a) The cross-section values noted here are taken from STAPRE calculations reduced by 25% to account for deuteron breakup. The reduction factor is somewhat more uncertain for the I nuclei because calculations here are outside our range of experience in matching deuteron data and calculations. The available experimental data for this reaction are highly uncertain and have not been used in our evaluation. The STAPRE cross sections for lower energies agree quite well with those from the ALICE.

Table 5. References and summaries of published information.

Sources	$^{79}\text{Br} (p,n) ^{79}\text{Kr}$
(1) R. Colle & R. Kishore, <i>Phys. Rev. C</i> , 2166 (1974).	Brookhaven Nat'l Lab. Van de Graaff accelerator; beam energy error ^a quoted as ± 100 keV in the average energy experienced by each target; individual targets irradiated; targets made by vacuum evaporating natural KBr or Al discs encapsulated in ~ 12 mg/cm ² Mylar, target thickness determined two ways with error 2-4%; atoms produced were deduced by Ge(Li) measurements ^b of γ -ray activity; absolute cross sections based on beam current and target thickness measurements; errors in measured values quoted for each point; primary reference.
(2) M. Diksic et al., <i>Phys. Rev.</i> 19, 1753 (1979).	McGill Univ. Synchrocyclotron, beam energy varied by placing targets at appropriate physical radii in the cyclotron, beam energy uncertainty ± 2 MeV; targets of isotopically enriched (95.06%) ^{79}Br sealed in Al capsules subsequently "flattened" to an absorption thickness of 2 MeV at 10 MeV; atoms produced were deduced from Ge(Li) measurements of γ -ray activity; absolute cross sections relative to copper standard, ^c errors in measured values are quoted for each data point, authors note that their results agree well with those of (1); secondary reference.
(3) K. Sakamoto et al., <i>Int. J. Appl. Radiat. Isot.</i> 36, 1335, (1983).	INS, Univ. of Tokyo fixed-energy cyclotron; beam energy error not given; stacked-foil technique ^e ; targets of natural KBr pressed into discs 110-330 mg/cm ² covered with 2.36-mg/cm ² Al sealed in Mylar 0.9 mg/cm ² ; atoms produced were deduced from Ge(Li) measurements of γ -ray activity; absolute cross sections relative to aluminum standard ^c ; reference presents no numerical tabulations but the data were obtained from the authors, errors are quoted for each data point; authors say their results are somewhat lower than previous measurements; secondary reference.
(4) R. Weinreich & J. Kneiper, <i>Int. J. Appl. Radiat. Isot.</i> 34, 1335 (1983).	Julich Institut für Kernphysik fixed-energy cyclotron, beam energy error ± 1 MeV; stacked-foil technique, targets of natural NaBr sealed in polyethylene foils of unquoted thickness; atoms produced were deduced from Ge(Li) measurements of γ -ray activity; absolute cross sections measured relative to copper standard, errors in measured values are quoted as ± 10 -15%; results are plotted but no numbers are given, authors quote excellent agreement with (1) and (2); secondary reference.
No data available	
$^{129}\text{I} (d,2n) ^{127}\text{Xe}$	
(5) R. Colle & R. Kishore, <i>Phys. Rev. C</i> , 2166 (1974).	See (1) above. Authors measured cross sections with KI targets under virtually identical conditions to (1); primary reference.
(6) K. Sakamoto et al., <i>Int. J. Appl. Radiat. Isot.</i> 36, 481 (1985).	See (3) above. Authors measured cross sections with KI targets under virtually identical conditions to (3); secondary reference.
(7) M. C. Lagunas-Solar et al., <i>Int. J. Appl. Radiat. Isot.</i> 37, 823 (1986).	Univ. of Calif., Davis, variable-energy cyclotron; beam energy error quoted to ± 1 %; stacked-foil technique, targets of natural NaI 0.045-cm thick mounted on Al discs sealed with 0.0025-cm thick Al; atoms produced were deduced from Ge(Li) measurements of γ -ray activity; absolute cross sections based on beam current and target thickness measurements; errors in measured values quoted to ± 9 %; authors quote excellent agreement with (5) above 20 MeV; however a value at ~ 12 MeV is a factor of 2.6 larger than a similar value quoted in (5); secondary reference.

Table 5. (Continued.)

Sources	$^{127}\text{I}(\text{d},\text{Zn})\ ^{127}\text{Xe}$
(8) S. Balestrini, <i>Phys. Rev.</i> 95 , 1502 (1954).	Univ. of Calif. Berkeley, 60-in. variable-energy cyclotron; beam energy error quoted for each energy; stacked-foil technique; targets made by spraying saturated alcohol solution of natural KI onto Al discs of known thickness, plated discs covered with Al disc and sealed; atoms produced were measured by an isotope separator; absolute cross sections based on beam current and target thickness measurements; errors in measured cross sections quoted for each point; primary reference.
(9) R. Weinreich et al., <i>Int. J. Appl. Radiat. Isot.</i> 25 , 535 (1974).	See (4) above. Authors measured cross sections with KI targets under virtually identical conditions and note good agreement with (8); secondary reference

Notes and definitions:

- ^aBeam energy error: This is generally an indication of the minimum uncertainty with which a cross-section point on an excitation-function curve can be fixed along the energy axis. The finite thickness of a target will, of course, compound this error because of additional uncertainties due to this thickness and the resultant energy loss of the beam. Such errors can multiply further if several foils are stacked together in a so-called "stacked-foil technique."
- ^bGe(Li) measurements: The number of atoms of a reaction product produced by a charged-particle beam can usually be determined by measuring the residual γ -radiation from reasonably long-lived β -decaying residues. Usually such measurements with Ge(Li) γ -ray spectrometer systems are quite good with γ -ray intensity errors of < 1 -3%. Such measurements, however, are relative and must be fixed to an absolute standard measured previously. That is, it must be known, *a priori* that x atoms of some radioactive material will give y γ -rays. Such absolute measurements are non-trivial and are also a source of error.
- ^cStacked-foil technique: In this type of measurement, several targets (perhaps separated by thin Al foils) of the same material are stacked in a cylindrical array and exposed to a charged-particle beam. To determine the average energy experienced by each foil, one must rely on energy-loss calculations. In arrays stacked with more foils, an error in the target thickness measurement or in the energy-loss calculation may propagate and cause a significant error in the cross section determined for the last or intervening foils. In (7), for example, a total of 35 foils were exposed to an incident proton energy of 67.5 ± 0.5 MeV. In this experiment, the cross section for the last foil was nearly a factor of 3 smaller than a similar measurement (1) conducted with thin, single foils. Thus, although the number of atoms of the reaction residue may be determined quite well, the energy at which these products were formed is very probably uncertain by as much as ± 2 MeV.
- ^dCopper standard: $^{63}\text{Cu}(p,n)^{63}\text{Zn}$. This excitation function is known with good accuracy and is sometimes used as an internal monitor to determine beam energy.
- ^eAluminum standard: $^{27}\text{Al}(d,pn)^{26}\text{Na}$ or $^{27}\text{Al}(p,apn)^{22}\text{Na}$ (see note^d).

Fig. 1 $^{79}\text{Br}(p,n)^{79}\text{Kr}$ cross sections. Our adopted values are shown along with measured data from the literature and our calculations.

Fig. 2 $^{79}\text{Br}(d, 2n)^{79}\text{Kr}$ cross sections. No measured data are available. Our adopted values are shown along with calculations.

Fig. 3 $^{127}\text{I}(p, n)^{127}\text{Xe}$ cross sections. Our adopted values are shown along with measured data from the literature and our calculations.

Fig. 4 $^{127}\text{I}(d, 2n)^{127}\text{Xe}$ cross sections. Our adopted values are shown along with measured data from the literature and our calculations.